

GRABEN HYDROCARBON PLAYS AND STRUCTURAL STYLES

T. P. HARDING¹

ABSTRACT

Harding, T. P. 1983 Graben hydrocarbon plays and structural styles. In: J. P. H. Kaasschieter & T. J. A. Reijers (eds.): *Petroleum geology of the southeastern North Sea and the adjacent onshore areas* (The Hague, 1982) – *Geol. Mijnbouw* 62: 003-023.

Hydrocarbon occurrences, types of traps, and structural styles have been synthesized from the Sirte, Suez, and Viking grabens. Hydrocarbons occur in a stacked succession of one or more basins: pregraben, graben and interior sag. Preservation of pregraben reservoirs depends on late initiation of crustal arching and limitation of uplift to the graben shoulders. Trap closure in pregraben and graben-fill deposits is primarily dependent on the multidirectional orientation of normal faults, tilting of fault blocks, and flexing or erosion parallel to block edges. Fault patterns include dominant longitudinal faults parallel to the graben axis and oblique faults. Block rotation is influenced by fault profile, amount of extension, fault pattern, downwarping of the sag basin, and isostatic adjustments between large blocks. Fold closures result from the upward termination of faults into forced folds that are subsequently accentuated by fault drag. Folds extend to shallower depths and into the interior-sag base by passive drape and differential compaction. Traps above this level are dependent on factors other than graben tectonics.

INTRODUCTION

This work documents the kinds of major hydrocarbon accumulations, here termed 'plays' that have thus far been found in the Sirte basin of Libya, the Gulf of Suez in Egypt, and the Viking graben of the North Sea. In past usage, plays have commonly been defined either by the stratigraphic level of the reservoir (e.g., a Middle Jurassic play) or by the kind of trap (e.g., a truncated fault-block play) that dominates a particular trend or region.

Applied in the proper context, the Sirte, Suez, and Viking grabens also provide models for basin development and prospect (trap) identification. The structural characteristics of hydrocarbon traps and the typical structural style of grabens are summarized from these basins and from a number of other normal faulted regions. Certain kinds of structures and relationships are repeated in most areas, and these similarities are emphasized (see also HARDING & LOWELL, 1979). The estimated ultimate recoverable hydrocarbons that they contain provide a measure of the relative importance of each trap type within its basin. Hydrocarbon richness, however, is

controlled by many factors, a number of which are not considered in the present discussion.

Past accounts of hydrocarbon occurrences in grabens have been treated either in detailed studies of individual fields or in basin overviews that emphasize statistics and stratigraphic levels of production. Hydrocarbons in the North Sea and Sirte basin have been discussed from the latter viewpoint by ZIEGLER (1979) and PARSONS ET AL. (1980), respectively. For the Gulf of Suez, GILBOA & COHEN (1979) have documented the characteristics of hydrocarbon traps in cross-section.

Discussions of the stratigraphy, reservoir development, and general geology of each basin are limited in the present article. The reader is referred instead to past work, such as that of GOURDAZI (1970) for Libya, GARFUNKEL & BARTOV (1977) for the Gulf of Suez, and ZIEGLER (1978, 1980) for the North Sea.

In the discussion that follows, the author first reviews the major hydrocarbon plays in the Sirte, Suez, and Viking grabens. Next, the tectonic controls for the development of these plays and for the development or preservation of the basins in which they occur are described. Last, the structural styles of grabens and controls for individual traps are summarized from a wide range of examples, and these are presented in the context of profile and map characteristics.

¹ Exxon Production Research Company, P.O. Box 2189, Houston, Texas 77001, USA.

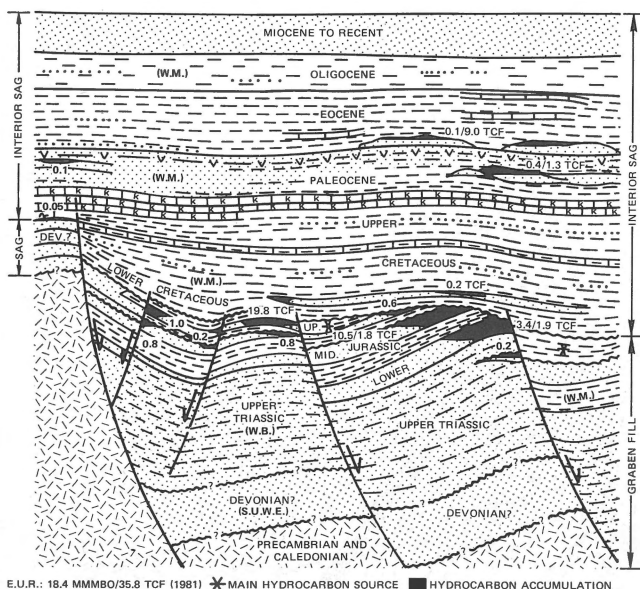


Fig. 4. Schematic diagram of major hydrocarbon plays and traps in Viking graben, North Sea, compiled from published data, augmented with data supplied by the exploration staffs of Esso Exploration and Production U.K. and of Esso Exploration and Production Norway. Devonian (?) 'sag' sequence was deposited in an incompletely known basin that predates graben cycle. Reserves include gas stated in trillions of cubic feet (TCF). Volcanic tuff indicated by v; other symbols explained in figure 2. Several traps related to salt flowage at far south end of graben are excluded.

Sirte basin hydrocarbon plays

In the Sirte basin all three potential sedimentary cycles (pregraben, graben, and interior sag) are present and productive. These cycles are found in three broad graben arms – Sirte basin deep/Hagfa trough, Tumayn subbasin, and Sarir-Hameimat trough (Fig. 5) – which define a large triple junction within the continental crust of the African plate. Graben formation started in the Late Cretaceous and ended with the downwarping of the interior sag in the middle Late Eocene (PARSONS ET AL., 1980). The northwestern arm (Sirte basin deep) of the triple junction is the most prolific; its hydrocarbon occurrences are summarized in figure 2.

Plays in pregraben reservoirs – During the Palaeozoic (KLITZSCH, 1970) and Early Cretaceous, passive margin sag and shelf sequences spread southward from the north margin of the ancestral African plate and covered the future site of the Sirte basin. Within these sediments, the fractured Cambrian-Ordovician quartzites of the Gargaf Formation provide reservoirs for a major play below the Upper Cretaceous and Palaeogene graben fill. Fluvial sandstones of the Lower Cretaceous Nubian Formation are the reservoir for a second major play, which is productive mostly in the Sarir-Hameimat Trough (SANFORD, 1970). A fractured and weathered granitic

basement is a third nonconformity reservoir, and it produces at one major field on the Amal platform (WILLIAMS, 1972).

In both the Gargaf and Nubian plays, hydrocarbons have accumulated directly under an angular unconformity at the base of the graben fill. Traps have been filled by hydrocarbons derived primarily from Upper Cretaceous marine shales deposited in adjacent graben deeps (PARSONS, ET AL., 1980). Gargaf pools and most other producing fields in the northwestern arm of the Sirte basin are located at the updip edge of broad platforms (e.g., fields on the Amal, Zelten, and Beda platforms in figure 5; platforms in this discussion are large, positive structures, usually formed by an agglomeration of several fault blocks, as in figure 6). Nubian production is mainly from midtrough structures where the relatively low structural position of the blocks has protected the reservoir from erosion (fields in the Sarir and Hameimat troughs in figure 5).

Individual closures in both the Gargaf (see Cambrian-Ordovician quartzite in figure 2) and Nubian formations are truncated fault blocks, some with vertical closure increased by block-edge drag or drape flexing and buried topographic highs. The geometries of individual traps and controls for their development are discussed in the section on graben structural styles.

One large Nubian field provides a notable exception to the dominance of structure-related traps in the pregraben sedimentary cover. Here, hydrocarbons have accumulated in a truncation trap at the base of the Upper Cretaceous shales, but in an off-structure position that is not block faulted (CLIFFORD ET AL., 1981).

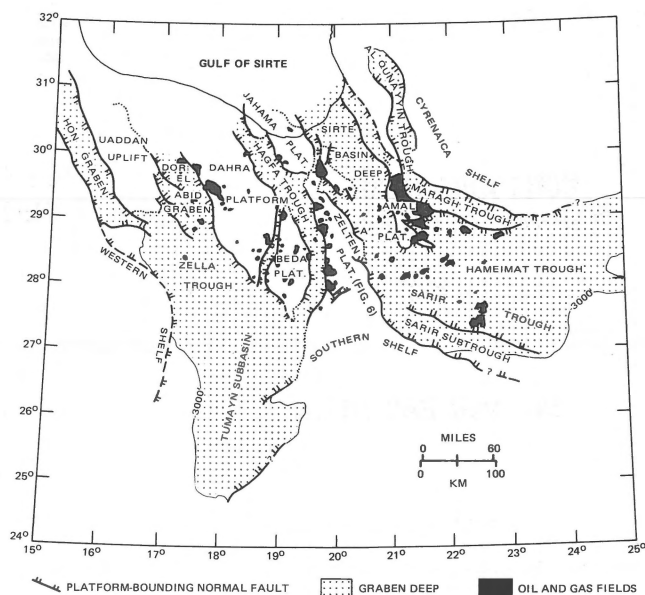


Fig. 5. Major tectonic elements of Sirte basin, Libya. Five major northwest-trending grabens have formed an unusually wide basin complex in northwest portion of basin and provide several sites for maturation of hydrocarbons. Accumulations in this area are summarized in figure 2.

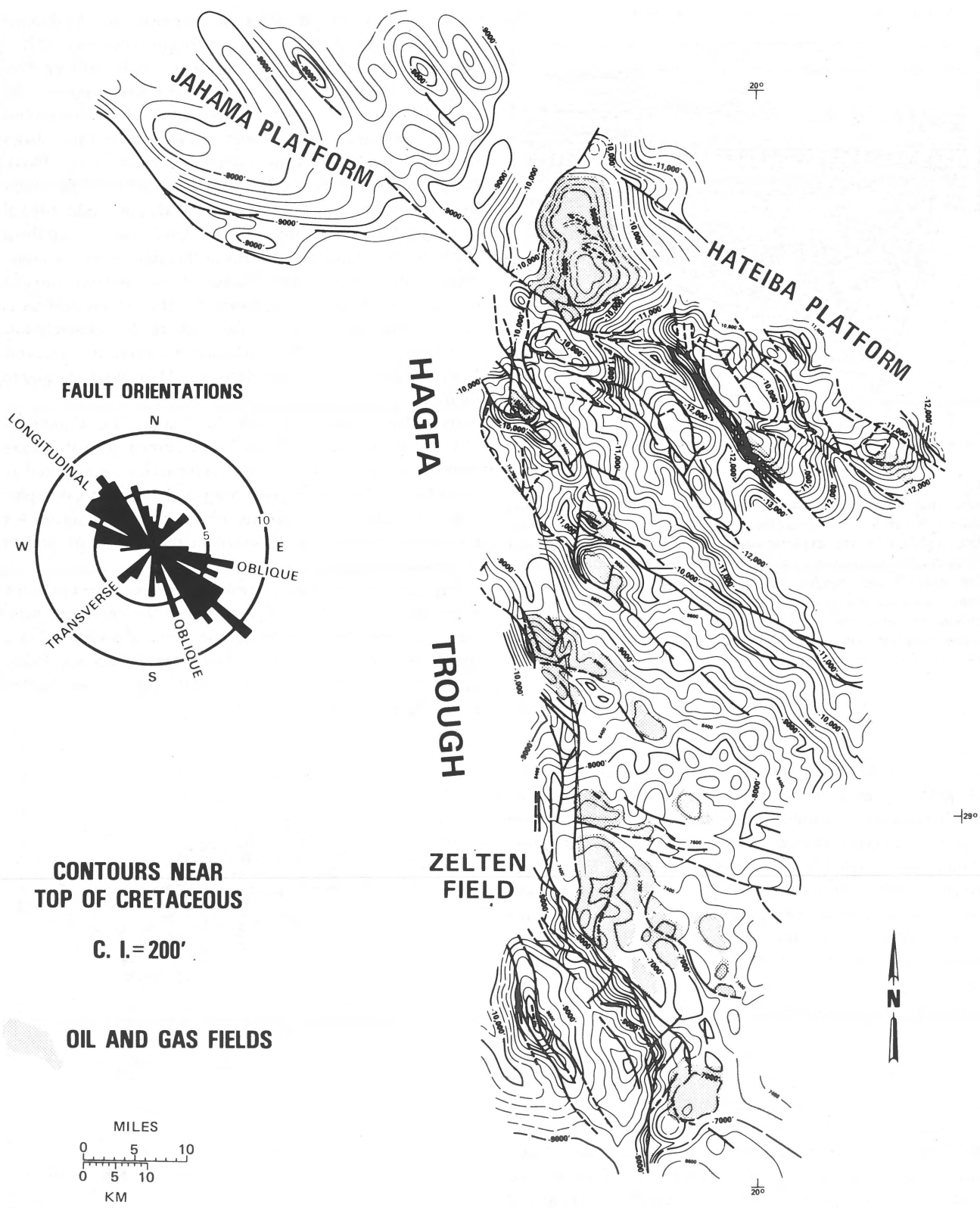


Fig. 6. Structure of Zelten Platform, north-central Sirte basin, and plot of numbers of major faults with orientations within each 5° geographic quadrant. Normal faults parallel to regional strike of Sirte basin deep are termed longitudinal: those trending at right angles to the deep are transverse. Faults whose orientations lie in between longitudinal and transverse are termed oblique. See figure 5 for orientation of Sirte basin deep and location of Zelten Platform.

Plays within the graben fill – The most prolific and varied of the Sirte basin plays, however, lie within the graben-fill cycle. At this level, rich Upper Cretaceous and Paleocene source rocks, Upper Cretaceous to Eocene shallow marine clastic and carbonate reservoir rocks, and abundant structures are all closely juxtaposed (Fig. 2).

Coarse clastics at the base of the graben fill were derived from Gargaf quartzites and from crystalline basement rocks that were exposed at the high edges of large platforms during the Cretaceous erosion. These basal sands are reservoirs for major accumulations at the west edge of the Zelten and the east side of the Amal platforms (Fig. 5; WILLIAMS, 1972). Sands with a similar provenance contain major reserves in a low-side fault trap opposite the east boundary of the Amal platform (WILLIAMS, 1968).

Prolific carbonate reservoirs occur stratigraphically above the basal sands. Productive Paleocene reefs are localized mostly at high fault-block corners (e.g., several fields at the west side of Dahra, Beda, and Zelten platforms, figure 5), and closures in Paleocene carbonate banks occur where the banks are draped across platform boundaries (Fig. 7). Porous Eocene carbonates, reworked at the unconformity at the top of the graben sequence, are reservoirs for another type of carbonate play, particularly near the south block of the Amal platform (Fig. 5). Pinnacle reefs located within the Sirte basin deep provide traps at a level where local structural closures are absent (BRADY ET AL., 1981).

In many cases the hydrocarbons within the graben-fill reservoirs are partially trapped against the upthrown side of the block-bounding faults. This has greatly increased the trap capacities of the associated block-edge flexures or sedimentary buildups. The spillpoint for these accumulations is commonly the highest level of the producing reservoir on the fault's low side.

Plays within the interior-sag basin – Since the end of the graben phase – or, approximately, since the end of the Eocene – the Sirte basin has subsided as a single tectonic unit. Subsidence has taken the form of a broad, simple downwarp superimposed across the earlier fault-block architecture. A small play within the sag fill has resulted from flexing associated with selective rejuvenation of an older platform-bounding fault (south block of Amal platform, figure 5). Other plays are absent because of the sparsity of structural closures.

Gulf of Suez hydrocarbon plays

Plays in pregraben reservoirs – At various times the Palaeozoic and Mesozoic shelves of the north margin of the African plate also extended southward across the location (Fig. 8) of the present Gulf of Suez (SOLIMAN & FARIS, 1963). The shelfal sediments again provide reservoirs for an important hydrocarbon play, here lying beneath a dominantly marine Miocene to Recent graben fill (Fig. 3).

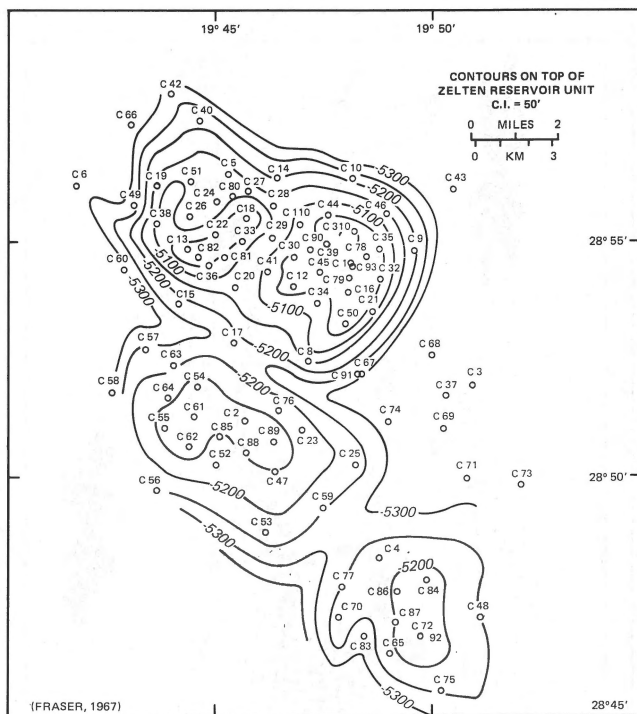


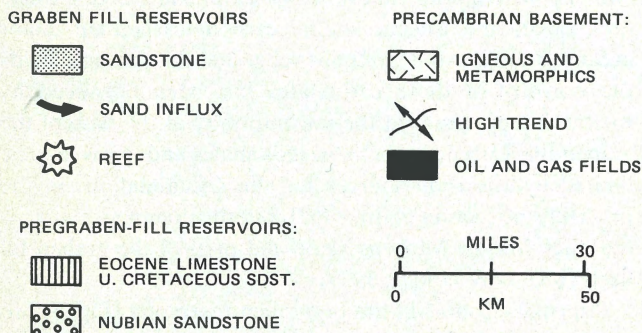
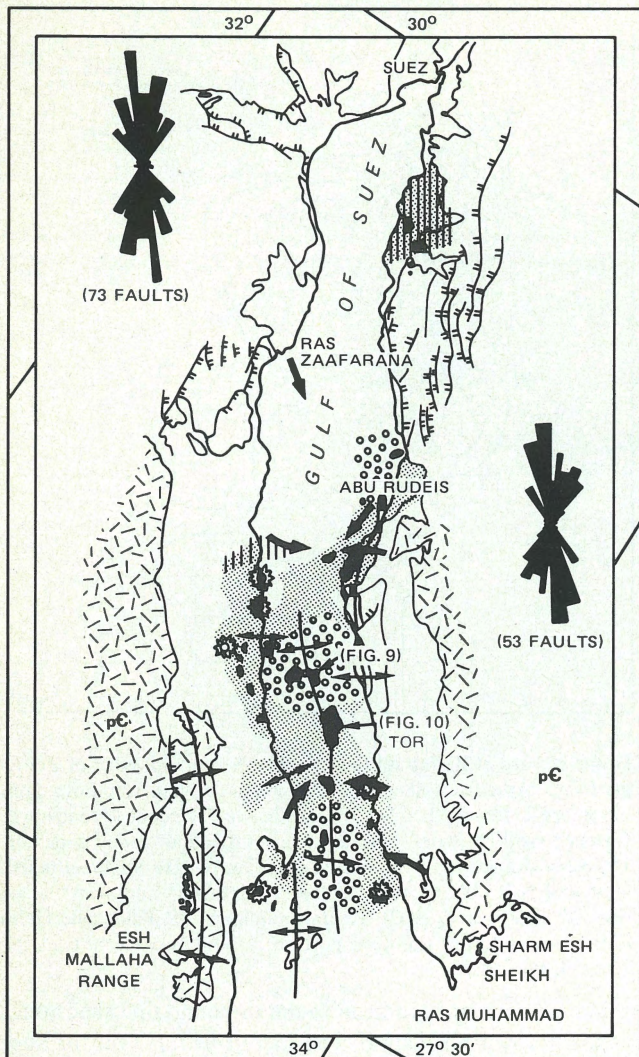
Fig. 7.

Drape closure at Zelten oil field on western, updip, edge of Zelten platform. Structure's shape reflects an underlying trap-door fault block (see Zelten field on Fig. 6). Productive Paleocene (?) and lower Eocene, shallow water limestone facies (Bebout and Pendexter, 1965) are draped over the buried junction of NW-SE longitudinal fault and N-S oblique fault at field's southwest and west flanks, respectively (Fraser, 1967). Reefal buildup in the Paleocene Heira Formation underlies northern portion of pool and accentuates the drape flexure there.

Major reserves have been found in nonmarine sandstones of the Nubian Formation, considered in this Gulf of Suez region to be Cambrian (?) and Carboniferous in age, and not equivalent to the Lower Cretaceous Nubian of the Sirte basin. Nonmarine to marine sandstones of Cenomanian age are also productive, and Eocene shelfal carbonates contain minor accumulations. SAID (1962) has suggested that in some fields the porosity of these carbonates has been enhanced by weathering processes at the unconformity at the base of the graben fill. Eocene and Cretaceous shales and marls may be limited hydrocarbon sources for the accumulations in the pre-Miocene section (SAID, 1962), but the dominant source is the thick Middle Miocene shale and marl of the graben fill itself (GILBOA & COHEN, 1979).

Principal closures in the pregraben reservoirs (Fig. 3) are provided by (1) the truncation of rotated fault blocks by an unconformity near the base of the graben fill, (2) faults (Fig. 9), and (3) fault-associated flexures (present in figure 9, but not a factor controlling this hydrocarbon accumulation). All of these features formed during deformation of the graben.

The pregraben reservoirs are most prolific along a mid-trough zone, which is the central element of three parallel, structurally high basement-block trends (Fig. 8). A fourth



(ADAPTED FROM GILBOA AND COHEN, 1979)

Fig. 8. Oil fields and distribution of productive zones in Gulf of Suez. Numbers of surface faults with orientations within each 5° geographic quadrant are plotted in rose diagrams for northeast (after Robson, 1971) and southwest margins of graben.

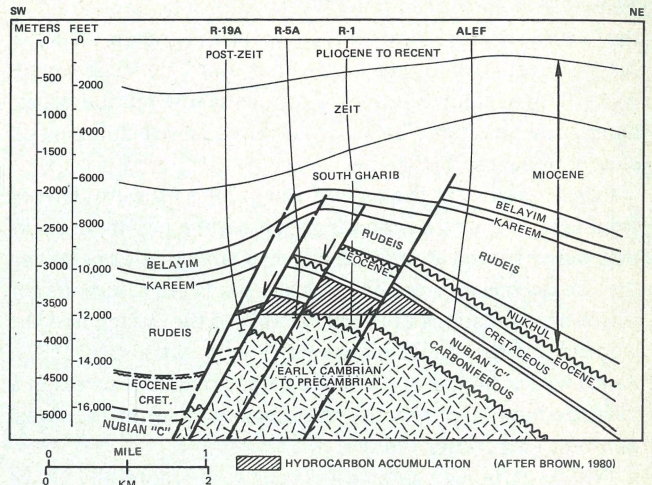


Fig. 9. Cross section across Ramadan oil field, Gulf of Suez, showing hydrocarbon trap in pregraben-fill reservoirs (Nubian 'C' sands) that is controlled by graben-age normal faulting. Associated flexing forms narrow rollover at high side of block boundary and broader syncline in low side. See figure 8 for location.

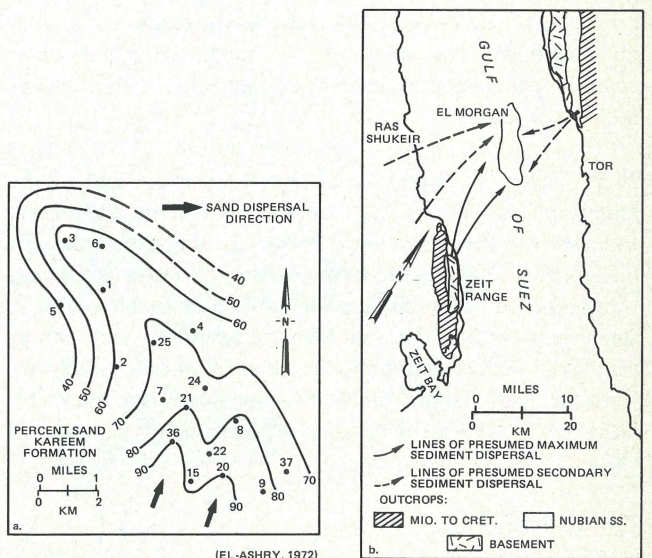


Fig. 10. Percent sand map of Middle Miocene Kareem reservoir within El Morgan producing area (a) and provenance for Kareem clastics at flanking fault blocks (b), Gulf of Suez. Sand-shale ratios and coarsening directions of sand grains corroborate this interpretation (El Ashry, 1972). Trap for hydrocarbons is longitudinal horst with block-edge flexure (Brown, 1980, Fig. 6 and 7). See figure 8 for location.

high trend at the southwest margin of the graben corresponds with the Esh Mallaha range where the basement crops out extensively. This trend completes the graben framework but is nonproductive.

Plays within the graben fill – Graben formation began in the Oligocene (GARFUNKEL & BARTOV, 1977). Important Middle Miocene reservoirs were derived from Nubian sands and from a crystalline basement, both still exposed in large fault blocks flanking either side of the central producing trend (Fig. 10). The graben-fill reservoirs are most prolific along the central 'uplift', but large reserves are also contained in the eastern producing trend. Major traps are fault closures or flexures draped across fault-block boundaries, or a combination of these two. Minor stratigraphic accumulations are controlled by the updip pinchout of sands in both upthrown and downthrown fault blocks, in several reefs located at the high edges of fault blocks, and in Lower Miocene sands deposited at the base of the graben (Fig. 3).

Graben faulting is still active, and there is no interior-sag basin.

Viking graben hydrocarbon plays

All three basin types – pregraben, graben fill, and interior sag – are present in the Viking graben, and two of the basins have prolific hydrocarbon plays (Fig. 4). Exploration for reservoirs below the base of the graben fill is still in an early stage, and the limits and significance of the pregraben play are not established.

Play in pregraben reservoirs – The basement underlying the northern North Sea sedimentary sequence had its final consolidation at the conclusion of the Caledonian orogeny. Directly following this event an undefined intracontinental basin or 'sag', termed the Orcadian basin, is thought to have subsided across the region (ZIEGLER, 1978, 1980). Coarse, nonmarine clastics of the Devonian-age Old Red Sandstone series are exposed on either flank of the Viking graben and have been encountered under the Mesozoic graben fill at several wells. Subsidence of this basin has been attributed to a late orogenic strike slip with extension (ZIEGLER, 1978; STEEL & GLOPPEN, 1980).

Thus far, two small oil fields have been discovered in the Quadrant 16 area in the play for graben reservoirs. Both fields are located on the high side of the western shoulder of the graben. Here the possibly fractured arkosic sandstone reservoirs of the Old Red Sandstone facies directly underlie anticlinal closures mapped at the unconformity at the base of the Cretaceous (Fig. 4).

Plays within the graben fill – Formation of the Viking graben started in the Triassic. Normal faulting culminated in the Middle Kimmerian (± 156 Ma), but it continued into the Early Cretaceous and rarely into the Tertiary (Fig. 11).

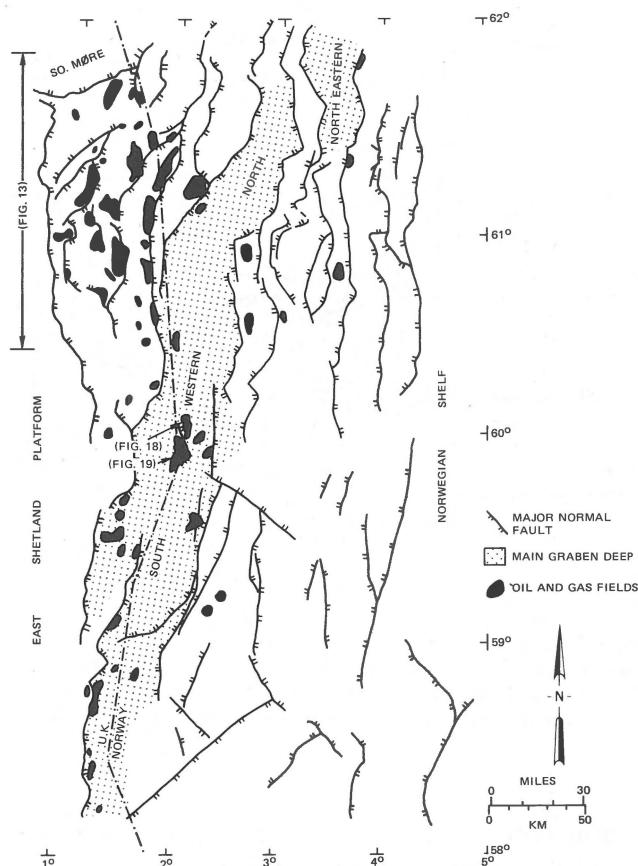


Fig. 11 Major faults, and oil and gas fields of Viking graben. Merger of north-south fault system with northeast-trending zones at north end of basin defines regional dogleg. Main graben deep shifts across basin axis within this dogleg; see figure 24 for possible explanation. (U.K. portion, after maps by Esso Exploration and Production U.K.; Norwegian portion, south of 60° north, after Ronnevik et al. (1975).)

Jurassic stages of the faulting were exceptionally intense and established the present series of rotated platforms characterizing the northwestern portion of the basin (Fig. 12). The upthrown edges of the platforms were eroded at approximately the end of the graben cycle. Closure was produced by a combination of the out-of-the-basin structural dip within the platform and the basinward-facing erosional scarps. Most major accumulations in the prolific northwestern flank of the Viking graben produce from Middle and Lower Jurassic sands truncated beneath such topographic highs (Fig. 13).

The truncation of the Jurassic reservoir sands is stratigraphically complex. VAIL & TODD (1981) have demonstrated that the nearly continuous platform rotation and episodic erosion during low stands of eustatic sea level combined to produce a series of angular unconformities and onlap sequences. These unconformities converge updip on the rotated slope of the platforms in rocks ranging in age from Jurassic to Early Cretaceous. VAIL & TODD (1981) have recognized a period of maximum truncation in the Late Middle Jurassic (± 156 Ma).

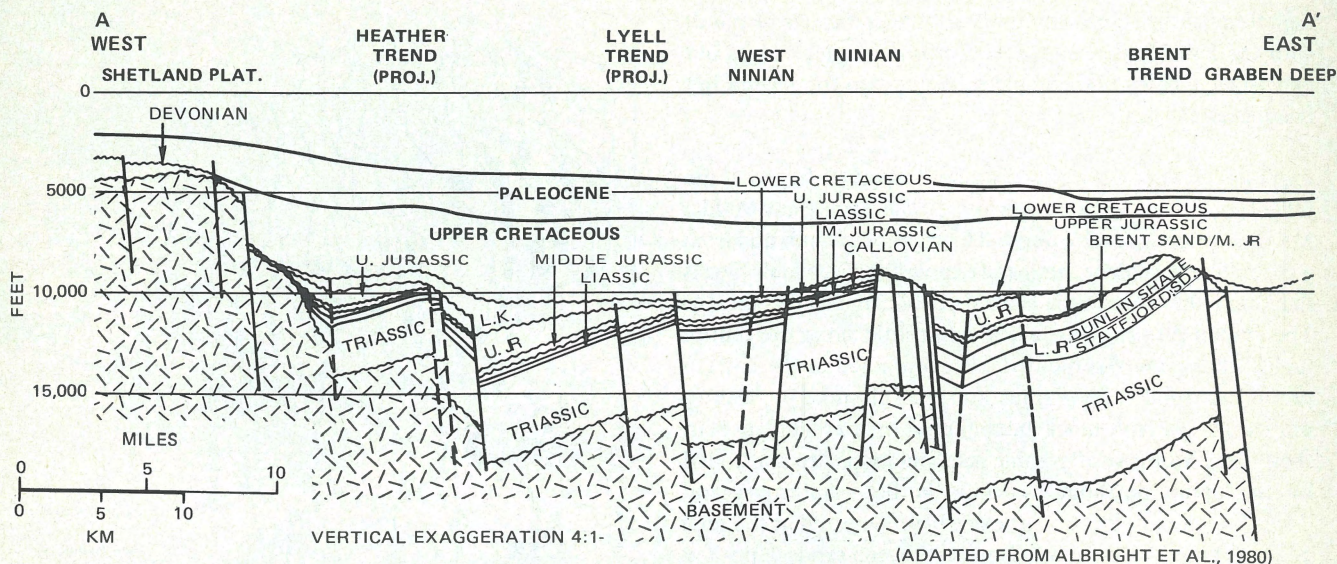


Fig. 12 East-west cross section across northwest flank of Viking graben; see figure 13 for location. Platforms at level of graben fill (i.e., Heather, Lyell, West Ninian, Ninian, and Brent) are rotated westward into large listric normal faults located at each platform's western boundary. Structural relief withing lower sag fill has flexure style expressed by Upper-Lower Cretaceous contact.

Hydrocarbon trapping at many of the truncated fault blocks is partially controlled in either the strike or updip direction by faulting or flexing (Figs. 14-17). The truncation traps are morphologically similar to those in the Sirte and Gulf of Suez basins, but in the latter areas they occur at the base of the graben fill instead of near its top. Closures controlled solely by structure are not as numerous in the Viking graben as in many other grabens, but are still important. These traps are high-side rollovers, high-side fault closures, or combinations of the two. Traps closed directly against the downthrown side of faults (Figs. 15 and 16) and rollovers associated with faults antithetic to platform fault boundaries (HARMS ET AL., 1981) are also productive, mostly from Upper Jurassic sands along the southwest edge of the Viking graben. Low-side fault traps, however, do not contain major reserves here or in most other grabens.

Plays within the interior-sag basin – The closely spaced, multiple unconformities near the top of the graben fill largely prohibit a precise dating of the contact between the fill and the interior-sag basin. On the basis of significantly diminished faulting, the base of the sag basin is considered in this work to be a transitional zone within the Lower Cretaceous.

Broad flexures dominate the structural style within the lowermost portion of the sag fill (Fig. 12). They are a result of passive drape and differential compaction across the buried topography, combined with varying amounts of fault offset and forced folding across certain platform boundaries that remained active during the waning stages of faulting. The

resulting structural relief is considerably greater than that observed in other sag basins, which mostly merge downward into the graben fill without an intervening structural discordance or angular unconformity. Several folds above the western shoulder of the graben contain hydrocarbons in Paleocene sands (Fig. 4). Within the graben proper, a general absence of Cretaceous reservoirs has precluded the development of a major hydrocarbon play in closures within the lower level of the interior-sag basin.

The upper portion of the sag fill is largely devoid of structural closures within the graben proper. Paleocene and basal Eocene turbidite sands, however, contain a major hydrocarbon play. Deep-water fans provide the reservoir facies; and their sedimentary mounding, occasionally amplified by gentle drape and differential compaction across buried graben structures, provides the closures (Figs. 18 and 19).

To the south, in the Central graben of the North Sea, thick Upper Permian evaporites provided a mechanism for deforming the upper portions of the interior-sag fill. The major hydrocarbons are contained in fractured uppermost Cretaceous and basal Paleocene chinks domed by salt diapirs (VAN DEN BARK & THOMAS, 1980). Between the diapirs, at the level of the graben fill, other closures have resulted from salt flowage. They include turtle structures, residual salt highs, and, possibly, nonpiercement salt pillows. These latter structures extend into the far south end of the Viking graben and provide traps for several additional fields (not included on figure 4).

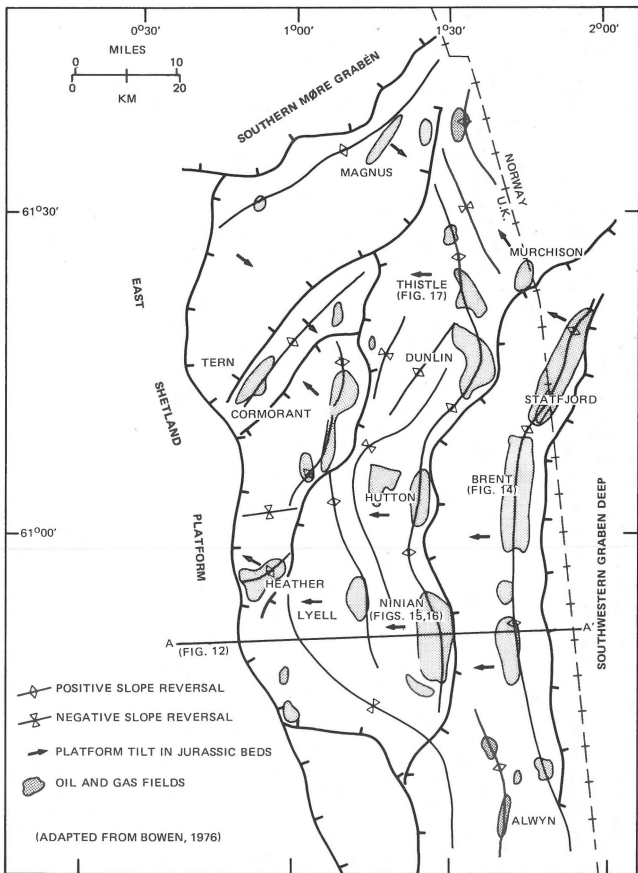


Fig. 13
 Topographic features, major faults, and major platforms at late Kimmerian unconformity (approximate Jurassic-Cretaceous contact) on northwest flank of Viking graben. Positive slope reversals are combination of platform tilt (mostly west slopes) and erosional 'scarps' at platform edges (mostly east slopes). See figures 11 and 12 for location and geologic cross section, respectively.

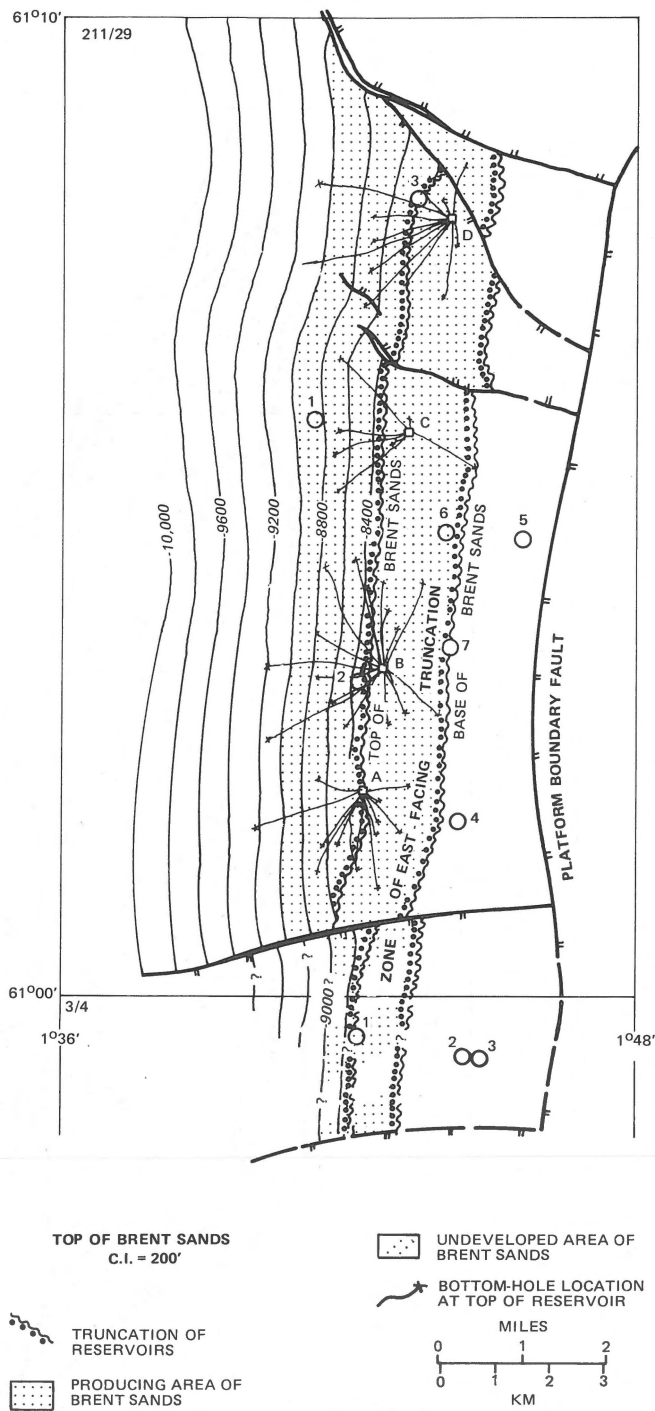
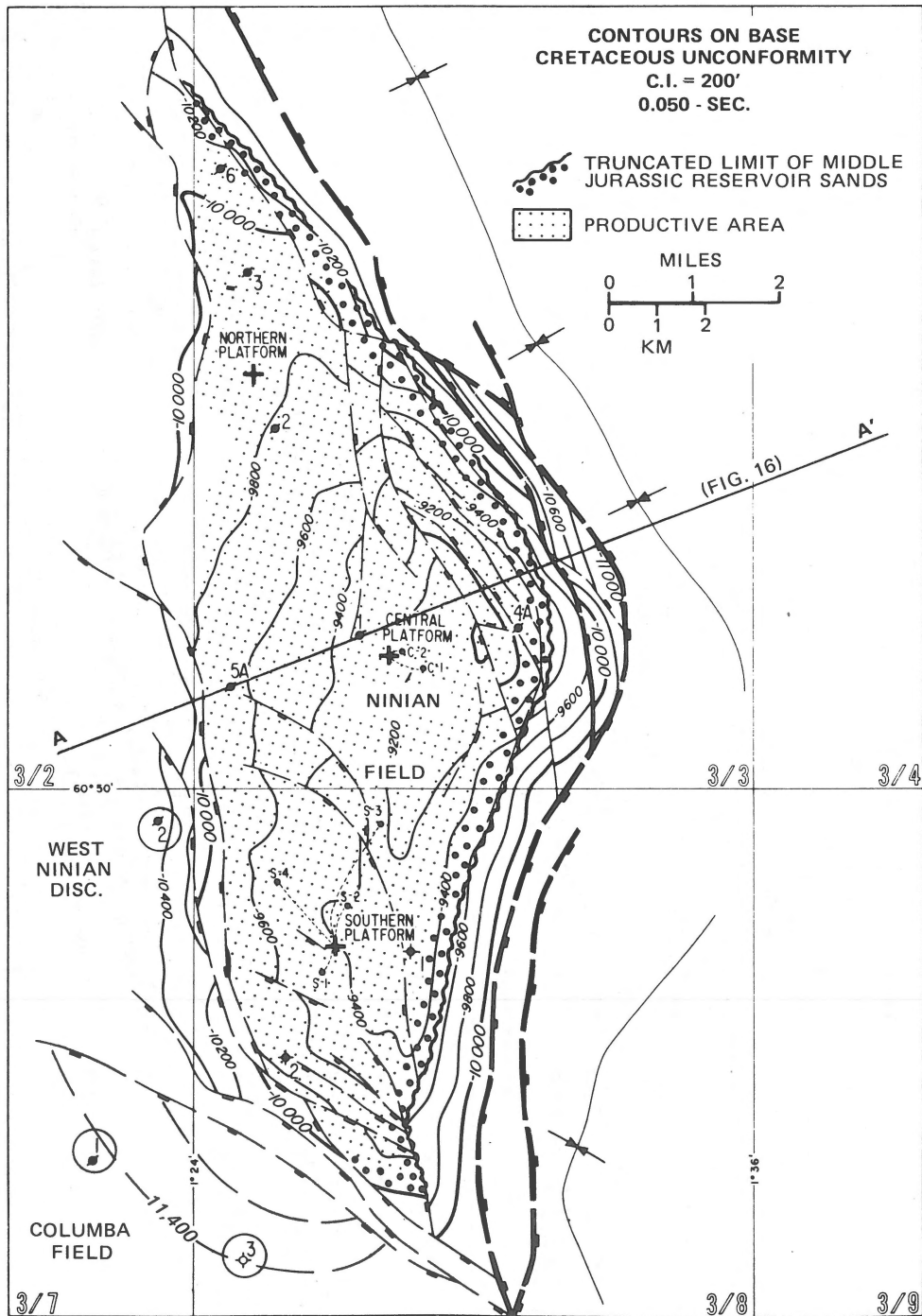


Fig. 14
 Structure of truncation trap in Middle Jurassic Brent sands at Brent oil field, Viking graben; see figures 12 and 13 for cross section and field location, respectively. Updip limit of reservoir sands parallels north-south platform boundary fault. This relationship demonstrates control exerted on pattern of reservoir truncations by such faults. Structure in block 211/29 north of southernmost transverse fault from Esso Exploration and Production U.K., 1981.



(ADAPTED FROM ALBRIGHT ET AL., 1980, FIG. 4, 11, AND 12)

Fig. 15
Structure of truncation trap at Ninian oil field and low-side fault traps at west and south Ninian discoveries, Viking graben; see figures 12 and 13 for geologic cross section and field location, respectively. Large northwest-southeast and north-south normal faults at field's east side bound a trap-door structure, which is reflected by truncated limits of Middle Jurassic reservoir sand. West Ninian Jurassic discovery appears to be a broad warp of field's west flank that extends across secondary longitudinal normal fault. At the Jurassic Columba field, closure occurs where oblique fault cuts across trap door's south plunge.

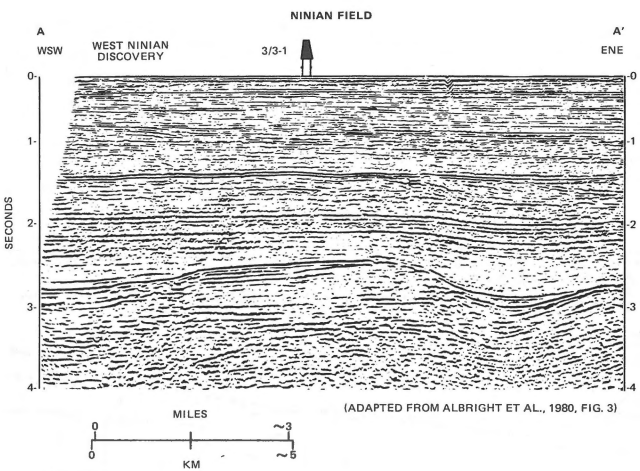
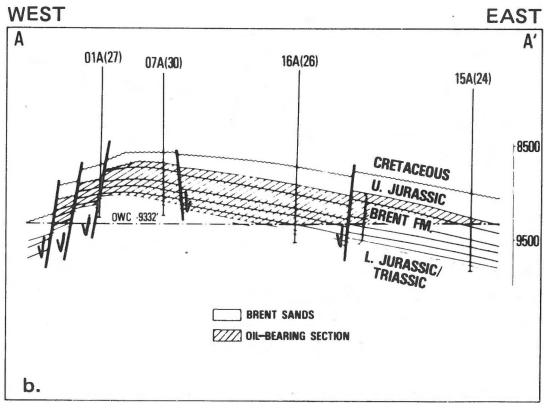
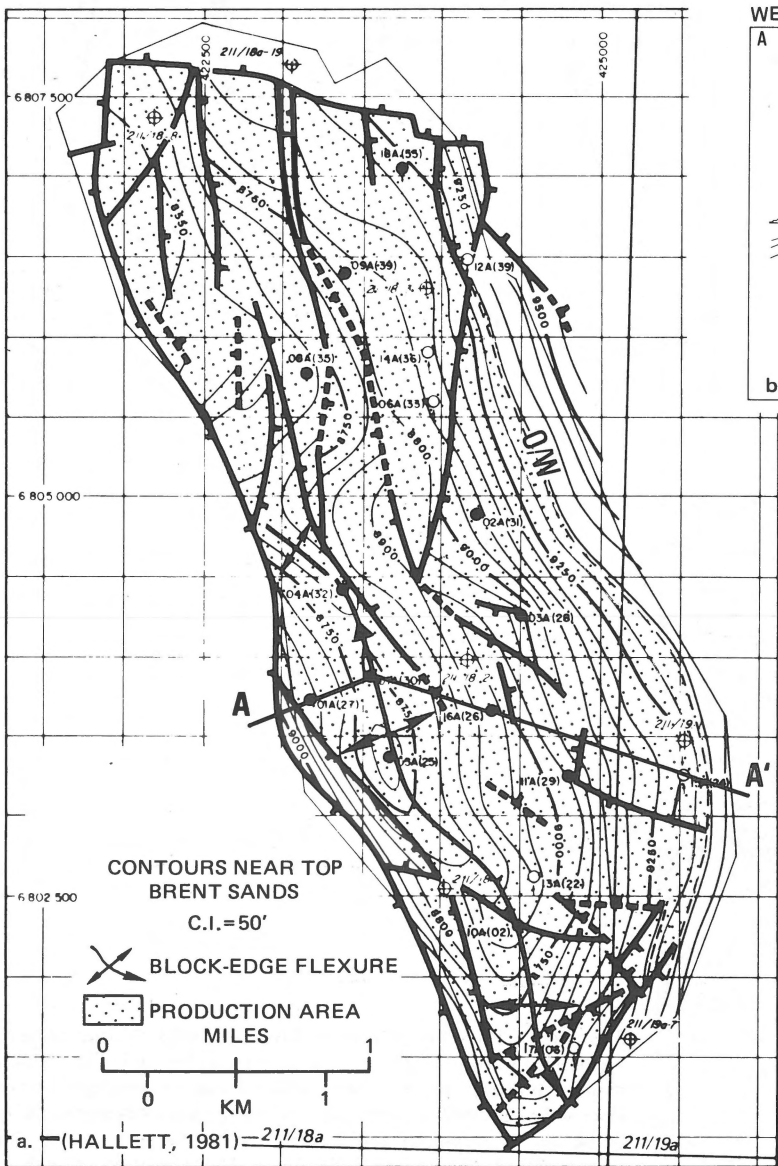


Fig. 16 East-west seismic profile of Ninian oil field and west Ninian discovery, Viking graben; see figure 15 for location. Truncation of Jurassic section and dip reversal at base of sag fill is apparent at structure's crest and east side (at 2.4 to 2.9 sec). Positive flexure caused by drape and differential compaction occurs above the unconformity. Below this surface, large normal faults are down-thrown to east at structure's east boundary, and smaller normal faults are downthrown to west at west Ninian.



(HALLETT, 1981)

Fig. 17 Structure map (a) and cross section (b) of Thistle oil field, Viking graben; see figures 13 for location. Updip trapping of hydrocarbons in Middle Jurassic sands is by combination of block-edge flexure and fault at south end, and by high side of block-edge fault at north end. Parallellism of flexure and block boundary demonstrates fold nucleation's dependency on block relief.

TECTONIC CONTROLS FOR DEVELOPMENT OF MAJOR HYDROCARBON PLAYS

Pregraben reservoir play

Grabens superimposed across a prior depositional site have a possible play for traps below the graben fill. To be effective for trapping hydrocarbons, the older sediments must be devoid of complex pregraben structures, which would disrupt the internal continuity of later fault-block closures. In addition, the older sediments must be preserved from erosional removal prior to and during graben formation.

The Sirte and Gulf of Suez grabens were superimposed on continental shelves, and these tectonic settings remained relatively stable until the start of rifting. Because of this, the graben fault blocks do not contain structures from previous deformation.

During normal fault deformation, broad arching of the crust is a mechanism potentially destructive to the preservation of the pregraben sediments. According to VIERBUCHEN ET AL. (in press), graben-inducing mechanisms of crustal and lithospheric stretching – and the consequent lithospheric heating and subsequent cooling – may be balanced in several ways to give differing sequences of subsidence or uplift. In some areas the surface of the crust may have been broadly downwarped at the initiation of faulting or perhaps just before (ASMUS & GUAZELL, 1981; MILANOVSKY, 1981), preserving the older sediments from erosion. In the Gulf of Suez, arching followed after significant graben subsidence by block faulting (see discussion to follow), and this timing controlled the preservation of the pregraben play. In the Sirte basin, however, Cretaceous arching preceded or accompanied initiation of faulting, and under central portions of that basin the Nubian and Gargaf formations are absent (PARSONS ET AL., 1980).

Graben-fill play

On the northeast side of the Gulf of Suez and in the Viking graben, graben faulting occurred in multiple stages. An initial, pervasive stretching phase apparently resulted in relatively closely spaced normal faults, mostly with moderate displacements (pre-Upper Gharandal faulting in figure 20). In the Gulf of Suez, the faulting was accompanied by rotation of fault blocks and deep erosion at some block edges. Extension in a later stage was concentrated on fewer and more widely spaced faults, some of which had had earlier movements as well. This last stage resulted in faults with large displacements (faults that offset both the older and younger sedimentary sections on figure 20).

During early pervasive faulting, the pregraben reservoirs were preserved from erosion in most blocks across the east flank of the Suez graben. While the entire graben system subsided, the base of the sedimentary cover was downfaulted below the erosional base level at each successive structure

(e.g., Eocene horizons and below on figure 20). The second stage of faulting produced platforms composed of agglomerations of the older and smaller fault blocks, and these outline the overall tectonic framework.

GARFUNKEL & BARTOV (1977) also noted this structural sequence in the Gulf of Suez and determined that the second phase of faulting was accompanied by arching of the rift shoulders. This latter faulting did not occur until the latest Early Miocene. In the Viking graben, major faulting, culminating in the present platform architecture and the arching, thought by ZIEGLER (1978, 1980) to have occurred south of the graben, were about coeval. The North Sea arching has been dated as Middle Jurassic (ZIEGLER, 1978, 1980), well after the initiation of graben deformation.

Arching is typically most obvious at the rift 'shoulders', the area outside the most external of the boundary faults. Cross sections of the Gulf of Suez (Fig. 20; SCHÜRMAN, 1966 Fig. 32), the Viking graben (Fig. 12; ZIEGLER, 1980, Fig. 32), and the Sirte basin (PARSONS ET AL., 1980, Fig. 5) demonstrate that subsidence by normal faulting has outpaced the broader arching of the crust. Differences in structural relief within these grabens were caused primarily by the rotation and displacement of individual blocks and do not appear to reflect an integrated upwarp.

Interior-sag play

Major subsidence of both the Sirte basin and the Viking graben continued well after block faulting ceased. This final stage of subsidence has resulted in a regional, mostly unfaulted downwarp that includes both the graben and the adjacent graben shoulders. In the Sirte basin the downwarp has over 12 000 feet of relief at the base of the Oligocene.

Formation of the interior sag basin in the Viking graben took two forms: initial differential subsidence of the major structural elements during the Early Cretaceous and into the Late Cretaceous (illustrated by the base of the Upper Cretaceous in figure 12), followed by overall subsidence of the basin as a single unit in the latest Cretaceous and Tertiary (illustrated by the base of the Paleocene in figure 12). The early period of differential subsidence caused significant structural relief within the Cretaceous section.

GRABEN STRUCTURAL STYLES AND CONTROLS FOR TRAP DEVELOPMENT

Closures associated with extensional block faulting are relatively easily interpreted on seismic data. This is partly because the structures often repeat the same cross-section characteristics. The lack of uniqueness in structural expression, however, makes it difficult to correlate block boundaries through successive profiles. Consequently, the conversion of profile control to structural maps is more difficult.

Rapid variations in displacement magnitude, abrupt

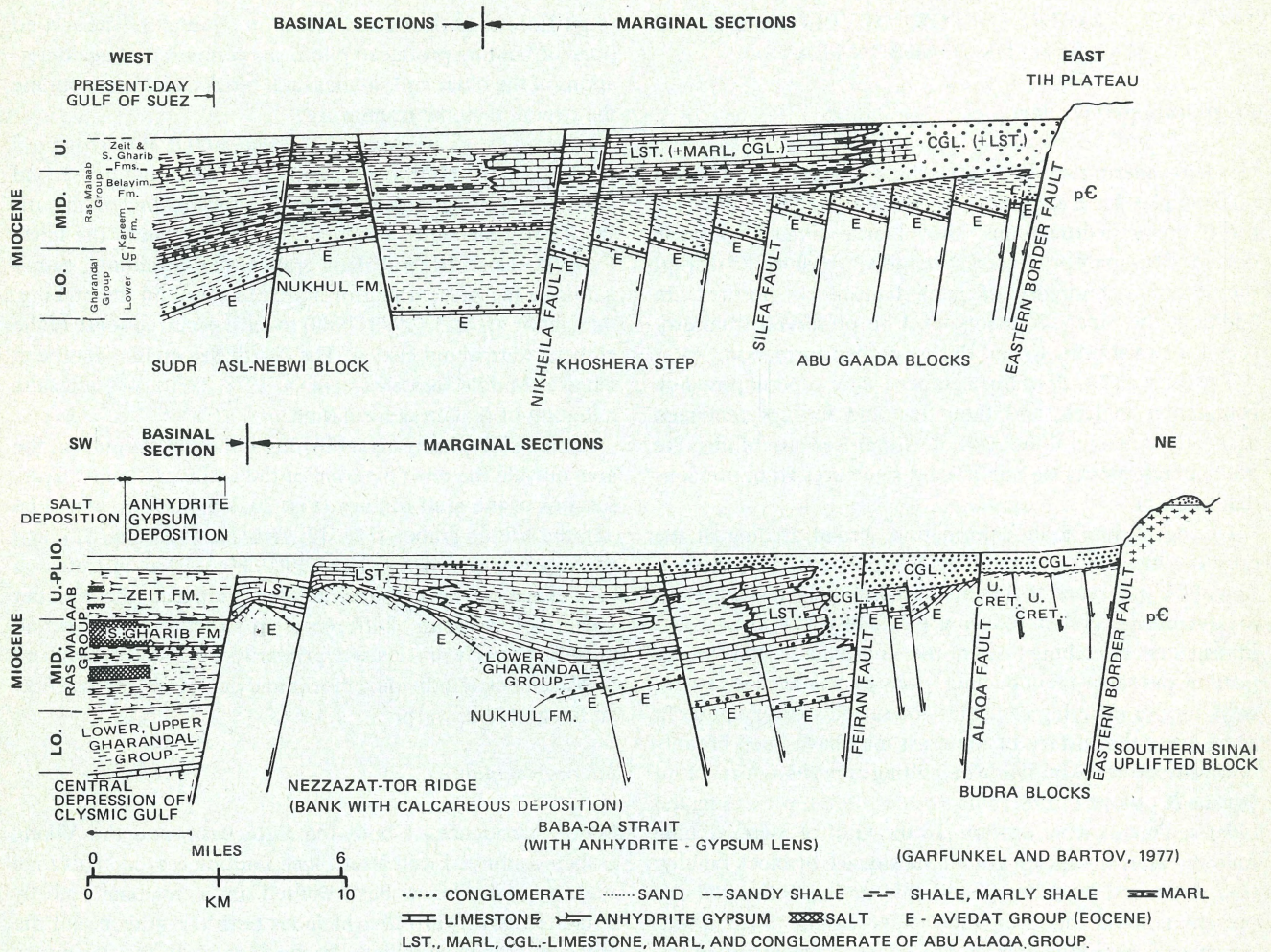


Fig. 20
 Schematic cross sections across northeast flank of Gulf of Suez graben. Faulting occurred during lower Gharandal time (earliest Miocene) and in post-lower Gharandal (late Early Miocene to Recent). Regional arching is pronounced on LANDSAT imagery of terrain external to graben, but does not appear to affect structures within trough itself. Conglomerate facies, derived from uplifted rift shoulders, mark onslaught of arching during second faulting event (Garfunkel and Bartov, 1977).

changes in fault orientation, termination of blocks, and the junctions of different fault trends all increase the mapping difficulty. These characteristics usually negate the potential for reasonably constant trend patterns. They cause reconnaissance mapping of fault blocks to be more dependent on control density than are other structural styles.

Profile style

Extensional fault blocks to depths resolvable with exploration data characteristically have a slablike or internally unflexed profile. The edges of fault blocks often have three vertically stacked styles, each with its own particular trap potential. At the deepest mappable level the structure may be a simple fault trap (prerift reflectors at the middle step block in figure 21). Within the sedimentary cover at the intermediate and higher structural levels, folding becomes progressively more important.

Block-edge flexures – Most folds in grabens are attributed to forced drape and the conventional fault drag associated with dip-slip displacements (upper portion of rift phase at the step block nearest the right margin of figure 21). This flexing may be initiated by an upward propagation of the dislocation surface. Seismic and surface data demonstrate that normal faults often die out upward (and along the strike) into flexures, which appear to develop prior to brittle rupture. Flexure form is concordant with the sense of the underlying offset, such as a positive rollover or monoclinical knee above the upthrown edge of a block. As continuing displacements propagate the faults further upward, the forced folds evolve into a faulted drag flexure typical of the intermediate level.

Establishment of positive closure from this block-edge flexing is dependent on a combination of block tilt and the direction of fault dip. If faults dip away from the direction of

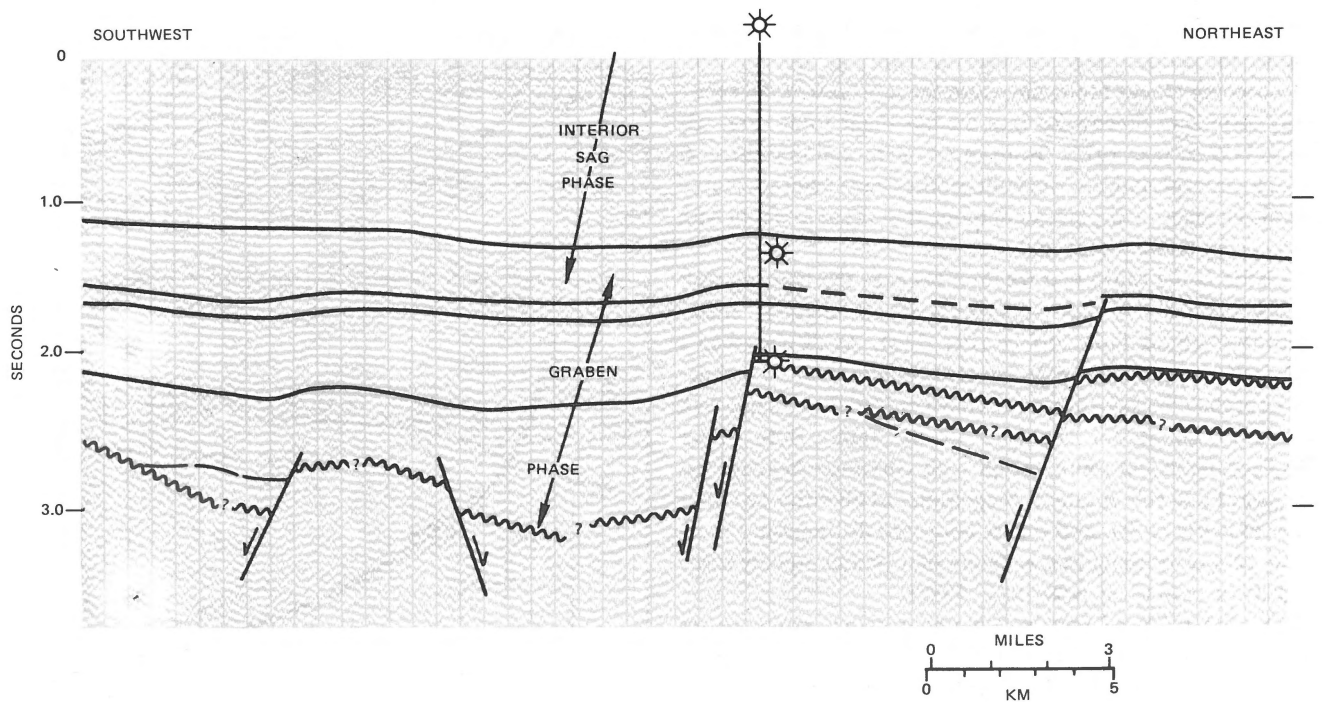


Fig. 21
Seismic profile parallel to regional dip, Zelten platform area, Sirte basin. Structure consists of two step blocks (right), small graben (center), and horst (left). Faulting is accompanied by conventional dip-slip drag flexing and forced drape at level of graben phase deposits. Flexing caused by passive drape and differential compaction becomes progressively more dominant upward within interior sag deposits. Gas accumulations have been found in both drape-flexure and fault-block traps.

tilt, downward dragging of beds toward the subsided block will either flatten or reverse the tilt, depending on the magnitude of the drag (southwest flank of the horst in figure 21). If the fault dip is similar to the direction of tilt, downward dragging of beds toward the low side of the fault will merely increase the degree of tilt. The result is a monoclin flexure with no structural closure (northeast flank of the horst in figure 21).

Where dip reversals are established, the low-side upturns into the fault (synclines) are typically broader than the companion high-side positive rollover. The latter's reversed limb may be only 2 to 4 km wide. In some cases only the syncline is present (middle and lower portion of the interior rift phase at the middle tilted block in figure 21). Combination flexure and fault traps develop where part of the hydrocarbon column is trapped directly against the block-bounding fault.

Rollover traps are common in the Sirte basin and the Suez graben, but they are rare in the Viking graben. Nucleation of the rollovers adjacent to the upthrown side of the faults causes them to be vulnerable to large-scale erosion on fault-block edges, and this erosion has occurred in the Viking graben at the level of the hydrocarbon reservoirs. Flattening of the regional tilt does appear at the high sides of the Ninian and Heather trends in figure 12, and rollover has been preserved at the Thistle oil field (Fig. 17).

Structures at the shallowest level are dominantly passive

drape and differential compaction flexures. Their rollovers provide relatively broad, unbroken 'anticlinal' closures. Differential compaction can also enhance closure in the lower structural levels.

Block rotation – In some regions block tilt is consistent, and this consistency has led to the establishment of prolific hydrocarbon trends and areas with numerous closures (e.g., those in figure 13). In other cases tilt is random, differing even between adjacent structures. Several block-rotation geometries have been observed in the basin and range province of Nevada. WERNICKE & BURCHFIEL (1982) have related these to different kinds of extensional faults: block-rotating listric and planar faults, and non-block-rotating, high-angle planar faults, and low-angle detachments. These faults often occur together in the areas studied by these authors, and examples have been observed on seismic profiles (MCDONALD, 1976). Sets of planar faults are nested in the hanging wall of a listric fault and terminate downward into that fault. The listric fault continues into a shallow, basal detachment that bounds unrotated sheets.

Application of WERNICKE & BURCHFIEL'S kinds of normal faults to rift settings is being studied. Most investigators of deeply subsided grabens, such as those described in this paper, suggest that the basement-involved listric normal faults cut to much deeper levels, possibly merging downward with a subhorizontal, ductile flow zone (Fig. 22a; PROFFETT,

1977). In this way, the faults mechanically thin the crust and induce the deep subsidence observed within the fault system. Deep-going planar faults have also been proposed, and they may terminate downward into ductile shear folds (Fig. 23; MORTON & BLACK, 1975). Both in PROFFETT'S and in MORTON & BLACK'S interpretations, the fault profiles have been attributed to the changes in displacement mode that occur at depth with increasing temperature and pressure.

Listric faults cause bed rotation because the hanging-wall block maintains an approximately constant angular contact with the curving fault surface (Fig. 22b). As displacements proceed, this block is progressively rotated. Steepest inclinations occur where displacements have moved the hanging wall down to the flatter segments of the fault. Both larger displacements and more abrupt fault curvature increase the degree of low-side rotation. Magnitudes of tilt differ on either side of listric faults, and this relationship distinguishes them from sets of rotating planar faults that bound equally tilted blocks (WERNICKE & BURCHFIEL, 1982).

The extension of terrain containing planar faults causes rotation of both the blocks and the fault planes bounding them (Fig. 23). The result can be compared geometrically with the incremental slip and rotation generated by tilting a row of dominoes sideways. The obvious space problems at the base of the blocks ('gaps') and at their margin may be alleviated in part by ductile flow.

The similarity between MORTON & BLACK'S (1975) scheme for planar faults and the pre-Upper Gharandal fault blocks in the Gulf of Suez shown in figure 20 (especially the upper cross section) tempts one to apply this style to the Suez region. The post-Gharandal faults mostly depressed each platform without rotation. These latter faults could belong to WERNICKE & BURCHFIEL'S category of high-angle, nonrotating planar faults.

In still other areas, platform tilt appears to be late and primarily imposed by subsidence of the interior-sag basin. In portions of the Sirte basin, for example, platform dips are subparallel with dips in the overlying sag fill (Fig. 21; PARSONS ET AL., 1980, Fig. 5), indicating negligible rotation during faulting.

Block tilt can be affected by many additional factors, including inherited pregraben dips (which affect pregraben reservoirs), ramping at fault terminations, isostatic adjustments, underlying intrusions, impinging uplifts or subsidences from external deformation, and superimposed stress systems not related to graben formation. Regional changes in the graben's trend, such as major junctions and doglegs, can also change the pattern of block rotation (see hereafter). The inconsistency of block rotation is not yet fully explained.

Map style

The suites of large- and small-scale structures that characterize grabens are combined in various spatial arrangements.

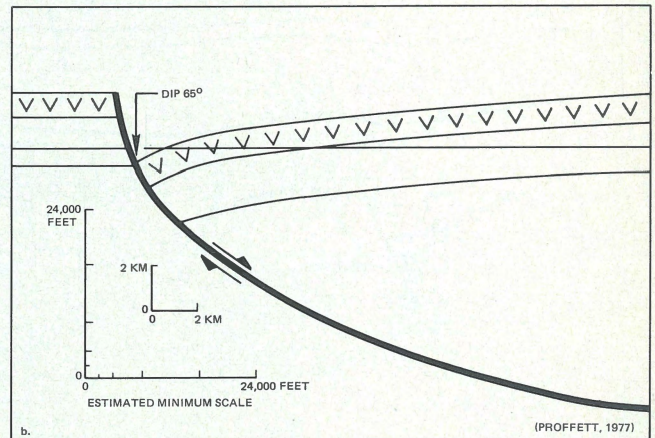
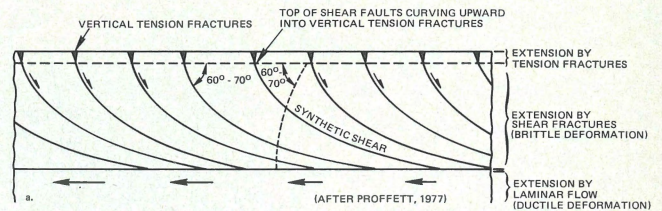


Fig. 22 Conceptual diagram of changes in failure mechanisms that are thought to result in deep-going listric fault profile (a) and block rotation induced by this profile (b). Depth at which fault soles out can be highly variable. Differing amounts of rotations result from differences in displacement magnitude, from abruptness of fault curvature, and from rotation superimposed by later generation of listric faults.

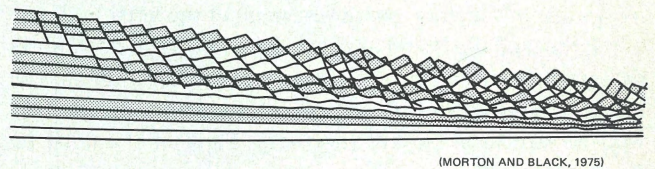


Fig. 23 Hypothetical illustration of crustal attenuation, and external rotation of planar normal faults and their intervening fault blocks. In this representation, time, progressive attenuation, and renewed faulting increase to the right. It is doubtful that hydrocarbon accumulations would survive extreme deformation shown at far right.

The resulting variability gives each graben its own structural individuality.

Regional trend patterns – On a regional scale, grabens typically have long straight or gently curving segments termed 'straightaways' connected by doglegs (the north and south-western segments of the Viking graben deep in figure 11) and loops. Adjacent grabens, not always with similar histories, can have widely differing orientations (MILANOVSKY, 1981, Figs. 18, 20-22). They may join at junctions whose configurations range from low-angle oblique to high-angle T-intersections and include the more idealized triple junctions (Fig.

5). In some instances grabens do not connect directly but, instead, overstep at their ends (the north and northeastern graben deeps in figure 11).

Doglegs form where the boundaries of a graben assume an oblique orientation for a short distance and then return to the regional trend (Fig. 24). Major faults within the oblique segment may continue across the entire system, taking the trough axis from one side of the basin to the other. This may change the relative positions of shallow- and deep-water facies, and the direction of block rotation can reverse abruptly. Areas with a high concentration of closures are formed where faults of the regional and oblique directions intersect at the dogleg bends. The well-structured northwest flank of the Viking graben is an example (Fig. 13).

If extension proceeds sufficiently, doglegs and overstepped grabens can become sites for strike-slip faults. Segments oriented most nearly in line with the regional extensional stress (e.g., the middle portion of the dogleg in figure 24) will ultimately require a strike-slip fault to accommodate the continued extension. Because of the spatial relationship between graben segments, the direction of strike-slip is opposite that of the apparent offset of the connected grabens, similar to transform faults at spreading centers. These spatial relationships also suggest that the strike-slip displacements would typically be accompanied by divergence. If so, compressional folding would be subdued or eliminated by the extensional components. In these instances, the potential wrench zone might inherit the style of the earlier dogleg faults, making its identification very difficult. HARDING (in press, b) has described the style of strike-slip deformation associated with extension.

Bathymetry and other data suggest that transform faults within oceanic crust in the northern and central Red Sea have been initiated at doglegs in the graben trend. Structures characteristic of strike-slip have not been documented, however, in the hydrocarbon-producing grabens that the author has studied. These basins have not had enough extension to require seafloor spreading, and their deformation is influenced by the underlying continental crust. The basins also, presumably, have not had sufficient extension and strain rates to generate a major strike-slip fault.

Multidirectional normal faults – On a smaller scale, grabens are internally complicated by the bifurcation, junction, interference, and termination of normal faults (HARDING & LOWELL, 1979). Structural vergence changes abruptly and sporadically because of this interaction between differently oriented faults. The development of multidirectional sets of normal faults has been reproduced with tectonic models (e.g., FREUND & MERZER, 1976) and has been studied theoretically (e.g., RECHES, 1978).

There is a degree of organization that is repetitive. Longitudinal faults parallel to the graben's regional strike are dominant. Oblique faults trend to either side of the longitudinal faults and, usually, both oblique orientations are

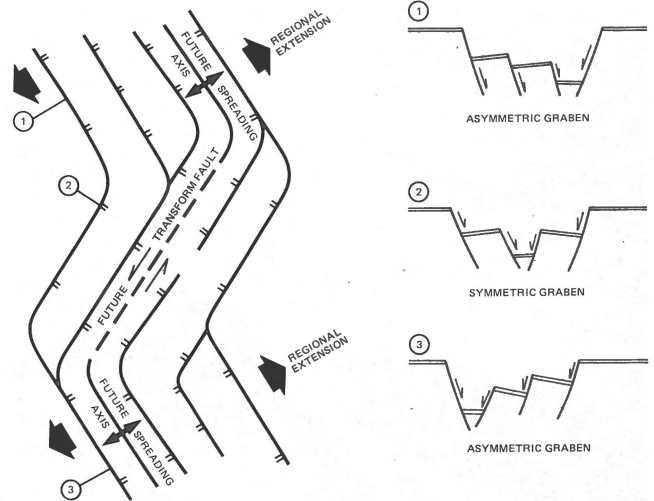


Fig. 24

Schematic map and cross sections of dogleg graben; scale ranges from few to many kilometers. Graben segments at map's top and bottom are in regional trend and normally would persist for greater distances than central, oblique segment. Faults are arbitrarily treated as listric and deep-going. Termination of right-dipping faults in cross section 1 by oblique fault set of central segment results in dominance of left-dipping faults in cross section 3. Direction of block rotation changes with this reversal of fault dip. Strike slip can occur along oblique segment after large extension.

equally developed. The oblique faults decrease in number as their obliquity to the graben trend increases, and transverse elements are rare. Typically, 90% of the block-bounding faults lie within an 80° quadrant (see rose diagrams in figures 6 and 8).

The oblique and longitudinal faults combine to form platform edges with zigzag borders, clusters of two- or three-sided blocks termed 'trap doors' (figures 15 and 25, respectively), and straightaways where only one trend is developed. Oblique faults often strike oblique to the dip of beds; and where the fault sets junction in an updip direction, they provide both updip and strike closure. Many of the productive traps in figures 6 and 13 are located at such fault intersections. Regional straightaways and blocks bounded by a single fault direction do not have as high a propensity for forming traps, because closure parallel to the strike may be lacking.

Slickensides on faults associated with shallow extension detachments in the basin and range province demonstrate a large component of divergent oblique slip on faults not oriented parallel to the regional trend (B. WERNICKE, pers. comm., 1982). In a number of graben basins, seismic profiles and surface exposures (ROBSON, 1971) demonstrate that the different fault orientations all have a similar 'dip slip' extensional style. That a significant strike-slip component may be absent on oblique normal faults was shown by KING'S (1965) piercing point and structural data on the Salt Flat graben of West Texas. For the purposes of hydrocarbon

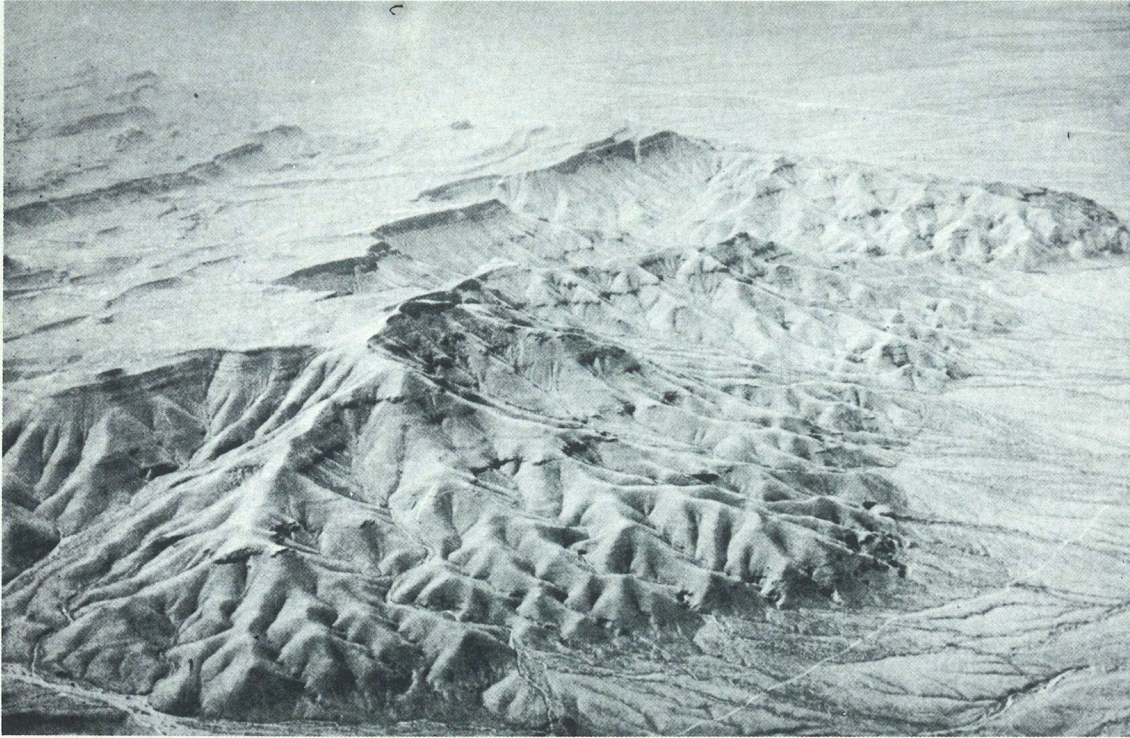


Fig. 25
Oblique air photo of three-sided trap-door fault block at east margin of Salt Flat graben, Texas. Structure is 3-6 mi wide. Style and age of boundary faults are similar on all three sides, and trap door appears to be result of simultaneous dip-slip displacement on the three faults.

exploration, the oblique faults are best treated as conventional normal faults.

The timing of displacements within the graben system varies in detail as activity shifts back and forth from one group of faults to another. But, locally, faults with different orientations can be synchronous. This synchronicity is demonstrated by trap-door corners where the total displacement is similar on adjoining sides of the fault block (Fig. 25).

The influence of basement anisotropy is critical in block faulting, and in some regions one or more of the fault orientations have been developed along preexisting zones of weakness. It is not clear, however, if this is a prerequisite for the development of multidirectional fault sets. At the north end of the Viking graben, the regional north-south faults turn abruptly northeastward (Fig. 13) to parallel the Caledonian basement trend exposed along the strike near Trondheim, Norway. The change in fault strike has formed a regional dogleg, and the interaction of the two fault systems has established a decidedly-closure-prone area.

In the northern Viking graben, the basement grain intersected the graben at an optimal oblique angle. Basement grain parallel to the graben would probably constrain faulting mostly to the longitudinal orientation and thus diminish closure development. Transverse grain is apparently utilized much less frequently. In some areas the observable basement anisotropy does not correspond with any of the fault orien-

tations, yet the multidirectional fault patterns are still developed (ILLES, 1970).

Secondary normal faults – Individual blocks may be segmented by secondary normal faults, which are faults that are restricted to the interior of a single block and do not bound the block. At some structures, these faults repeat the trend of the block boundaries (Fig. 15), but in other areas they have a different set of orientations (Fig. 14). The latter patterns may result from local stress within the block. Secondary faults that trend perpendicularly or obliquely to the trend of the structure can be an important source of closure along the structure's strike and have provided additional hydrocarbon pools (Figs. 14 and 15).

Block-edge flexures – The trend of most flexures repeats the multidirectional orientations of the primary longitudinal and oblique faults (Figs. 6 and 7). This relationship occurs because the flexures are nucleated by forced drape, drag, or differential compaction across block edges. The fold patterns include parallel, relay, dogleg, zigzag, and interference. The patterns are combined in various ways, and they present a gridded appearance on flexure maps, which is characteristic of fault-block deformation. In the Viking graben, trends of the block-bounding faults have localized the fault-face erosion (Figs. 14 and 15). Because of this, the distribution of

topographic features there also suggests a fault-block style.

Other graben styles – Some grabens have structural styles that differ importantly from the examples described in this report. Notable are grabens distinguished by a unidirectional set of normal faults, or large vertical tension gashes that are arranged en echelon along the trough axes. MOHR (1968) related such faulting in the main Ethiopian rift to a diffuse, divergent crustal couple. At the Wonji fault belt here, the en echelon fractures are closely spaced and trend obliquely to the axis of subsidence (Fig. 26). Because of their orientations, the fractures probably also trend obliquely to the bed strike. Traps associated with this style may be highly segmented by the close spacing of faults, and the fault strike could cause structures to be open obliquely up the dip of potential reservoirs.

In other grabens, the superpositioning of several differently oriented extensional stress systems has resulted in increased structural segmentation. In addition to various longitudinal and oblique faults, faults transverse to the regional trend may be common. In Malta, two-stage faulting has produced a complex trellislike pattern (ILLES, 1981, Fig. 6).

CONCLUSIONS

Two tectonic factors are critical to the occurrence of hydrocarbon accumulations in graben settings, and these have been emphasized in the present work: They are (1) the subsidence and stacking of sedimentary basins and (2) the internal deformation of these basins by multidirectional normal faulting.

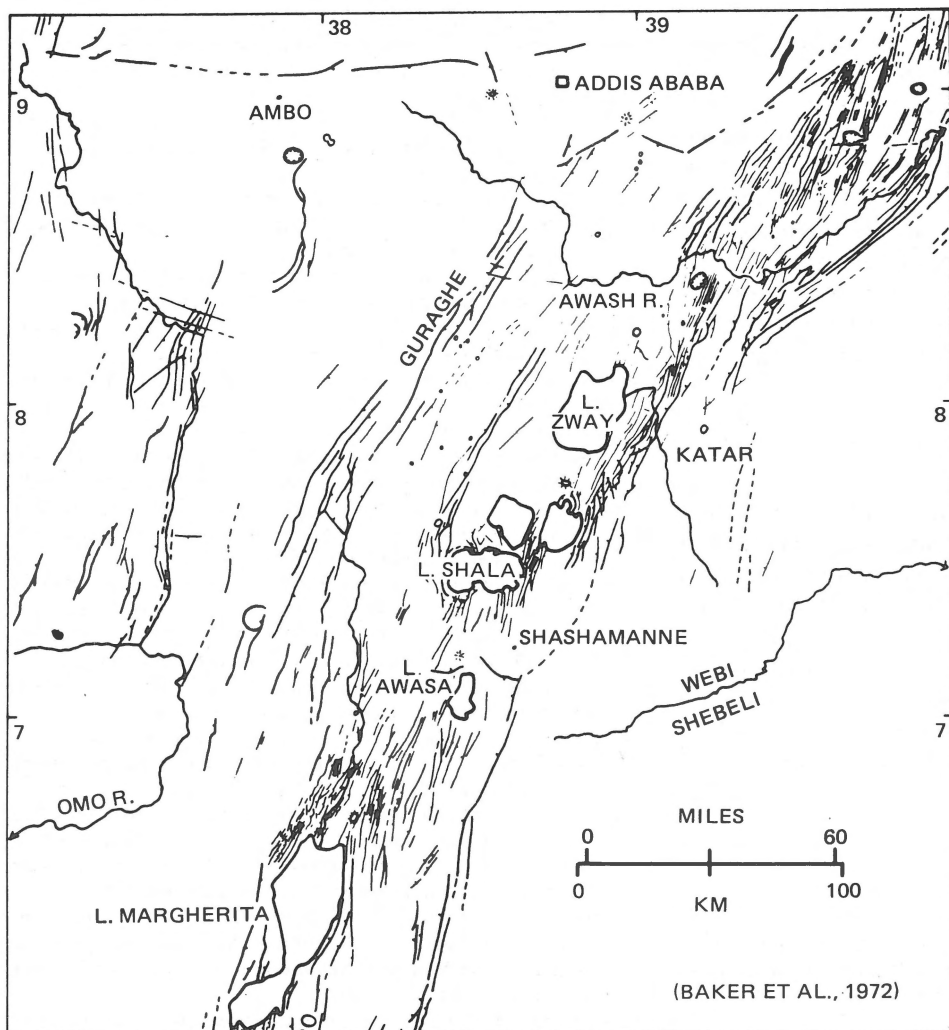


Fig. 26
Northeast segment of Main Ethiopian rift and Wonji fault belt, Ethiopia. Wonji fault belt is composed of high-angle, north-northeast trending en echelon faults; it extends southward from northeast corner of map to Lake Margherita. The rift's border faults were initiated first. They outline a regional dogleg, only the southern portion of which is visible on map.

Basin subsidence follows several different sequences. Early workers have proposed that grabens result from crestal normal faulting of a rising arch and, therefore, that the initiation of arching must precede basin formation. This apparently was the sequence at the Sirte basin. In the Gulf of Suez, however, the start of graben faulting coincided with regional subsidence. This timing is critical, in that reservoirs predating the graben fill were preserved from erosion and a major hydrocarbon play was thereby established in the older section. Numerous closely spaced, comparatively small displacement faults occurred first. Their movements were shifted later to the fewer, more widely spaced, larger displacement zones and this established the broad platforms. Arching in the Gulf of Suez came during the second state, after considerable graben infill. It then affected only the rift shoulders. The continuing graben subsidence established and preserved a second major hydrocarbon play, this one within the graben-fill section.

The zigzag, gridded patterns of multidirectional normal faulting establish many of the hydrocarbon traps. The repetition of patterns suggests that this fault style, and therefore its hydrocarbon traps, do not require unique circumstances for development, as has been proposed in the past. At several grabens, the differently oriented faults are seen to be synchronous, to have a similar kind of slip, and not to be dependent on corresponding basement grains for each of their multiple orientations. If these observations prove generally acceptable, all grabens can be considered to have a high probability of containing abundant hydrocarbon traps.

ACKNOWLEDGMENTS

I am indebted to the exploration staffs of Esso Exploration and Production U.K. and of Esso Exploration and Production Norway, Inc., for their assistance in the study of Viking graben hydrocarbon occurrences. Instructive discussions and helpful suggestions for the manuscript were provided by K. T. Biddle, R. P. George, S. H. Lingrey, D. W. Phelps, and R. C. Vierbuchen of Exxon Production Research Company; and by G. C. Mudd of Esso Exploration and Production U.K. Rebecca A. Miller drafted most of the figures, for which I am grateful.

REFERENCES

- Albright, W. A., W. L. Turner & K. R. Williamson 1980 Ninian Field, U. K. sector, North Sea. In: M. T. Halbouty (ed.): Giant Oil and Gas Fields of the Decade 1968-1978 – AAPG Mem. 30: 173-193.
- Asmus, H. E. & W. Guazelli 1981 Descrição sumária das estruturas da margem continental Brasileira e das áreas oceânicas e continentais adjacentes – hipóteses sobre o tectonismo causador e implicações para os prognósticos do potencial de recursos minerais. In: H.E. Asmus (ed.): Reconhecimento global da margem continental Brasileira – Petrobrás CENPES DINTEP., Série Projecto REMAC, n. 9: 187-261.
- Bebout, D. G. & C. Pendexter 1975 Secondary carbonate porosity as related to Early Tertiary depositional facies, Zelten field, Libya – AAPG Bull. 59: 665-693.
- Blair, D. G. 1975 Structural styles in North Sea oil and gas fields. In: A. W. Woodland (ed.): Petroleum and the continental shelf of northwest Europe. 1 – Geology – Applied Sci. Publ. London: 327-335.
- Bowen, J. M. 1976 The Brent Oil Field. In: A. W. Woodland (ed.): Petroleum and the continental shelf of northwest Europe. 1 – Geology – Applied Sci. Publ. London: 353-361.
- Brady, T. J., N. D. J. Campbell & C. E. Maher 1981 Intisar 'D' oil field, Libya. In: L. V. Illing & G. D. Hobson (eds.): Petroleum geology of the continental shelf of northwest Europe – Heyden and Son (for Inst. Pet.) London: 543-564.
- Brown, R. N. 1980 History of exploration and discovery of Morgan, Ramadan and July oil fields, Gulf of Suez, Egypt. In: A. D. Maill, (ed.): Facts and principles of world petroleum occurrence – Can. Soc. Pet. Geol. Mem. 6: 733-764.
- Clifford, A. J., R. Grund & H. Musrati 1981 Geology of a stratigraphic giant: Messla oil field, Libya. In: L. V. Illing & G. D. Hobson (eds.): Petroleum geology of the continental shelf of northwest Europe – Hayden and Son (for Inst. Pet.) London: 507-524.
- El-Ashry, M. T. 1972 Source and dispersal of reservoir sands in the El Morgan field, Gulf of Suez, Egypt – Sediment Geol. 8: 317-325.
- Fraser, W. W. 1967 Geology of the Zelten field, Libya, North Africa: 7th World Pet. Cong. Proc. (Mexico) – Elsevier Publ. Co. Amsterdam, NY, 2: 259-264.
- Freund, R. & A. M. Merzer 1976 The formation of rift valleys and their zigzag fault patterns – Geol. Mag. 113: 561-568.
- Garfunkel, Z. & Y. Bartov 1977 The tectonics of the Suez rift – Geol. Surv. Israel Bull. 71: 43 pp.
- Gilboa, Y. & A. Cohen 1979 Oil trap patterns in the Gulf of Suez – Israel Jour. Earth Sci. 28: 13-26.
- Gourdazi, G. H. 1970 Geology and mineral resources of Libya – a reconnaissance – U.S. Geol. Surv. Prof. Paper 660: 104 pp.
- Hallet, D. 1981 Refinement of the geological model of the Thistle field. In: L. V. Illing & G. D. Hobson (eds.): Petroleum geology of the continental shelf of northwest Europe – Heyden and Son (for Inst. Pet.) London: 315-325.
- Harding, T. P. (in press, a) Structural inversion at the Rambutan oil field, south Sumatra basin. In: A. W. Bally (ed.): Structural styles on seismic profiles – An atlas AAPG.
- Harding, T. P. (in press, b), Divergent wrench fault and negative flower structure, Andaman Sea: In: A. W. Bally (ed.): Structural styles on seismic profiles – An atlas AAPG.
- Harding, T. P., & J. D. Lowell 1979 Structural styles, their plate-tectonic habitats and hydrocarbon traps in petroleum provinces – AAPG Bull. 63: 1016-1058.
- Harms, J. C., T. Tackenberg, E. Pickles & R. E. Pollock 1981 The Brae oil field area. In: L. V. Illing & G. D. Hobson (eds.): Petroleum geology of the continental shelf of northwest Europe – Heyden and Son (for Inst. Pet.) London: 352-357.
- Heritier, F. E., P. Lassel & E. Wathne 1981 The Frigg gas field. In: L. V. Illing & G. D. Hobson (eds.): Petroleum geology of the continental shelf of northwest Europe – Heyden and Son (for Inst. Pet.) London: 380-391.
- Illes, J. H. 1970 Graben tectonics as related to crust-mantle interaction. In: J. H. Illes & St. Muellar (eds.): Graben problems – Schweizerbart'sche Verlagsbuchhandlung, Stuttgart: 4-27.
- 1981 Graben formation – the Maltese Islands – a case history – Tectonophysics 73: 151-168.

- King, P. B. 1965 Geology of the Sierra Diablo region, Texas – U.S. Geol. Surv. Prof. Paper 480: 185 pp.
- Klitzsch, E. 1970 Die Struktur-Geschichte der Zentralsahara – Geol. Rundsch. 59: 459-527.
- McDonald, R. E. 1976 Tertiary tectonics and sedimentary rocks along the transition: Basin and range province to plateau and thrust belt province, Utah. In: J. G. Hilt (ed.): Symposium on geology of the Cordilleran hinge line – Rocky Mtn. Assoc. Geol., Denver, CO: 281-317.
- Milanovsky, E. E. 1981 Aulacogens of ancient platforms – problems of their origin and tectonic development – Tectonophysics 73: 213-248.
- Mohr, P. A. 1968 Transcurrent faulting in the Ethiopian rift system – Nature 218: 938-941.
- Morton, W. H. & R. Black 1975 Crustal attenuation in Afar. In: A. Pilger & A. Rosler (eds.): After depression of Ethiopia – Proc. Intern. Symp. Afar region and related rift problems, Schweizerbart'sche Verlagsbuchhandlung, Stuttgart: 55-65.
- Parsons, M. G., A. M. Zagaar & J. J. Curry 1980 Hydrocarbon occurrences in the Sirte basin, Libya. In: A. D. Maill (ed.): Facts and principles of world petroleum occurrence – Can. Soc. Pet. Geol. Mem. 6: 723-732.
- Proffett, J. M. 1977 Cenozoic geology of the Yerington district, Nevada, and implications for the nature and origin of basin and range faulting – Geol. Soc. Amer. Bull. 88: 247-266.
- Reches, Z. 1978 Analysis of faulting in three-dimensional strain field – Tectonophysics 47: 109-129.
- Robson, D. A. 1971 The structure of the Gulf of Suez (clysmic) rift, with special reference to the eastern side – J. Geol. Soc. 127: 247-276.
- Ronnevik, H. C., W. v. d. Bosch & E. H. Bandlien 1975 A proposed nomenclature for the main structural features in the Norwegian North Sea. In: Norwegian Pet. Soc. – Jurassic Northern North Sea Symp. Proc. JNNSS/18: 1-16.
- Said, R. 1962 The Geology of Egypt – Elsevier Publ. Co., Amsterdam, NY: 377 pp.
- Sanford, R. M. 1970 Sarir oil field, Libya – desert surprise – AAPG Mem. 14: 449-476.
- Schürmann, H. M. E. 1966 The Precambrian along the Gulf of Suez and the northern part of the Red Sea – E. J. Brill, Leiden: 404 pp.
- Soliman, S. M. & M. I. Faris 1963 General geologic setting of the Nile delta province and its evaluation for petroleum prospecting – 4th Arab Pet. Cong., Beirut, Paper 23 (B-3): 11 pp.
- Steel, R. & T. G. Gloppen 1980 Late Caledonian (Devonian) basin formation, western Norway: Signs of strike-slip tectonics during infilling. In: P. F. Ballance & H. G. Reading (eds.): Sedimentation in oblique-slip mobile zones – Int. Assoc. Sed. Spec. Publ. 4: 79-103.
- Vail, P. R. & R. G. Todd 1981 Northern North Sea Jurassic unconformities, chronostratigraphy and sea-level changes from seismic stratigraphy. In: L. V. Illing & G. D. Hobson (eds.): Petroleum geology of the continental shelf of northwest Europe – Heyden and Son (for Inst. Pet.) London: 21.
- Van den Bark, E. & O. D. Thomas 1980 Ekofisk: First of the giant oil fields in western Europe. In: M. T. Halbouty (ed.): Giant oil and gas fields of the decade 1968-1978 – AAPG Mem. 30: 195-224.
- Vierbuchen, R. C., R. P. George & P. R. Vail (in press) A thermal-mechanical model of rifting with implications for outer highs on passive continental margins. In: J. Watkin (ed.): Proceedings of the Hedberg Conference on origins of passive margins – AAPG Mem.
- Wernicke, B. & B. C. Burchfiel 1982 Modes of extensional tectonics – J. Struc. Geol. 4: 105-115.
- White, D. A. 1980 Assessing oil and gas plays in facies-cycle wedges – AAPG Bull. 64: 1158-1178.
- Williams, J. J. 1968 The sedimentary and igneous reservoirs of the Augila oil field, Libya. In: Geology and archeology of northern Cyrenaica, Libya – Pet. Explor. Soc. Libya 10th Ann. Field Conf. Guidebook: 197-204.
- 1972 Augila field, Libya: Depositional environment and diagnosis of sedimentary reservoir and description of igneous reservoir – AAPG Mem. 16: 623-632.
- Ziegler, P. A. 1978 Northwest Europe: Tectonics and basin development – Geol. Mijnbouw 57: 589-626.
- 1979 Factors controlling North Sea hydrocarbon accumulations. – World Oil, November: 111-124.
- 1980, Northwest Europe basin: geology and hydrocarbon provinces. In: A. D. Maill (ed.): Facts and principles of world petroleum occurrence – Can. Soc. Pet. Geol. Mem. 6: 653-706.