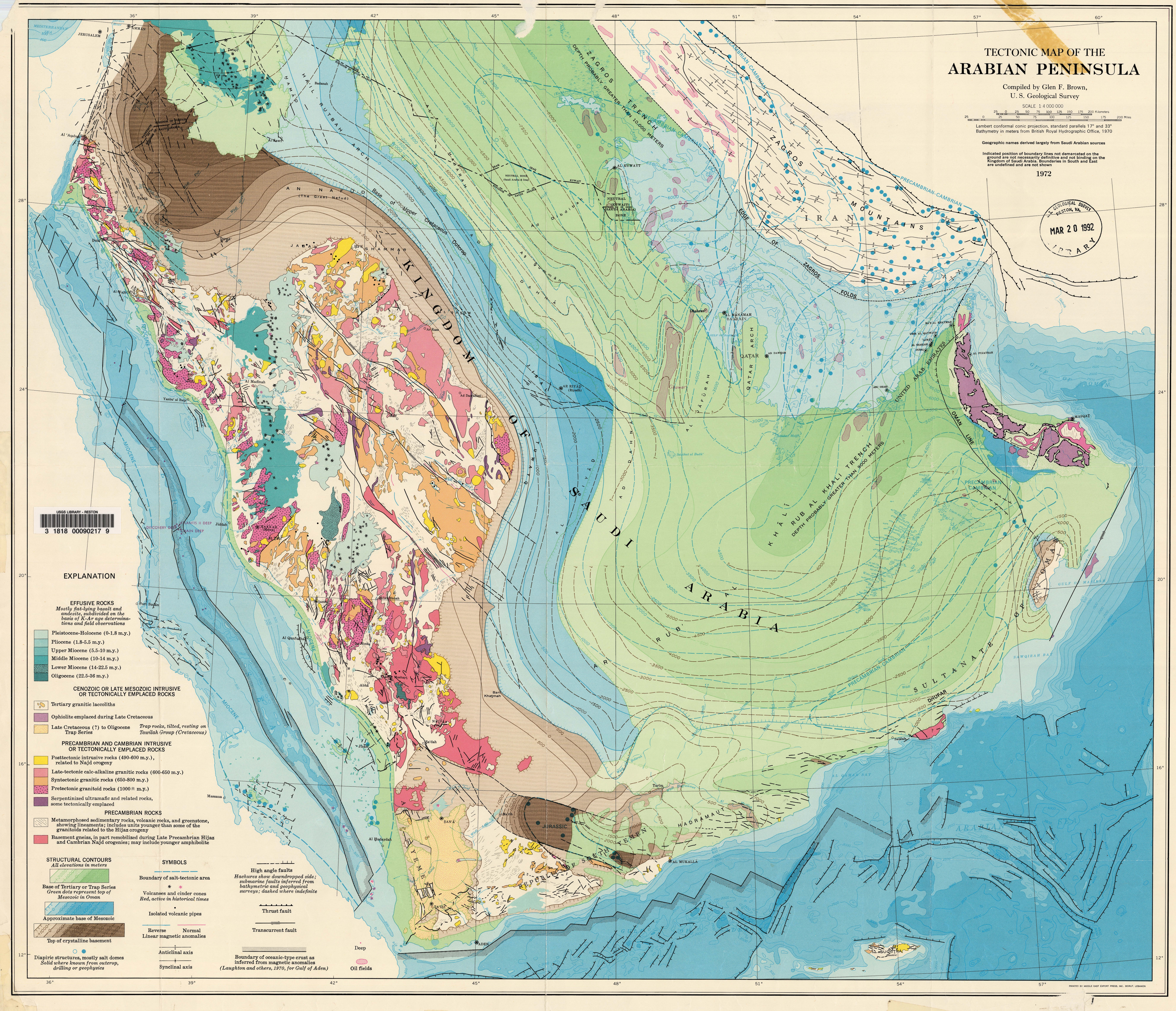

TECTONIC MAP OF THE
ARABIAN PENINSULA

Compiled by Glen F. Brown,
U. S. Geological Survey

SCALE 1:4 000 000

25 0 25 50 75 100 125 150 175 200 Kilometers
25 0 25 50 75 100 125 150 175 200 Miles

Lambert conformal conic projection, standard parallels 17° and 33°
Bathymetry in meters from British Royal Hydrographic Office, 1970

Geographic names derived largely from Saudi Arabian sources

Indicated position of boundary lines not demarcated on the ground are not necessarily definitive and not binding on the Kingdom of Saudi Arabia. Boundaries in South and East are undefined and are not shown

1972

EXPLANATION

EFFUSIVE ROCKS

Mostly flat-lying basalt and andesite, subdivided on the basis of K-Ar age determinations and field observations

- Pleistocene-Holocene (0-1.8 m.y.)
- Pliocene (1.8-5.5 m.y.)
- Upper Miocene (5.5-10 m.y.)
- Middle Miocene (10-14 m.y.)
- Lower Miocene (14-22.5 m.y.)
- Oligocene (22.5-36 m.y.)

CENOZOIC OR LATE MESOZOIC INTRUSIVE OR TECTONICALLY EMPLACED ROCKS

- Tertiary granitic laccoliths
- Ophiolite emplaced during Late Cretaceous
- Late Cretaceous (?) to Oligocene Trap Series — *Trap rocks, tilted, resting on Tawilah Group (Cretaceous)*

PRECAMBRIAN AND CAMBRIAN INTRUSIVE OR TECTONICALLY EMPLACED ROCKS

- Posttectonic intrusive rocks (490-600 m.y.), related to Najd orogeny
- Late-tectonic calc-alkaline granitic rocks (600-650 m.y.)
- Syntectonic granitic rocks (650-800 m.y.)
- Pretectonic granitoid rocks (1000± m.y.)
- Serpentinized ultramafic and related rocks, some tectonically emplaced

PRECAMBRIAN ROCKS

- Metamorphosed sedimentary rocks, volcanic rocks, and greenstone, showing lineaments; includes units younger than some of the granitoids related to the Hijaz orogeny
- Basement gneiss, in part remobilized during Late Precambrian Hijaz and Cambrian Najd orogenies; may include younger amphibolite

STRUCTURAL CONTOURS

All elevations in meters

Base of Tertiary or Trap Series
Green dots represent top of Mesozoic in Oman

Approximate base of Mesozoic

Top of crystalline basement

○ ●
Diapiric structures, mostly salt domes
Solid where known from outcrop, drilling or geophysics

SYMBOLS

Boundary of salt-tectonic area

Volcanoes and cinder cones
Red, active in historical times

Isolated volcanic pipes

Reverse — Normal
Linear magnetic anomalies

Anticlinal axis

Synclinal axis

High angle faults
Hachures show downdropped side; submarine faults inferred from bathymetric and geophysical surveys; dashed where indefinite

Thrust fault

Transcurrent fault

Boundary of oceanic-type crust as inferred from magnetic anomalies
(Laughton and others, 1970, for Gulf of Aden)

Deep

Oil fields

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EXPLANATION

Introduction

This tectonic map of the Arabian peninsula, prepared for the Saudi Arabian Ministry of Petroleum and Mineral Resources, is the first of a series of peninsular maps that attempt to show regional features. Much recent information resulting from detailed geologic mapping notably within the Arabian craton, from geophysical surveys, both airborne and oceanographic in adjacent seas, from deep exploratory drilling, and from photography from the Gemini and Apollo space programs, has been used in the tectonic evaluation.

Sources of information

Various segments of the Arabian Shield or craton have been mapped by members of the Saudi Arabian Directorate General of Mineral Resources, Bureau de Recherches, Géologiques et Minières of France, the Japanese Geological Survey, and the U.S. Geological Survey (see index map for individual credit). For information outside the Shield area, various published maps were consulted, of which the U.S. Geological Survey-Arabian American Oil Company (1963) geologic map of the Arabian Peninsula, the topographic map of the Arabian peninsula (Saudi Arabian Dir. Gen. Mineral Resources, 1972), and the new bathymetric maps of the Red Sea and the Gulf of Aden (Laughton, 1970; Laughton and others, 1970) were the principal sources. The Directorate General of Petroleum Resources of the Ministry of Petroleum and Mineral Resources supplied evaluations of formation tops in oil exploration test holes, and the Ministry of Agriculture and Water gave similar information from borings drilled for water to depths of 2,400 m or less, except for a deep test at Riyadh which was drilled to 3,000 m.

The geologic map of Iran (Iran Oil Co., 1957) provided source data on folds and salt domes in southern Iran, as did later published (Kamen-Kaye, 1970) and unpublished information. Information on salt tectonics is from Stöcklin (1968), Beydoun (1964), and Frazier (1970). In addition, earlier reports on salt domes along the eastern shore of the Red Sea (Mac Fadyen, Cox, and Brighton, 1930) were noted. The tectonic interpretation of northwestern Arabia has been adjusted to that shown for Jordan (Bender, 1968). Nappe structures shown in the Oman Mountains follow the description of Reinhardt (1969). Faults shown on the peninsula are mostly from geologic maps (U.S. Geol. Survey, 1963; Bender, 1968; Gillman, 1968, and Beydoun, 1970), and fault extensions are plotted from satellite photography. Faults in the Red Sea and Gulf of Aden are inferred from submarine escarpments as shown on the British Hydrographic Office charts (Laughton, Whitmarsh, and Jones, 1970) and by Phillips and Ross (1970). Structure maps of the peninsula compiled by Andre and Dubertret (1968) have been helpful for general interpretations.

The crystalline shield

Basement gneiss is believed to represent the oldest rocks exposed in the Arabian Shield, although it has not been dated radiometrically. In places massive bodies of the gneiss occupy diapiric structures squeezed upward through younger schistose rocks along north- and northwest-striking transverse faults. Some gneissic boundaries are sheared. Some bodies have an intrusive aspect, as though reactivation approached palingenesis, and these may actually be regenerated and therefore younger. Most of the rocks are orthogneisses derived from diorite, quartz diorite, granodiorite, or granite, and are in the amphibolite metamorphic facies, although some are greenschist and others, questionably, are granulite. One large roof pendant at the east edge of the Shield is almost entirely metaanorthosite; elsewhere paragneiss crops out.

Greenwood and Bleackley (1967) have described three outcrops of older gneiss in South Yemen. Two are along the upthrown southwest flank of a fault striking southeast from Sa'dah into the Hadramaut in a structure similar to that along the southern segment of the Najd fault system in Saudi Arabia. The third outcrop is in southwestern South Yemen and is opposite the Harrar Massif of Ethiopia and Somalia in Africa, which is considered Archean (Kazmin, 1971). Kazmin's brief description and the geographic position of the African gneiss suggest that it may be correlative with older gneiss of South Yemen and with basement gneiss of Yemen and Saudi Arabia.

The oldest radiometrically dated rocks are granodiorite and related quartz diorite exposed in the vicinity of Mecca and in discontinuous outcrops to the north and east (shown as older granitic rocks, 1,000 ± m.y.). Rb-Sr ages determined by L. T. Aldrich of the Carnegie Institution, as shown on the geologic map of Southern Hijaz (Brown and others, 1962), average about 1,000 m.y. These determinations, together with somewhat younger K-Ar ages, point to a plutonic episode correlative with or slightly younger than the African Kibaran orogeny of about 1,100 ± 200 m.y. (Clifford, 1970).

Younger plutonic rocks are classified as somewhat arbitrary time units of syntectonic and late tectonic (related to the Hijaz orogeny), and posttectonic (related to the Najd orogeny) stages; the isotopic ages of these rocks come within the time span of 800-490 m.y., primarily on the basis of 50 determinations made by Aldrich. The locations of the dated samples are shown on geologic maps at 1:500,000 scale (Bramkamp and others, 1963, 1964; Brown and others, 1962, 1963a, b; and Jackson and others, 1963).

The syntectonic rocks date from about 800 to 650 m.y., the late tectonic from 650 to 600 m.y., and the posttectonic from about 600-490 m.y. The syntectonic stage has, among its diagnostic features, gneissic or migmatitic rocks commonly sheared and somewhat metamorphosed, with zones of schlieren and xenoliths. These rocks are mostly diorite or granodiorite, with four samples of quartz diorite averaging near 800 m.y. The late tectonic granitic rocks tend to be calc-alkalic and massive, but in places they show metasomatic layering and porphyritic zones. The posttectonic plutons are alkaline or peralkaline, and are commonly characterized by one of the sodic pyroboles, arfvedsonite, riebeckite, or aegirite; they are widely variant in silica content, ranging from gabbro to granite and from syenite to highly silicic albite granite.

This grouping by stages is based on the structural forms and textures of the granitoid rocks as well as on a general trend from basic calc-alkaline (older) through peralkalic types (younger). The stages possibly represent more than one magmatic cycle, but may also be dependent on the level of exposure of the plutonic masses, the gneissic, syntectonic types being in general more characteristic of root zones of batholiths, and the discordant posttectonic forms typical of roof zones. This general megacycle appears to be synchronous with the polyphase East African "Mozambiquian" orogeny (*sensu lato*) which extends northward from East Africa into Arabia (Bloomfield, 1970; Kazmin, 1971).

However, the fold-fault pattern of the Shield surface, together with what is known of the stratigraphy of the nonplutonic rocks in the metamorphosed septa and screens, suggest that there were two major orogenic cycles, each with more than one period of folding and igneous activity, subsequent to the igneous invasion of the 1,000 m.y. granitic rocks. Although these younger cycles appear to be synchronous with similar orogenies in the African Shield, until more is known about the correlations it seems best to give them regional Arabian names. Accordingly, the older of the two, which is more widespread, both areally and in time, and more intense, especially in the southern part of the Shield, is called the Hijaz orogeny, an historical name for western Arabia, (Schmidt and others, 1972). At least one culmination of folding, together with the intrusion of syntectonic granitic rocks in the central and southern part of the Shield, came about 660 m.y. ago. Rhyolite flows and tuffs accumulated in the central and northern part of the Shield at about the same time. Characteristically the orogeny was dominated by east-west compression, and the strongly folded, faulted (some strike-slip), and locally overthrust beds crop out in meridional or north-northeast-trending belts and lineaments. Greenstone pillows, clastic material, and some marble with ultramafic rocks of questionable age have been raised to amphibolite metamorphic facies in many places, and older beds contain evidence of retrogressive metamorphism to the greenschist facies in other areas. Younger clastic rocks were also metamorphosed during east-west compression, but only locally to greenschist facies, perhaps during the dying phases of the Hijaz orogeny.

The name Najd orogeny, a name taken from the classical Arabic for the highlands east of the Hijaz ranges in central Arabia, is here applied to the younger period of mountainbuilding and cratonization. Effects of the younger and shallower movements are most characteristically seen in a system of northwest-trending left-lateral faults referred to as the Najd fault system by Delfour (1970). Serpentinized ultramafic and related rock masses, possibly representing dismembered ophiolites among the older rocks of the Shield, have been left-laterally displaced as much as 240 km along segments of the Najd fault system after being injected during the Hijaz orogeny. Basement gneiss crops out along the wrench faults, and in most places implies a substantial vertical component of movement. Horizontal displacements along individual faults range from 2 to 25 km, where rock units could be accurately correlated across the strike-slip faults. As an example, slate beds believed to be somewhat older than 647 m.y. are left-laterally displaced about 25 km near the northwestern end of the Najd fault system; a gabbroic lopolith is displaced left-laterally 9 km (Igarashi, written commun., 1970); another fault displaces the same gabbro about 2 km (Higashimoto, written commun., 1970). Although some granitic rocks of the Najd orogeny came into place under differential pressure and froze during the orogeny, most were emplaced late or after the fault movement. Numerous widely scattered granitic samples average 570 m.y. by K-Ar age determinations, and slightly older by Rb-Sr determinations, and may date the early part of the Najd orogeny. The posttectonic alkalic intrusives generally occupy stocks and pipes, although six rather large batholiths also date from the Najd period.

The youngest cratonized group in the Shield, the J'Balah Group (Delfour, 1970), crops out along the northwest-trending strike-slip faults of the Najd system and is limited almost entirely to valley floors or grabens developed in the sheared rocks of the fault zones. The J'Balah Group postdates most of the movement on the faults and most of the Shield cratonization. It is nonetheless folded and synforms are asymmetrical, with steeper limbs toward the northeast within the narrow outcrop belts, a result of post-J'Balah fault movement. Andesite flow rock within the J'Balah Group has yielded a K-Ar whole-rock age of 540 ± 18 m.y., determined by Richard Marvin, H. H. Mehnert, and Violet Merritt of the U.S. Geological Survey (written commun.). Related andesite flows and intrusives in the northern part of the Shield average 519 ± 17 m.y. (K-Ar determinations on whole rock and biotite from widely scattered localities).

Younger age determinations have been reported for rocks near the Precambrian Shield but their relationship to orogeny is not known. K-Ar ages as young as 470 m.y. have been reported from eastern South Yemen (Snelling *in* Greenwood and Bleackley, 1967), and several Rb-Sr dates cluster around 500 m.y. for potash-rich granite correlative with quartz porphyry intrusive into the Cambrian of Jordan (Bender, written commun., 1971).

The Najd orogeny apparently involved at least two periods of igneous activity, interrupted by long quiescent intervals and intermittent fault movements. The time span is similar to that of the Katangan-Damaran (Pan-African) orogeny, and the youngest plutons in general are along the eastern shore of the Red Sea and along the eastern edge of the Arabian Shield.

The Hijaz and Najd orogenies represent two tectonic cycles that have resulted from different primary forces. Rotation of a proto-Arabian plate may have been a contributing force. The older Hijaz folding and plutonism may have occurred at greater depth, whereas the younger Najd orogeny may reflect shears from shallower movement. The time span and tectonic history appear to closely parallel events in the central African Hoggar (Black and Girod, 1970).

Structural contours

Structural contours drawn on the subterranean extension of crystalline and cratonized rocks exposed in the Shield area are based on drill records for drill holes as deep as about 2,000 m. Below that depth extrapolated stratigraphic thicknesses and geophysical interpretation are used, and the shape is speculative, especially where the surface plunges into the troughs parallel to the Zagros Mountains and the Oman Line. One of the factors that prevents simple analysis is a wedge of Carboniferous and older Paleozoic subsurface strata that extends nearly across the peninsula. Furthermore, because the sedimentary rocks in the upper part of the Precambrian and the overlying Cambrian are not thoroughly recrystallized, as for example in Jordan and in the western Rub' al Khali southeast of the Arabian Shield, stratigraphic thicknesses projected into the subsurface from measured outcrops or from wells are likely to differ from those based on geophysical interpretation. At Badanah (near the north edge of the map) a test well entered the Devonian at a depth of 1,380 m. If the nearby outcrop thickness of the underlying Paleozoic strata is added to this depth, the depth to basement would be about 2,800 m below sea level. An earlier estimate to the basement in this area is about 2,000 m, which seems reasonable, however, airborne magnetic profiles across the Badanah area suggest a depth of about 6,700 m to magnetic basement, and a depth analysis based on a regional gravity survey west of Badanah indicates a maximum depth to basement of 5,000 m (Andreasen, writen commun., 1971). In a deep test boring for water near Riyadh, about 750 m of upper Paleozoic or possibly lower Mesozoic sedimentary beds were penetrated above a depth of 3,000 m; the basement there is probably at least 3,300 m below sea level. In the western Rub' al Khali at least 1,100 m of Paleozoic strata overlies wacke or slate. These structural data together with those from the Badanah boring have been used to extrapolate basement contours adjusted to limited geophysical information.

Two troughs are apparent, one parallel to the Arabian Gulf in southwestern Iran and one nearly at right angles to it beneath the northeastern Rub' al Khali and extending northeastward along the western side of the Oman Line. However, there is insufficient information to complete the contouring. At Riyadh, contours on the top Minjur Sandstone, together with the information from the deep test boring, indicate westerly lateral or down-dropped normal-fault movement along the north side of the Dhrumah-Nisah fault system. Such movement is sympathetic to the sinistral strike-slip faults within the Shield and beneath the Paleozoic cover south of Riyadh. The eastward extension of the Dhrumah-Nisah fault system south of Riyadh coincides with the southern end of the oil-field structures that are identified by north-south folding, notably the large Ghawar structure, and the southern end of the Qatar arch as well. Farther east an eastward extension of the faults may coincide with the northern edge of the structural depression of the northeastern Rub' al Khali. An extension of the Dhrumah-Nisah fault system represents a major change in tectonic development with the crust to the south having been folded and deepened progressively eastward towards the Oman Line.

Salt tectonics

Boundaries are drawn around areas where diapiric salt structures have been mapped or have been reported from drilling or geophysical evidence. Many oil fields are located on structural highs and gravity lows that may have resulted from salt flowage at depth, but these are not shown as diapiric structures even though many may be. The outlined areas attempt to show the active and presumably the deeper parts of the evaporite basins. Five of the diapiric salt areas are above the late Precambrian-Cambrian Hormuz basin which underlies much of the Arabian Gulf geosyncline and which has contributed salt to exposed domes in the Zagros Mountains and farther east in Iran. Domes from the Hormuz extend southward into the Oman below 21° north latitude and salt has been encountered in exploratory wells along the north side of the Dhufar still farther south near the southern coast of the Peninsula.

The town of Sa'dah in northern Yemen is in a graben of Jurassic sedimentary rocks (Geukens, 1966) that extends southeastward toward Wadi Hadramaut between border faults that can be clearly seen on Apollo and Gemini space photographs. Nine salt domes have been mapped (Beydoun, 1964) in the lower southern part of the graben; accordingly basement contours have been questionably added and closure shown to suggest considerably less than a sedimentary thickness sufficient for the diapiric structures to develop. It is assumed that local stress resulting from opening of the Gulf of Aden was partially effective in causing the salt domes to form. The evaporite series containing the salt is assigned to the Upper Jurassic.

The youngest salt-tectonic basins contain Miocene salt. The largest basin is the Red Sea. Whether the Red Sea trough arched and broke in early Tertiary time, or the Arabian plate drifted away from Africa at about the same time is still being debated by geologists and geophysicists (Falcon and others, 1970; Picard, 1970; Dubertret, 1969). Regardless of origin, during middle and late Miocene time, more than 3,000 m of salt was deposited in the trough northward from 14° north latitude to the Gulfs of Suez and Aqaba. All reported diapiric structures have been found south of 19° north latitude, but there would seem to be no reason why similar structures may not exist farther north (Gillman, 1968). As Miocene and Pliocene volcanism is involved with the evaporite series, some piercement structures may be volcanic necks similar to those on the Arabian Shield.

Another smaller Tertiary salt-tectonic area lies along the west side of the Oman Line near the Strait of Hormuz where downbuckling is continuing.

Oman Mountains

The Oman Mountains are composed of the Semail nappe and related rocks of the ophiolitic suite. They may have accumulated on the ocean floor as early as Middle or Late Permian but certainly during early Late Cretaceous time—and were subsequently overthrust during the Alpine orogeny as Arabia drifted against Asia (Reinhardt, 1969; McKenzie, 1970; Coleman, 1971). The deep downbuckling of the continental crust in the eastern segment of the Arabian Gulf geosyncline, together with the increase of intensity of folding eastward culminating in the Zagros overthrust as the leading edge of the Arabian plate, are probably the result of impingement of the Arabian and Asian continental plates.

Tertiary volcanism

The oldest lavas associated with rifting of the Red Sea are a thick series of plateau or flood-type basalt, andesite, trachyte, and rhyolite flows interbedded with tuff and nonmarine sedimentary rocks, some of which contain fresh-water fossils suggestive of Oligocene to Miocene age (Geukens, 1966). The lowermost flows of this so-called "Trap Series", resting on Cretaceous clastics in Yemen, are possibly as old as Late Cretaceous or Eocene and lie in a broad faulted anticline parallel to the Red Sea rift. Both in Yemen and Ethiopia they form the crests of ramped flanks of the Red Sea rift valley. A K-Ar whole-rock analysis from a basalt feeder dike to the lavas at Asmara, Ethiopia, gave 36.6 ± 1.2 m.y. (analyst: Isotopes, Inc.), which could be latest Eocene or earliest Oligocene. In southwestern Saudi Arabia a thick series of basalt flows ranging in age from 24 to 29 m.y. (Oligocene) is most likely an equivalent part of the Trap Series (Coleman and Brown, 1971). The Trap Series was elevated during early Tertiary time, or flowed out on an elevated surface, and then was flexed and faulted during early Miocene when the rift valley was formed.

Volcanic activity has continued up to the present time (fig. 1). The Miocene to Holocene flows of western Saudi Arabia are composed of alkali olivine basalt and are chemically similar to the Trap Series in Yemen and Ethiopia, in contrast to the oceanic character of basalt from the mid-trench of the Red Sea (Gass, 1970).

Samples from some flows or intrusives considered to be of Miocene age gave K-Ar Mesozoic or early Tertiary ages, probably because of excess argon inherited from older rocks. These older ages have been omitted from fig. 1. Gabbroic dikes and related intrusives, including a layered lopolith east of Jizan, give an average K-Ar age of about 22 m.y., and all are strongly and reversely magnetized. The remarkably linear reversed anomalies, extending as far north as 28° 30′ north latitude to the east of the Gulf of Aqaba, are parallel to tholeiitic gabbro dikes which are only sporadically exposed along the trace of the anomalies and have not been dated north of Jiddah; they are undoubtedly coextensive in the subsurface. Although they closely parallel the Red Sea trough and cut across the northwest-trending strike-slip faults, they do not follow the zig-zag pattern of the younger middle trench. Linear positive magnetic anomalies are associated with antiforms of gneissic amphibolitic rocks or are related to faults; if they represent dikes, they are not the same age as the dated gabbroic dikes.

Red Sea-Gulf of Aden

Most students of the Gulf of Aden and the Red Sea believe these features were formed by crustal extension. The Gulf of Aden is largely underlain by oceanic crust, and its topography, structure, seismicity, and linear magnetic anomalies fit the classical concept of ocean-floor spreading, at least for crust as old as 10 m.y. (Laughton, Whitmarsh, and Jones, 1970). The eastern limit of downbuckling associated with the Gulf of Aden is marked by the Oman Line.

The origin of the Red Sea rift is more complicated. The basin consists of an outer structural trough in which is a deep inner trench. At the north end of the outer trough, basement granite has been found at 2,900 m below sea level, beneath Quaternary and Tertiary deposits. To the south a thick series of Miocene evaporites underlies the outer trough. Both flanks of the trough show downwarping as well as faulting. Seismic profiles suggest that the floor of the Miocene salt basin rises ramp-like on either side of the axial trough, though this is not reflected in the submarine topography (Frazier, 1970).

The inner trench in the Red Sea is underlain mostly by sedimentary volcanic material, as shown in cores obtained by the Woods Hole Oceanographic Institution survey ship RV *Chain* in March 1971 (Ross and others, written commun., 1971). Tholeiitic basalt has been recovered, apparently confirming views based on geophysical evidence that the floor of the trench may be oceanic crust (Drake and Girdler, 1964). The limits of rock interpreted as oceanic crust in the floor of the Red Sea are not certain but at least the inner trench south of 24° north latitude is floored by such material. The boundary of zebra-like striped anomalies parallel to the mid trench or at right angles to the transform faults is shown as demarcating the area believed to be directly underlain by oceanic crust in both the Red Sea and the Gulf of Aden. Areas between this central and younger region and the coasts may be underlain by continental (granitic) or oceanic type mantle, attenuated and diluted or as alternate fragments of the two types, but certainly some of this region contains sialic crust. The deeps, which contain hot metalliferous brines, lie along a linear magnetic anomaly (Kabbani, 1970) which may represent a transform fault (Whiteman, 1970). In rift faults onshore, basaltic dikes (5 m.y. or later) contain mantle type xenoliths, suggesting deeper sources for the continuing magmatic activity that may be related to the hot brines in the depths of the trough.

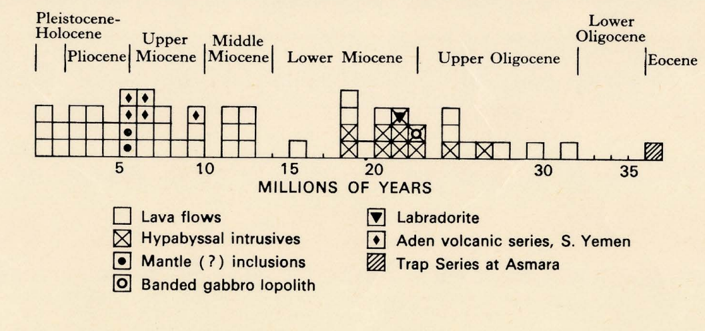

Figure 1. Histogram of K-Ar radiometric ages of basaltic flows and hypabyssal intrusives in western Arabia. Each square represents one lava flow or intrusive, in some cases an average of several samples. Where multiple flood basalts occur, the uppermost and lowermost flows were sampled. All samples were whole-rock except one of labradorite. Determinations made by Isotopes, Inc. and R. F. Marvin, H. H. Mehnert, and Violet Merritt, U.S. Geological Survey, except five samples from South Yemen made by D. C. Rex (Dickinson and others, 1969).

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References

Andre, C., and Dubertret, L., 1968, Peninsule Arabique, carte orographie, hydrographie, mers et cartes structurales: Extrait des notes et memoires sur le Moyen-Orient. Mus. Nat. d'Histoire Naturelle, tome X, Paris, 285-318.

Bender, F., 1968, Geologie von Jordanien: Berlin, Gebruder Borntraeger, 230 p. *Area 1 on index map.*

Beydoun, Z. R., 1964, The stratigraphy and structure of the Eastern Aden Protectorate: Overseas Geol. and Min. Res. Supp. Series, Bull. no. 5, 107 p. *Area 5 on index map.*

——— 1970, Southern Arabia and northern Somalia—comparative geology: Royal Soc. London Philos. Trans., v. A267, p. 267-293. *Area 5 on index map.*

Black, R., and Girod, M., 1970, Late Paleozoic to Recent igneous activity in West Africa and its relationship to basement structure, p. 185-210, *in* African magmatism and tectonics: Hafner Pub. Co., New York.

Bloomfield, K., 1970, Orogenic and post-orogenic plutonism in Malawi, p. 119-155, *in* African magmatism and tectonics: Hafner Pub. Co., New York.

Bramkamp, R. A., Ramirez, L. F., Brown G. F., and Pocock, A. E., 1963, Geologic map of the Wadi ar Rimah quadrangle: U.S. Geol. Survey Misc. Geol. Inv. Map I-206A.

Bramkamp, R. A., Brown, G. F., Holm, D. A., and Layne, N. M., Jr., 1964, Geologic map of the Wadi as Sirhan quadrangle: U.S. Geol. Survey Misc. Geol. Inv. Map I-200A.

Brown, G. F., 1970, Eastern margin of the Red Sea and the coastal structures in Saudi Arabia: Royal Soc. London Philos. Trans., v. A267, p. 75-89.

Brown, G. F., Jackson, R. O., Bogue, R. G., and MacLean, W. H., 1962, Geologic map of the southern Hijaz quadrangle: U.S. Geol. Survey Misc. Geol. Inv. Map I-210A.

Brown, G. F., Jackson, R. O., Bogue, R. G., and Elberg, E. L., Jr., 1963a, Geologic map of the northwestern Hijaz quadrangle: U.S. Geol. Survey Misc. Geol. Inv. Map I-204A.

Brown, G. F., Layne, N. M., Goudarzi, G. H., and MacLean, W. H., 1963b, Geologic map of the northeastern Hijaz quadrangle: U.S. Geol. Survey Misc. Geol. Inv. Map I-205A.

Clifford, T. N., 1970, The structural framework of Africa, p. 1-26, *in* African magmatism and tectonics: Hafner Pub. Co., New York.

Coleman, R. G., 1971, Plate tectonic emplacement of upper mantle peridotites along continental edges: Jour. Geophys. Research, v. 76, no. 5, p. 1212-1222.

Coleman, R. G., and Brown, G. F., 1971, Volcanism in southwest Saudi Arabia (abs): Geol. Soc. America, Abs., v. 3, no. 7, p. 529.

Delfour, J., 1970, Le Groupe de J'balah, une nouvelle unite du bouclier arabe: Bull. du BRGM, Deux. serie, sec. IV, no. 4, p. 19-32.

Dickinson, D. R., and others, 1969, Correlation of Initial $^{87}\mathrm{SR}^{86}\mathrm{SR}$ with Rb-Sr in some late Tertiary volcanic rocks of South Arabia: Earth Planetary Sci. Letters 6 (1969), p. 84-90.

Drake, C. L., and Girdler, R. W., 1964, A geophysical study of the Red Sea: Royal Astron. Soc. Geophys. Jour., v. 8, p. 473-495.

Dubertret, Louis, 1969, Le Liban et la derive des continents: Rev. Libanaise, de geog., v. IV, Hannon, p. 53-61.

Falcon, N. L., Gass, I. G., Girdler, R. W., and Laughton, A. S., 1970, Organizers for a discussion on the structure and evolution of the Red Sea and the nature of the Red Sea, Gulf of Aden, and Ethiopia rift junction: Royal Soc. London Philos. Trans., v. A267, 417 p.

Frazier, S. B., 1970, Adjacent structures of Ethiopia—that portion of the Red Sea coast including Dahlak Kebir Island and the Gulf of Zula: Royal Soc. London Philos. Trans., v. A267, p. 131-141.

Gass, I. G., 1970, The evolution of volcanism in the junction area of the Red Sea, Gulf of Aden and Ethiopian rifts: Royal Soc. London Philos. Trans., v. A267, p. 369-381.

Geukens, F., 1966, Geology of the Arabian Peninsula, Yemen: U.S. Geol. Survey Prof. Paper 560-B, 23 p. *Area 3 on index map.*

Gillman, Michel, 1968, Preliminary results of a geological and geophysical reconnaissance of the Jizan coastal plain in Saudi Arabia: AIME Symp. 2nd regional, Dhahran, Saudi Arabia, p. 159-209.

Girdler, R. W., 1969, The Red Sea — a geophysical background, p. 38-55, *in* Hot brines and recent heavy metal deposits in the Red Sea — A geochemical and geophysical account: Springer-Verlag, New York.

Girdler, R. W., and Darracott, R. W., 1972, African poles of rotation: Comments on the Earth Sciences, Geophysics 2, no. 5, p. 7-15.

Greenwood, J. E. G. W., and Bleackley, D., 1967, Geology of the Arabian Peninsula, Aden Protectorate: U.S. Geol. Survey Prof. Paper 560-C, 96 p. *Area 4 on index map.*

Iran Oil Co., Geological Staff, 1957, Geological Map of Iran: Nat. Iran. Oil Co. (1:250,000). *Area 7 on index map.*

Jackson, R. O., Bogue, R. G., Brown, G. F., and Gierhart, R. D., 1963, Geologic map of the Southern Najd quadrangle: U.S. Geol. Survey Misc. Geol. Inv. Map I-211A.

Kabbani, F. K., 1970, Geophysical and structural aspects of the central Red Sea rift valley: Roy. Soc. London Philos. Trans., v. A267, p. 89-97.

Kamen-Kaye, Maurice, 1970, Geology and productivity of Persian Gulf synclinorium: Am. Assoc. Petroleum Geologists Bull., v. 54, no. 12, p. 2371-2394.

Kazmin, V., 1971, Precambrian of Ethiopia: Nature Phy. Sci., v. 230, p. 176-177.

Laughton, A. S., 1970, A new bathymetric chart of the Red Sea: Royal Soc. London Philos. Trans., v. A267, p. 21-22. *Area 8 on index map.*

Laughton, A. S., Whitmarsh, R. B., and Jones, M. T., 1970, The evolution of the Gulf of Aden: Royal Soc. London Philos. Trans., v. A267, p. 227-266. *Area 9 of index map.*

MacFadyen, W. A., Cox, L. R., and Brighton, A. G., 1930, The geology of the Farasan Islands, Gizan and Kamaran Island, Red Sea: Geol. Mag. (Great Britain), v. 67, p. 310-315; addendum, v. 68, 333 p.

McKenzie, D. P., 1970, Plate tectonics of the Mediterranean region: Nature, v. 226, p. 239-243.

McKenzie, D. P., Davies, D., and Molnar, P., 1970, Plate tectonics of the Red Sea and East Africa: Nature, v. 226, p. 243-248.

Phillips, J. D., and Ross, D. A., 1970, Continuous seismic reflexion profiles in the Red Sea: Royal Soc. London Philos. Trans., v. A267, p. 114-153.

Picard, L., 1970, On Afro-Arabian graben tectonics: Geol. Rundschau, v. 59, p. 337-381.

Reinhardt, B. M., 1969, On the genesis and emplacement of ophiolites in the Oman Mountains geosyncline: Schweiz. Mineral. u. Petrog. Mitt., v. 49, no. 1. *Area 6 on index map.*

Saudi Arabian Dir. Gen. Mineral Resources, 1972, Topographic Map of the Arabian Peninsula: Saudi Arabia Directorate General of Mineral Resources Map, 1:4,000,000 scale.

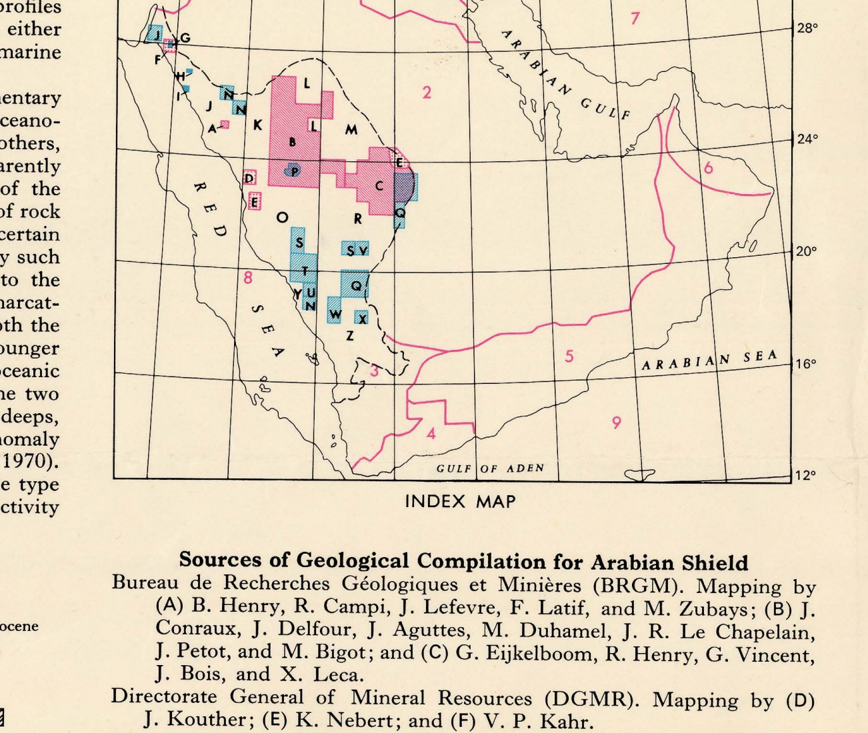
Schmidt, D. L., Hadley, D. G., Greenwood, W. R., Gonzalez, Louis, Coleman, R. G., and Brown, G. F., 1972, The stratigraphy and tectonism of the Precambrian Shield in the southern part of Saudi Arabia: U.S. Geol. Survey Interagency rept. 139, open-file rept., 36 p.

Stöcklin, Jovan, 1968, Salt deposits of the Middle East: Geol. Soc. America Spec. Paper 88, p. 157-181.

Tramontini, C., and Davies, D., 1969, A seismic refraction survey in the Red Sea: Royal Astron. Soc. Geophys. Jour., v. 17, no. 2, p. 225-241.

U.S. Geological Survey-Arabian American Oil Company, 1963, Geologic Map of the Arabian Peninsula: U.S. Geol. Survey Misc. Geol. Inv. Map I-207A. *Areas 2, 3, and 4 on the index map.*

Whiteman, A. J., 1970, The existence of transform faults in the Red Sea depression: Roy. Soc. London Philos. Trans., v. A267, p. 407-408.



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Sources of Geological Compilation for Arabian Shield

Bureau de Recherches Géologiques et Minières (BRGM). Mapping by (A) B. Henry, R. Campi, J. Lefevre, F. Latif, and M. Zubays; (B) J. Conraux, J. Delfour, J. Aguttes, M. Duhamel, J. R. Le Chapelain, J. Petot, and M. Bigot; and (C) G. Eijkelboom, R. Henry, G. Vincent, J. Bois, and X. Leca.

Directorate General of Mineral Resources (DGMR). Mapping by (D) J. Kouther; (E) K. Nebert; and (F) V. P. Kahr.

Japanese Geological Mission (JGM). Mapping by (G) S. Higashimoto; (H) T. Igarashi; and (I) S. Okumi, K. Komura, and T. Hatanaka.

U.S. Geological Survey (USGS). Reconnaissance mapping by (J) R. F. Johnson and V. A. Trent; (K) C. L. Hummel and H. Hakim; (L) G. F. Brown; (M) J. W. Mytton and A. O. Ankari. Detailed mapping by (N) D. G. Hadley. Reconnaissance mapping by (O) G. F. Brown, R. O. Jackson, and R. Goldsmith. Detailed mapping by (P) R. Goldsmith and J. Kouther. Reconnaissance mapping by (Q) W. C. Overstreet, J. W. Whitlow, V. P. Kahr, and A. O. Ankary; (R) R. O. Jackson, J. W. Whitlow, R. G. Bogue, and G. F. Brown. Detailed mapping by (S) L. Gonzalez; (T) W. R. Greenwood; (U) R. W. Bayley; (V) D. L. Schmidt; (W) R. G. Coleman; and (X) W. C. Overstreet and D. L. Rossman. Reconnaissance mapping by (Y) R. O. Jackson and (Z) G. F. Brown and R. O. Jackson.