X

SA(IR)-242

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

[Report-Open file series]

SAUDI ARABIAN PROJECT REPORT 242

TM
(OF) CM
(IR) CM
Twenals

PROTEROZOIC SEDIMENTARY ROCKS AND BASINS OF THE ARABIAN SHIELD AND THEIR EVOLUTION

by
Donald G. Hadley and Dwight L. Schmidt

PREPARED FOR
DIRECTORATE GENERAL OF MINERAL RESOURCES
MINISTRY OF PETROLEUM AND MINERAL RESOURCES
JIDDAH, SAUDI ARABIA
1979

U.S. GEOLOGICAL SURVEY

SAUDI ARABIAN PROJECT REPORT 242

PROTEROZOIC SEDIMENTARY ROCKS AND BASINS OF THE ARABIAN SHIELD AND THEIR EVOLUTION

by

Donald G. Hadley and Dwight L[yman]. Schmidt, 1926-

U.S. Geological Survey
Jiddah, Saudi Arabia

1979

CONTENTS

ILLUSTRATIONS

TABLES

PROTEROZOIC SEDIMENTARY ROCKS AND BASINS OF THE ARABIAN SHIELD AND THEIR EVOLUTION

by

Donald G. Hadley and Dwight L. Schmidt[1/]

ABSTRACT

Proterozoic sedimentary rocks of the Arabian Shield consist of three depositional phases. Phase I (the oldest) includes the Baish, Bahah, and Jiddah groups, which consist of an immature assemblage dominated by fine-grained metagraywacke, graphitic schist, chert, marble, and subordinate polymictic conglomerate and metasiltstone. Clastic rocks of Phase I are composed solely of volcanic material and do not contain plutonic or sialic detritus. Metasandstone, polymictic conglomerate, coarse-grained metagraywacke, and abundant marble (stromatolitic in places) constitute Phase II, the Ablah, Halaban, and Murdama groups. Plutonic and volcanic components are abundant in the clastic suite; K-feldspar detrital fragments are common in the Halaban and Murdama. The Shammar and Jubaylah groups form Phase III. Sedimentary rocks of this phase are fine- to coarse-grained terrigenous clastic rocks, boulder conglomerate, and stromatolitic limestone and dolomite. All phases include abundant volcanic rocks.

Sedimentary basins, excluding those containing Phase III rocks, generally trend north, especially in the central and southern parts of the shield. In the central and northerm parts of the shield, north-trending basins and structures are truncated abruptly by parallel northwest-trending sedimentary troughs (Jubaylah basins) formed by sinistral wrench-fault tectonics.

Textural and compositional characteristics of the Proterozoic sedimentary rocks together with spatial relations of the depositional basins document a progressive change from oceanic to shallow marine and continental sedimentation with time, and a shift in the basin axes from west to east. Sedimentary parameters during this lengthy timespan show general increases in compositional and textural maturity, carbonate content, grain size, the ratio of sedimentary rocks to volcanic rocks, and plutonic and K-feldspar-bearing detritus. The sedimentary style of each phase was a function of tectonic conditions during deposition.

[1/] U.S. Geological Survey, Denver, CO

INTRODUCTION

Early work (1950-1962)

Reconnaissance geologic mapping and mineral resource studies of the Arabian Shield by the U.S. Geological Survey began in the early 1950's, culminating in geologic map coverage of the Arabian Shield at 1:500,000-scale (Bramkamp and Ramirez, 1958; Bramkamp and others, 1963a, b; Brown and Jackson, 1958, 1959; Brown and others, 1963a, b, c; Jackson and others, 1963) and the Arabian Peninsula at 1:2,000,000-scale (U.S. Geological Survey-Arabian American Oil Co., 1963). On the basis of this early work, several reports were published that summarized the basic geology, age relations, and geomorphology of the shield (Brown and Jackson, 1960; Aldrich and Brown, 1960; Brown, 1960). Several other studies were conducted during this period under the auspices of the Ministry of Petroleum and Mineral Resources along the Red Sea coastal plain and in Precambrian rocks along the western margin of the shield (Richter-Bernburg and Schott, 1954; Karpoff, 1957).

The scope of these early maps and reports was such that only brief treatment could be given to specific geologic aspects of the shield, and discussion of the sedimentary rocks was confined to very general terms.

Middle period studies (1963-1968)

In the early sixties, detailed geologic studies of the Arabian Shield were begun by personnel of the Directorate General of Mineral Resources (DGMR), in cooperation with the U.S. Geological Survey (USGS), the Bureau de Recherches Géologiques et Minières (BRGM), and the Japanese Geological Mission (JGM). The work included: reconnaissance geologic mapping at 1:100,000-scale of selected areas containing known and potential mineral deposits; detailed mineral assessment; geochemical prospecting; and geophysical studies of ancient mines, mineral belts, and sedimentary and volcanic formations showing considerable mineral potential. Reports on Precambrian sedimentary rocks and formations during this period were few and were restricted primarily to descriptions of sedimentary ore deposits. Among these were publications related to the Wadi Sawawin iron ore deposits (Hirayama and Assad, 1967; Hirayama and others, 1967), copper mineralization and mineral deposits in the Ablah formation (Earhart, 1969a, 1969b, Gaskill, 1970), and studies of other stratified units (Delfour, 1970b; Overstreet and others, 1972).

Recent investigations (1969-1978) and purpose of this paper

In 1969, detailed mapping of the Arabian Shield at a scale of 1:100,000 began on controlled photomosaic bases; the principal objective was to establish a geologic framework for all of the Arabian Shield. As a result of that work, several papers have been published dealing with detailed studies of regional geology, including stratigraphic and sedimentologic reports related to defined formations (Delfour, 1970a; Greenwood, 1975b; Hadley, 1973, 1974b) and the first regional stratigraphic and tectonic synthesis of the shield (Schmidt and others, 1973). During this period, other summary papers dealt briefly with the sedimentary geology of the shield (Brown and Coleman, 1972; Greenwood and others, 1973, 1976), but no overall synthesis or summary of the sedimentary rocks of the Arabian craton has been made to date.

Very little evidence has been presented so far regarding the sedimentary rocks and their bearing on evolution of the shield. Do they have an ensialic affinity or are they oceanic in character? What does the mineralogy of the sedimentary rocks indicate about their origin, sources of the detritus, and water depth? These and other questions have not been studied. Thus, in this paper we have aimed: 1) to summarize descriptively and quantitatively the Eocambrian and Phanerozoic sedimentary geology of the Arabian Shield, and 2) to determine and document how the shield evolved by the record of sedimentation through time.

Acknowledgements

During the past 7 years many individuals have assisted us in the field and have contributed to our knowledge of the geology of the Arabian Shield, and the sedimentary rocks in particular. We would like to acknowledge and thank them for their help and the numerous, enlightening discussions we have held.

First of all, we greatly appreciate the assistance and support of Sheikh Ghazi Sultan, Deputy Minister of the Ministry of Petroleum and Mineral Resources, and the past Deptuy Minister, Dr. Fadil Kabbani. Within the USGS Mission we are deeply indebted to J.J. Norton, Thor H. Kiilsgaard, R.E. Anderson, G.F. Brown, R.G. Coleman, F.C.W. Dodge, R.J. Fleck, W.R. Greenwood, R.O. Jackson, Robert James, R.J. Roberts, D.B. Stoeser, Henry Williams, and R.G. Worl.

Fieldwork in the Kingdom could not have been accomplished adequately without Boyd Shaw and many others in Special Flight Services. To them, sincere appreciation is extended for assisting us with aircraft support in the field. Finally, we are grateful to Dr. Ahmed Al-Shanti, Director of the Institute of Applied Geology, King Abdulaziz University, Jiddah, for convening the symposium on Evolution and Mineralization of the Arabian-Nubian Shield (February 1978, Jiddah) at which this paper was presented.

The work on which this report is based was financed by the Saudi Arabian Government under a cooperative agreement between the Ministry of Petroleum and Mineral Resources and the U.S. Geological Survey.

STRATIGRAPHIC FRAMEWORK

Previous syntheses

Brown and Jackson (1960) were the first to present a synthesis of the stratigraphy of the Arabian Shield (table 1). They recognized a threefold stratigraphy on the basis of major unconformities and plutonic-orogenic episodes. In their review, three sequences of rocks constitute the oldest stratigraphic assemblage, which they considered to be older than 1,000 m.y. These included a gneiss unit, the Hali schist, greenstone of the Baish group, and the Lith complex, all considered to be of equivalent age. Schists of various kinds, slate, marble, quartzite, and metavolcanic rocks are the dominant lithologies within this sequence.

The second stratigraphic assemblage ranges between 1,000 m.y. and 700-750 m.y. and includes andesite of the Halaban group and sedimentary rocks of the Murdama group. Metavolcanic rocks dominated by andesite make up the Halaban, whereas the Murdama is described by Brown and Jackson (1960) as being chiefly sedimentary, including pelite, quartzite, and conglomerate. They describe no marble, nor do they note the presence of sialic detritus in the Murdama.

Characterized by a basal unconformity, the youngest assemblage includes two sequences, the Fatima and Ablah formations and Shammar rhyolite of Brown and Jackson (1960), ranging in age from about 700 m.y. to about 530 m.y. The Fatima and Ablah, considered by Brown and Jackson (1960, p. 73) to be correlative, are described as sedimentary units consisting of fine- to coarse-grained clastic rocks, conglomerate, and stromatolitic limestone. Rhyolitic ash-flow tuff and related pyroclastic beds and subordinate dacite and andesite are the main rock types described in their Shammar rhyolite.

Table 1.--*Chronology of stratigraphic syntheses of the Arabian Shield*

Brown and Jackson (1960)	Schmidt and others (1973)	Roberts and others (1975)		Greenwood and others (1976)		Delfour (1976)		This paper	
Shammar rhyolite	Jubaylah group	Late Phase	Jubaylah group	Third Episode	Murdama group		Jibalah group	Phase III	Jubaylah group
							Shammar group		
Fatima and Ablah formations	Shammar group		Shammar group				Murdama group		Shammar group
Murdama formation	Murdama group-Ablah formation	Middle Phase	Murdama group	Second Episode	Halaban group	Hulayfah group	Nuqrah formation	Phase II	Murdama group
			Halaban group				Afna formation		Halaban group
Halaban andesite	Halaban group Jiddah group		Ablah group			Urd group	Abt formation		Ablah group
Baish greenstone and Lith complex	Bahah group		Jiddah group		Ablah group		Ar Ridayniyah formation		
	Baish group		Bahah group Baish group	First Episode	Jiddah group		Ophiolitic complex	Phase I	Jiddah group
Hali schist	Hali group	Early Phase	Sequence uncertain		Bahah group		Rharaba complex Hali group		Bahah group
Gneiss	Khamis Mushayt gneiss				Baish group		Old basement		Baish group

Following the first phase of detailed 1:100,000-scale geologic mapping in the early 1970's, Schmidt and others (1973, table 1) reexamined the stratigraphy of the shield and recognized eight groups and an older gneiss unit that constitute six major lithostratigraphic sequences (table 1), separated by erosional and angular unconformities. In contrast to the earlier interpretation, which recognized three tectonic episodes, Schmidt and others (1973) concluded that the six lithostratigraphic sequences were each marked by periods of tectonism. Moreover, their synthesis defined or incorporated three additional units, the Bahah group, Jiddah group (equivalent to the Jiddah greenstone, U.S. Geological Survey-Arabian American Oil Company, 1963; Schmidt and others, 1973, p. 7), and the Jubaylah group (Delfour, 1970a; Hadley, 1973, 1974b), not discussed previously in a regional synthesis.

Roberts and others (1975, p. 3) modified the earlier stratigraphic synthesis and devised a framework consisting of three phases and four rock assemblages (table 1). The phases, termed early, middle, and late, are defined on the basis of rock assemblages and tectonic episodes, but the stratigraphic units generally follow the usage of Schmidt and others (1973, p. 3), except for the older rocks in the southern part of the shield, where the framework of Greenwood and others (1975, p. 5) is used.

In a paper presented before the Royal Society of London, Greenwood and others (1976, p. 519) re-evaluated the stratigraphy and tectonic framework of the southern part of the shield (table 1) and defined a stratigraphic framework on the basis of three episodes. The episodes are separated by unconformities, and each is culminated by an orogenic event. Use of the Hali group and the older Khamis Mushayt gneiss of Schmidt and others (1973) was abandoned, and the Ablah formation was elevated to group status and depicted as being older than the Halaban and younger than the Jiddah group rather than being equivalent to the Murdama group (Schmidt and others, 1973, p. 3) or younger than the Murdama (Brown and Jackson, 1960, p. 76).

Delfour (1976, p. 4) presented a complex stratigraphy of the central and northern parts of the shield, consisting of three units more than 1000 to 1200 m.y. old: the Rharaba complex, the Hali group, and an older basement succeeded by five groups (table 1). In addition to the oldest plutonic event, four younger igneous cycles mark the end of each stratigraphic sequence except for the youngest (Jibalah= Jubaylah).

Correlation of the stratigraphic units as used by Delfour (1976, p. 4) with the earlier syntheses is relatively simple, except for the Urd group, because the same basic units are used by all the investigators. The Halaban group is redefined as the Hulayfah group. Correlation of the Urd group and Rharaba complex with units older than the Halaban is not clear. The Abt formation of the Urd group, being dominantly sedimentary, is best correlated with the Bahah group. On the basis of composition, the Ar Ridayniyah formation and part or all of the ophiolitic complex appears to be equivalent to the Baish group. The relationship of the Jiddah group to Delfour's stratigraphy is likewise not clear, and there is no obvious correlative of the Rharaba complex, although this is not a sedimentary or volcanic sequence, but rather a layered gabbro.

Present interpretation

The stratigraphic framework proposed herein for the shield (table 1) is a modification of that presented by Roberts and others (1975, p. 3) and Greenwood and others (1976, p. 519). It is based primarily on sedimentologic characteristics, wherein a series of stratigraphic units (phases) are viewed in terms of their sedimentologic continuity. As will be shown in the last section of this paper, the general sedimentologic cohesiveness of the phases is a function of the sedimentary environments in which the rocks were deposited, which in turn is a function of tectonic conditions existing during each phase.

SEDIMENTARY ROCKS AND BASINS

Distribution

The distribution of the three phases of sedimentary rocks and the groups in which they occur is shown on a generalized geologic map (fig. 1) of the shield that has been modified substantially from Greenwood and others (1974) according to the stratigraphic framework presented in this paper. Groups (for example, Bahah, Halaban, Murdama, and so forth) are shown rather than individual sedimentary rock types because of the scale.

Phase II rocks are clearly the most abundant in the shield. Phase I rocks dominate the southern part; Phase III rocks are most abundant in the central and northern parts but are subordinate to Phase II rocks. The Phase III Jubaylah group rocks are bounded exclusively by the Najd faults (Brown and Jackson, 1960, p. 76; Brown, 1970, p. 79; Delfour, 1970a, p. 16).

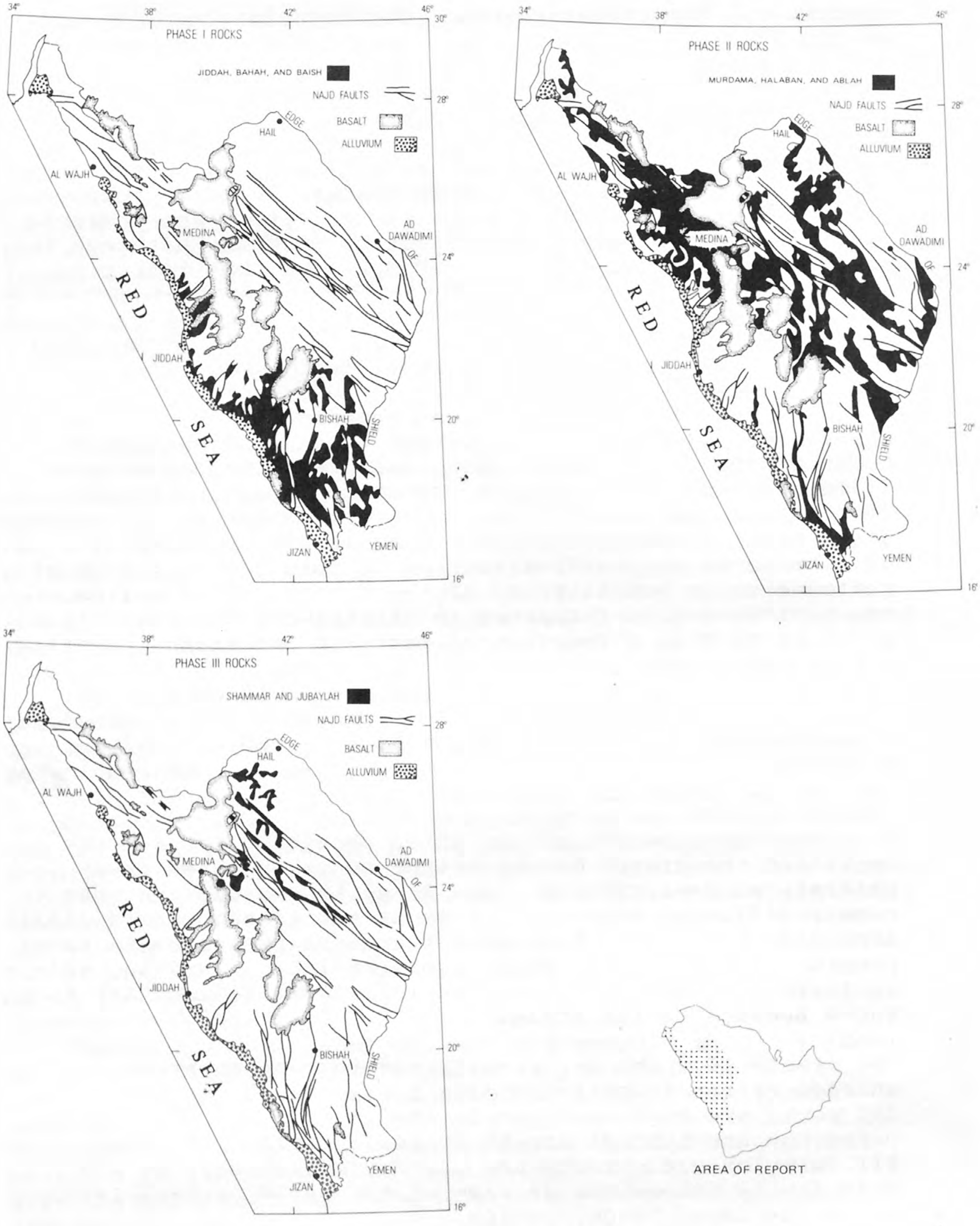


Figure 1. Maps showing distribution of Phase I, II, III sedimentary and volcanic groups of the Arabian Shield.

General lithologic discussion

Sedimentary rock types of the three depositional phases include five major lithologic classes--conglomerate, graywacke, nongraywacke clastic rocks, argillaceous rocks and chert, and carbonate rocks--which are divided into 12 main rock types (table 2). Conglomerate is found in every group. Graywacke is common to all groups except those in Phase III; chert and slate are found mainly in Phase I rocks. Marble or limestone is present in all groups but the Shammar.

Conglomerates

Outcrop description.--Basal and intraformational conglomerates are the two main types of conglomerate of the shield. They can be classified according to clast size and apparent degree of water sorting (table 3). The distinction between boulder and pebble conglomerate is based on clast diameter (Pettijohn, 1975, p. 30); conglomerates containing abundant clasts larger than 256 mm are classified as boulder conglomerates, and those containing clasts averaging 4-64 mm in diameter are classified as pebble conglomerates. Conglomerates also are classified herein as transported and short-transported. In transported conglomerates, most clasts are subround to well rounded; the clasts are surrounded by finer grained material that is similarily subrounded to rounded. Short-transported boulder conglomerate contains angular clasts and matrix material and, in places, rare interbedded stratified material. Short-transported pebble conglomerate is of the flat-pebble and chip-pebble types. The pebbles are angular, are broken parts of thin beds, and show no significant transport (rounding of the clasts).

Basal conglomerates are found at the base of the Ablah, Halaban, Murdama, Shammar, and Jubaylah groups. In most areas, all basal conglomerate is of the transported boulder type and represents major unconformities in the geologic record of the shield. Because of the regional extent of the conglomerate (Delfour, 1977, p. 13) and the abrupt metamorphic and structural difference between Phase II and III groups (Hadley, 1973; Schmidt and others, 1973), the conglomerate at the base of the Shammar is believed to represent a major unconformity between Phase II and III rocks.

Intraformational conglomerates occur in all groups of all three phases. Examples of all the transported and short-transported boulder and pebble conglomerate types shown in table 3 can be found among the intraformational conglomerates. Table 4 lists the main characteristics for the shield conglomerates according to the classification scheme in table 3.

Table 2.--*Sedimentary rock classes and types and their distribution in the eight stratigraphic groups of the Arabian Shield*

		PHASE I			PHASE II			PHASE III	
Class	Rock Type	Baish	Bahah	Jiddah	Ablah	Halaban	Murdama	Shammar	Jubaylah
Carbonate rocks	Limestone and dolomite								●
	Marble	●	●	●	●	●	●		
Argillaceous rocks and chert	Mudstone		●		●				
	Chert	●	●	●		●			●
	Shale							●	●
	Slate/argillite	●	●	●	●	●	●		
Nongraywacke clastic rocks	Siltstone	●	●	●	●	●	●	●	●
	Quartzite		●						
	Sandstone			●	●	●	●	●	●
Graywacke	Graywacke	●	●	●	●	●	●		
Conglomerates	Pebble conglomerate		●		●		●	●	●
	Boulder conglomerate	●		●	●	●	●		●

Table 3.--*Types of conglomerates of the Arabian Shield and their conditions of deposition*

	DEGREE OF TRANSPORT AND CONDITIONS OF DEPOSITION	
	TRANSPORTED	SHORT-TRANSPORTED
Boulder	Fluvial, Alluvial Fan, and Marine	Submarine Slump
Group	Jubaylah Shammar Murdama Halaban Ablah	Halaban Jiddah Baish
Pebble	Fluvial, Alluvial Fan, and Marine	Tidal Flat
Group	Jubaylah Shammar Murdama Ablah	Ablah Jiddah Bahah

Table 4.--*Sedimentary characteristics of Arabian Shield conglomerates*

Sedimentary characteristics		BAISH	BAHAH	JIDDAH	ABLAH		HALABAN		MURDAMA	SHAMMAR	JUBAYLAH	
		GROUP AND CONGLOMERATE TYPE										
		[1]B/ST[2]	[5]P/ST	B/T[7]	B/T	P/ST	B/T	B/ST	B/T	B/T	B/T	P/T
Color		Green Gray	Gray	Green Gray	Red Green Gray	Reddish	Greenish Gray	Green	Reddish brown	Reddish brown	Reddish brown	Reddish brown
Sorting		Very poor	Poor	Poor	Poor	Poor	Poor	Very Poor	Poor	Poor	Poor	Poor to moderate
Basal relief		NI[3]	NA[6]	NI	1-3m	NA	NI	NI	5m		15m	
Clasts	Maximum size	40cm	10cm	1m	1m	10cm	50cm	50cm	1m	5cm	1m	10cm
Clasts	Shape	Irregular	Tabular	Irregular	Subcircular	Flat to tabular	Irregular	Irregular	Subcircular	Irregular	Subcircular to circular	Subcircular to circular
Clasts	Rounding	Subangular to subrounded	Angular to subangular	Angular to subangular	Subangular to rounded	Angular	Subrounded to rounded	Angular to subangular	Subrounded to rounded	Angular to subrounded	Subrounded to rounded	Subangular to subrounded
Clasts	Composition	Oligomictic (volcanic)	Oligomictic (siltstone)	Polymictic	Polymictic	Oligomictic siltstone and shale	Polymictic	Oligomictic (volcanic)	Polymictic	Polymictic	Polymictic and oligomictic	Polymictic
Clasts	Granitic	None	None	None	None	None	Sparse to common	None	Common	Common	Abundant	Abundant
Graded bedding		Sparse	Common	Common	Common	Common	Common	NP	NI	Common	NP	Common
Cross-bedding		NP[4]	Rare	Rare	Common	Common	NP	NP	NI	NP	NP	Minor
Inter-beds	Thickness	3-10cm	2-8cm	5-20cm	3-15cm	3-15cm	5-15cm	NP	NP	5-10cm	NP	2-10cm
Inter-beds	Uniformity	Lenticular	Lenticular	Lenticular	Lenticular	Tabular	Lenticular	NP	NP	Tabular	NP	Lenticular
Cement		Mica and calcite	Mica and silica	Mica and silica	Calcite	Silica and calcite	Silica and calcite	Mica and calcite	Silica and calcite	Silica and calcite	Calcite	Calcite

1. Boulder conglomerate; 2. Short-transported; 3. No information; 4. Not present; 5. Pebble conglomerate; 6. Not applicable; 7. Transported. –

All conglomerates of the shield contain immature and metastable clast assemblages. Some are oligomictic (Pettijohn, 1957, p. 255) but contain metastable sedimentary fragments (table 4, Bahah and Ablah), or volcanic fragments (Baish, Halaban, and Jubaylah), or oligomictic granophyre clasts, as in the Jubaylah boulder conglomerate in the Qal'at as Sawrah quadrangle (Hadley, 1975b, p. 20). The short-transported boulder conglomerates (Baish and Halaban; table 3) are chaotic rubble masses. Granitic clasts are not present in the conglomerates that were deposited prior to deposition of the Halaban. Granitic detritus is present in the Halaban, but is not abundant. Clasts first appear in quantity in the basal part of the Murdama conglomerate, excellent exposures of which can be seen 25 km northeast of Bishah, and are common to abundant throughout the younger groups.

Graywacke

Outcrop description.--Walker and Pettijohn (1971, p. 2127) concluded that graywacke is a product of, and genetically related to, mafic and intermediate volcanism. Although most graywackes of the Arabian Shield are associated with volcanic rocks, they do not all contain recognizable volcanic rock fragments. In this paper, the definition of graywacke follows that of Pettijohn (1957, p. 291) meaning a sandstone containing more than 15 percent matrix. It is found in all groups (table 2) except the two youngest, and each graywacke-bearing group contains some basaltic or andesitic flow rocks.

Graywacke is intimately interbedded with the lavas, and in most groups it is thousands of meters thick. It is thickest in the Baish, Jiddah, and Halaban groups. The exact thickness of the graywacke is not known, but graywacke is estimated to constitute 30-40 percent of the Halaban, which in the Bir Juqjuq area is computed to have a minimum thickness of 19,500 m (Hadley, 1976).

Graywacke forms monotonously uniform units in all groups. Many of the classic graywacke sedimentary structures are present, but common structures associated with turbidites, such as flute casts, ball and pillow structure, and various other kinds of sole marks, are not. Beds range in thickness from 2 to 30 cm and are strikingly uniform or tabular. Graded beds ranging from coarse to very fine grained are present in most exposures, and some beds contain pebbly bases. Other internal features of the beds are millimeter-scale laminations, ripple drift, climbing ripples, and small-scale crossbeds. Exposures containing ripple-marked bedding-plane surfaces are not common. Shades of gray, green, red, and purple are the main graywacke colors. Gray and green are predominant in Phase I rocks, whereas red and purple are common to abundant in Phase II rocks. Volcanic rocks, conglomerate, chert, slate, and marble are commonly interbedded with the graywacke sequences.

Petrography.--Modal analyses for some typical graywackes of the shield are shown in table 5. Plagioclase and volcanic-rock fragments dominate most graywacke samples; quartz, magnetite, mica, hematite, epidote, sphene, matrix or cement, and minor accessory minerals are also present in most of the samples. Rock fragments could not be readily identified in most Phase I graywackes because of shearing. The order of abundance of the petrographic constituents other than plagioclase and rock fragments may differ substantially from sample to sample. For example, in some rocks the matrix may be almost as abundant as the principal-framework constituents. Potassium feldspar may or may not be present in graywacke in groups commonly containing potassium feldspar (in Halaban and Murdama dacite and rhyolite). Some graywacke samples contain as much as 6 percent potassium feldspar. Graywacke older than the Halaban does not contain potassium feldspar.

Framework components in a typical graywacke are surrounded by finely comminuted quartz, feldspar, and mica (matrix) or by the cement materials, quartz (clear, polycrystalline, microcrystalline, and rarely chalcedony), calcite, and hematite. Fragmental matrix material is less than 0.02 mm in diameter (Pettijohn, 1957, p. 284). Framework grains range from subangular to subrounded, and sorting is fair to good.

Nongraywacke clastic rocks

Outcrop description.--Nongraywacke clastic rocks include quartzite, arkosic and lithic sandstones, and siltstones, rock types that generally contain less than 15 percent matrix (Pettijohn, 1957). One or more of these rock types are found in all groups. Quartzite is used herein as meaning a recrystallized sandstone (Pettijohn, 1957, p. 169) containing abundant quartz (Holmes, 1920, p. 194). Nongraywacke clastic rocks form substantial parts of some groups, but nowhere do they have the immense thicknesses of graywacke. In total thickness, they rank next to graywacke. Sandstone and siltstone are the most abundant; they are thickest and form the most continuous outcrops in the Ablah (Bayley, 1972) and Murdama groups (Schmidt and others, 1973, p. 8). The Hadiyah slate (Brown and others, 1963a), probably equivalent to parts of the Murdama group, is more than 90 percent sandstone and siltstone. The Jubaylah group is composed of 30 to 50 percent sandstone and siltstone.

The nongraywacke rocks are gray, green, red, maroon, and brown, in beds ranging in thickness from a few centimeters to

Table 5.--*Modal analyses of some Arabian Shield graywackes*

	PHASE I						PHASE II					
	BAISH		BAHAH		JIDDAH		ABLAH		HALABAN		MURDAMA	
Quartz	19.3	24.9	14.7	18.3	9.9	15.3	10.7	17.9	16.0	19.1	35.0	27.5
Potassium feldspar	--	--	--	--	--	--	--	--	4.0	5.6	6.4	5.3
Plagioclase	21.2	17.8	34.6	29.2	24.3	22.0	22.3	20.7	10.0	12.3	14.6	12.1
Rock fragments												
Volcanic	--	--	--	--	23.2	16.7	29.5	27.2	33.5	32.8	7.9	19.6
Plutonic	--	--	--	--	--	--	2.0	--	--	3.1	2.0	4.7
Metamorphic + sedimentary	--	--	--	--	--	--	1.6	--	6.5	5.3	--	1.7
Biotite	2.3	1.6	5.6	3.6	Tr	0.9	0.5	1.2	0.7	--	1.0	0.5
Chlorite	16.7	15.4	11.4	9.4	3.7	4.2	2.3	3.8		0.5	0.5	1.1
Muscovite + sericite	1.6	2.4	3.3	4.6	4.1	1.0	1.6	0.5	0.3	1.0	--	0.4
Phlogopite	--	--	--	--	--	--	--	--	--	--	--	--
Sphene	0.8	1.1	0.4	--	Tr	--	Tr	Tr	--	--	2.1	--
Epidote	3.8	5.3	5.2	4.4	Tr	1.2	0.8	1.2	5.6	0.3	9.3	0.4
Apatite	--	0.3	--	0.2	--	--	--	--	--	--	2.3	Tr
Zircon	--	--	--	--	--	--	--	--	--	--	0.1	Tr
Magnetite	5.1	4.9	6.1	7.2	7.6	3.6	4.8	5.0	--	2.5	Tr	2.4
Hematite	2.6	3.1	0.9	1.7	2.2	1.8	1.6	1.7	1.0	1.0	Tr	0.6
Calcite	1.7	2.5	1.1	1.2	3.2	0.5	0.7	--	3.4	1.0	1.0	0.6
Matrix or cement	24.9	20.8	16.6	20.2	21.8	32.8	21.7	20.8	19.0	15.5	19.2	23.6
Total	100.0	100.1	99.9	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.4	100.1
No. point counts	723	678	300	566	700	588	416	593	531	620	632	800
Sample number	74281	74274	74563	74540	74515	74507	74455	74456	74735	81302	81448	81396
Percent of plutonic rock fragments	--	--	--	--	--	--	6.0	--	--	7.5	20.2	18.1

as much as a meter. Bedding as a rule is uniformly tabular, and at many outcrops individual beds may be traced without interruption for tens of meters.

Internal and bedding-plane sedimentary structures include millimeter-scale laminations, graded bedding, ripple drift, small- and moderate-scale crossbedding, graded bedding, massive bedding (in the mudstones), convolute laminations, and ripple marks. These features, which indicate shallow-water deposition in an environment of current transport, are found in the groups dominated by sedimentary rocks, such as the Bahah, Ablah, Murdama, and Jubaylah, as opposed to those dominated by volcanic rocks--the Baish, Jiddah, Halaban, and Shammar (table 2).

Petrography.--Modal analyses of some representative non-graywacke clastic rocks are shown in table 6. Quartzite has been mapped only in the Bahah group in the southern part of the shield. It is medium grained, moderately well sorted, and contains as much as 69 percent recrystallized quartz and feldspar and a few percent accessory minerals. The matrix is composed of recrystallized quartz, probably originally silica cement, and about 5 percent very fine grained detritus. The detrital grains appear to have been well rounded before recrystallization.

The nonquartzitic clastic rocks (mostly immature lithic sandstones) contain variable amounts of feldspar. Arkosic sandstone and siltstone are found in the Ablah, Halaban, Murdama, and Jubaylah groups. Plagioclase is the dominant feldspar in Phase II groups and is also abundant in Phase III rocks, although in some Phase III samples potassium feldspar (table 6) is dominant. Rock fragments are abundant in these rocks in all three phases (table 6). Sorting ranges from poor to good, and detrital fragments range from sub-angular to rounded; the better sorted rocks contain better rounded framework components. The matrix and cement, which comprises quartz, calcite, hematite, sericite, and finely comminuted detrital material, may be more than 15 percent of the rocks.

Argillaceous rocks and chert

Outcrop description.--Argillaceous rocks of the shield include slate, argillite, shale, and mudstone. Because of its grain size, chert is arbitrarily included in this grouping. Stratigraphic distribution of these rocks is shown in table 2. Slate and argillite are found in Phase I and II, and are particularly abundant in Phase I rocks. Phase III rocks contain minor amounts of shale. Chert is most abundant in Phase I groups, but is also common in the Jubaylah group.

Table 6.--*Modal analyses of some Arabian Shield clastic rocks*

	PHASE I		PHASE II					PHASE III			
	BAHAH	JIDDAH	ABLAH		HALABAN	MURDAMA		SHAMMAR		JUBAYLAH	
	Quartzite	Lithic Sandstone	Lithic Sandstone	Lithic Sandstone	Lithic Sandstone	Arkose	Lithic Sandstone	Lithic Sandstone	Lithic Sandstone	Lithic Sandstone	Lithic Sandstone
Quartz	66.3	14.7	18.6	17.2	15.9	35.0	33.9	12.0	20.4	13.2	5.3
Potassium feldspar	--	--	--	--	7.8	10.4	3.4	10.3	7.8	18.1	4.0
Plagioclase	2.3	27.9	20.7	14.3	16.6	14.6	4.0	15.7	21.6	6.2	10.5
Rock fragments											
Volcanic	--	10.8	21.8	18.4	21.6	4.7	29.3	11.5	14.4	3.0	40.1
Plutonic	--	--	4.0	2.5	2.8	1.2	7.8	14.1	14.9	36.2	5.2
Metamorphic + sedimentary	--	--	--	1.6	3.4		2.3	2.4	3.9	1.1	3.0
Biotite	0.2	1.0	0.9	0.9	--	1.5	0.3	1.3	0.7	Tr	3.0
Chlorite	1.7	2.2	4.3	3.0	--	--	1.9	1.5	0.1	--	--
Muscovite + sericite	1.2	1.2	0.4	0.6	--	--	--	0.2	--	1.4	--
Phlogopite	--	--	--	--	--	--	--	--	--	--	--
Sphene	--	0.3	Tr	--	--	--	Tr	--	Tr	--	0.3
Epidote	0.7	2.9	3.0	2.2	0.3	13.8	Tr	--	0.6	Tr	1.3
Apatite	--	0.7	0.2	Tr	--	--	--	--	--	Tr	--
Zircon	--	--	Tr	--	--	--	--	--	Tr	Tr	Tr
Magnetite	1.3	8.7	5.5	3.4	1.7	Tr	0.9	--	2.6	3.5	1.3
Hematite	0.3	4.5	2.2	1.2	Tr	10.7	0.6	--	0.4	Tr	0.3
Calcite	0.4	--	--	0.8	0.7	--	0.8	--	0.3	--	--
Matrix or cement	25.6	25.1	19.5	33.8	29.4	8.5	14.8	31.0	12.6	17.4	26.2
Total	100.0	100.0	100.1	99.1	100.2	100.4	100.0	100.0	100.3	100.2	100.5
No. of point counts	955	497	576	650	477	300	1112	600	631	576	302
Sample number	75377	74491	74450	74445	55007	55636	55641	55295	74295	74742	74035
Percent of plutonic rock fragments	--	--	15.5	11.1	10.1	20.3	19.8	50.4	44.8	89.8	10.8

The argillaceous rocks are fine grained, gray, green, and black, and are thin to medium bedded. Because of shearing, alternating light and dark bands are juxtaposed in some outcrops to produce mottled zebra-like rock. Graphitic material is common to abundant in argillitic rocks of Phase I (Greenwood, 1975a, b, c, d; Hadley, 1975a, c) and the rocks show a black sooty appearance when rubbed. The slates are highly siliceous in some areas, such as the graphitic schist unit of the Baish group in the Wadi Hali quadrangle (Hadley, 1975c).

The stratigraphic thickness of argillitic rocks in the shield was not computed because these rocks are generally interbedded with other sedimentary or volcanic rocks and cannot be separated easily. The graphitic schist unit of the Baish is one of the thickest and most continuous argillitic units of the shield, comprising a thickness of 1 to 3 km or about 15 percent of the Baish.

Chert in the Phase I rocks is not abundant. It is found as tabular and irregular beds in argillite, graywacke, and volcanic sequences. Beds range from 3 to 15 cm in thickness, can be traced for several tens of meters in some outcrops, and are devoid of internal structure. The chert is medium gray to black and reddish gray where ferruginous.

In the Jubaylah group primary chert forms tabular beds as thick as 1 m, and secondary chert forms irregular and lenticular masses and nodules replacing limestone in the lower part of the upper part of the Muraykhah formation of the Jubaylah group (Hadley, 1974b). Unicellular microfossils, probably blue-green algae, and the coiled microfossil, *Obruchevella*, have been extracted from Jubaylah chert by P.E. Cloud (written commun., 1977), who states that *Obruchevella* in the USSR is found mainly in the Lower Cambrian with one species of Yudomian (Vendian, Ediacarian, or "Eocambrian"), but pre-Nemakit-Daldin. The Yudomian (Siberian equivalent of Vendian) is considered by many Soviet geologists to be the terminal time-rock unit of the Proterozoic.

Petrography.--Fine-grained material comprising mica, quartz, and feldspar commonly makes up more than 50 percent of the argillitic rocks; very fine-grained but recognizable quartz, mica, opaque minerals, and hematite (table 7) make up 30 percent or less of the rocks. In addition to massive textures, primary and secondary laminae are recognizable in thin section, but intragrain textures cannot be distinguished.

A mosaic of microcrystalline quartz characterizes the chert in thin section. Bedding laminae are defined by alternating fine-and coarser-grained mosaic bands in some samples and by very fine-grained opaque minerals in others. Other samples are massive and of uniform grain size.

Table 7.--*Modal analyses of some argillaceous rocks, chert, and marble of the Arabian Shield*

	PHASE I					PHASE II				PHASE III
	B A I S H			B A H A H		A B L A H		HALABAN	MURDAMA	JUBAYLAH
	Marble	Argillite	Chert	Slate	Marble	Marble	Mudstone	Marble	Marble	Limestone
Quartz										
Detrital	6.1	2.3	--	11.2	5.0	7.7	12.2	5.0	6.3	10.3
Microcrystalline	--	--	94.6	--	--	--	--	--	--	--
Secondary	--	--	--	7.8	--	--	--	2.5	--	--
Potassium feldspar	--	--	--	--	--	--	--	--	--	1.4
Plagioclase	1.3	--	0.9	3.4	2.7	5.6	6.9	--	8.3	4.6
Biotite	3.4	--	0.7	1.7	1.2	--	2.2	--	3.3	0.8
Chlorite	1.0	--	0.5	3.8	3.9	--	3.6	--	--	--
Muscovite + sericite	2.1	32.7	0.8	10.5	4.9	--	16.7	--	--	--
Phlogopite	--	--	--	--	--	2.3	--	--	--	--
Sphene	--	--	--	--	--	--	--	--	--	--
Epidote	0.1	--	--	1.1	Tr	--	Tr	--	--	Tr
Magnetite	2.4	3.3	2.7	5.6	4.7	3.1	5.2	2.5	0.4	3.3
Hematite	--	--	--	0.7	--	--	0.6	--	2.5	Tr
Carbonate	83.8	--	Tr	0.6	77.5	81.7	Tr	90.0	79.2	78.1
Argillaceous material	--	61.7	--	53.6	--	--	53.2	--	--	--
Total	100.2	100 0	100.2	100.0	99.9	100.4	100.0	100.0	100.0	100.1
No of point counts	700	300	439	425	398	470	300	1200	480	900
Sample number	74120	74433	74380	74284	74242	74149	74458	55048	81112	55555

Carbonate rocks

Outcrop description.--Carbonate rocks are found in all three phases of the shield and in all groups except the Shammar (table 2). Phase I and II carbonate rocks are metamorphosed to the greenschist and amphibolite facies and are therefore marble. Limestone and dolomite are found in the Phase III Jubaylah group.

The marbles are pure, siliceous, dolomitic, and carbonaceous, and show a wide assortment of colors, including several shades of gray, green, pink, blue, brown, buff, red, yellow, and black and white. In some exposures, the marble is more or less uniformly color banded, and at others, a variegated rock is present where shearing has intricately juxtaposed marble bands of several colors. In general, marble is black, shades of gray, or white in groups dominated by volcanic rocks such as the Baish, the Jiddah, and the Halaban (Hulayfah) (Hadley, 1975c, 1976; Delfour, 1977). In contrast, marble in the groups dominated by sedimentary rocks (Bahah, Ablah, and Murdama) shows a wide range of color.

Marble beds and units of the shield are resistant to erosion and may be traced without break for scores of kilometers. Examples are marble units in the Bahah, Ablah, and Murdama groups in the Wadi Yiba, Wadi Hali, Jabal Sawdah, Jabal Aya, Wadi Harjab, and Bir Juqjuq quadrangles in the southern part of the shield (Bayley, 1972; Cornwall, 1973; Hadley, 1975c, 1976; Prinz, 1975; Ratte and Andreasen, 1974) and marble of the Halaban group in the Sahl al Matran and Nuqrah quadrangles in the northern part of the shield (Delfour, 1977; Hadley, 1973).

The marble is exposed as individual beds and as units containing numerous beds. Individual marble beds, characteristic of volcanic units (Baish, and so forth), range from 10 to 25 cm thick. Marble units in the volcanic sequences, however, may attain thicknesses of as much as 200 m. Bedding and unit thicknesses of marbles in the sedimentary sequences are 10 cm to 1 m and as much as 500 m, respectively. Bedding is generally constant in thickness over long distances. Tops and bottoms of beds are undulatory in stromatolitic sequences, but otherwise are nearly straight and parallel. Internal structure is massive or laminated in nonstromatolitic marble, and is undulatory in stromatolitic marble.

Carbonate rocks of the Jubaylah group (Phase III) consist of pure calcarenite and calcilutite limestone, dolomitic limestone, and dolomite (Delfour, 1967, 1970a, 1977; Hadley, 1973, 1974b). The carbonate rocks are buff and gray, consist of beds that range from 5 to 30 cm in thickness, and contain abundant bedding and internal structures, including tabular to lenticular millimeter-scale laminae, lenticular anastomosing calcilutite and dolomite, ripple drift, undulose stromatolitic laminae, laterally linked stromatolitic hemispheres, and mud cracks.

Petrography.--Marble and limestone of the shield consist of fine- to medium-grained mosaics of carbonate minerals (more than 75 percent) and detrital quartz and feldspar, microcrystalline quartz, opaque minerals, hematite, and metamorphic biotite and phlogopite. Laminae are defined by minute layers of minerals and opaque minerals.

SEDIMENTARY TRENDS

Stratigraphic thicknesses and ratios

Measured and computed thicknesses of shield groups (table 8) range from 500 m (Jubaylah group, Hadley, 1974b) to almost 20,000 m (Halaban group, Hadley, 1976). Calculated and measured thicknesses of sedimentary rocks range from about 200 m (Shammar group) to 10,000 m (Murdama group in the Bir Juqjuq quadrangle, Hadley, 1976) and, excluding Phase III, generally fall in the 3,000 to 5,000 m range. The Murdama group has the thickest section of sedimentary rocks, and Phase II groups appear to contain the thickest sedimentary sections of all the phases.

The computed thicknesses are somewhat arbitrary. For example, some thicknesses (Jubaylah group) are derived from carefully measured stratigraphic sections. Other thicknesses were computed from areas containing faults of unknown displacement. However, most of the thicknesses were measured in areas where the rocks were not folded or faulted or in areas where the effects of folding and faulting on apparent thickness could be accounted for; therefore, the data are considered reasonably reliable.

The second row of table 8 shows the estimated and computed percentage, both the average and the range, of sedimentary rocks in the total stratigraphic thickness for each group of the shield. Some groups contain a minimum of 10 to 30 percent sedimentary rocks (Baish, Halaban, and Shammar), whereas others, depending on the area, consist totally of sedimentary rocks (Ablah in the Wadi Hali area, Hadley, 1975c; Jubaylah in the Jabal Umm al Aisah area, Delfour, 1970a, 1977). The most significant aspect that emerges from the thickness data is the cyclical nature of volcanism and sedimentation, defined by periods dominated by volcanism followed by periods dominated by sedimentation (fig. 2; table 8).

In order to identify trends related to grain size within the sedimentary rocks, the proportion of clastic rocks,

Table 8.--*Some sedimentary characteristics for the eight stratigraphic groups of the Arabian Shield*
[The data presented here are mostly approximate but are based on the best available information

	Phase I			Phase II			Phase III	
Sedimentary characteristics	Baish	Bahah	Jiddah	Ablah	Halaban	Murdama	Shammar	Jubaylah
Sedimentary Thickness (in meters)	4,000	3,500	3,000	4,000-6,000	2,500-4,000	4,000-10,000	200-2,000	500-3,000
Sedimentary Rocks (Percent of total section)	15-25[1] (20)[2]	70-85 (80)	30-80 (50)	60-100 (70)	15-30 (25)	70-85 (80)	10-20 (15)	35-100 (75)
Coarse-Grained Nongraywacke Clastic Rocks (Maximum percent)	10	20	10	70	40	75	90	95
Carbonate Rocks (Percent of total sedimentary rocks)	5	5-10	10	10-25[1] (18)[2]	3-15 (9)	10-25 (18)		10-55 (30)

1 - Range
2 - Average

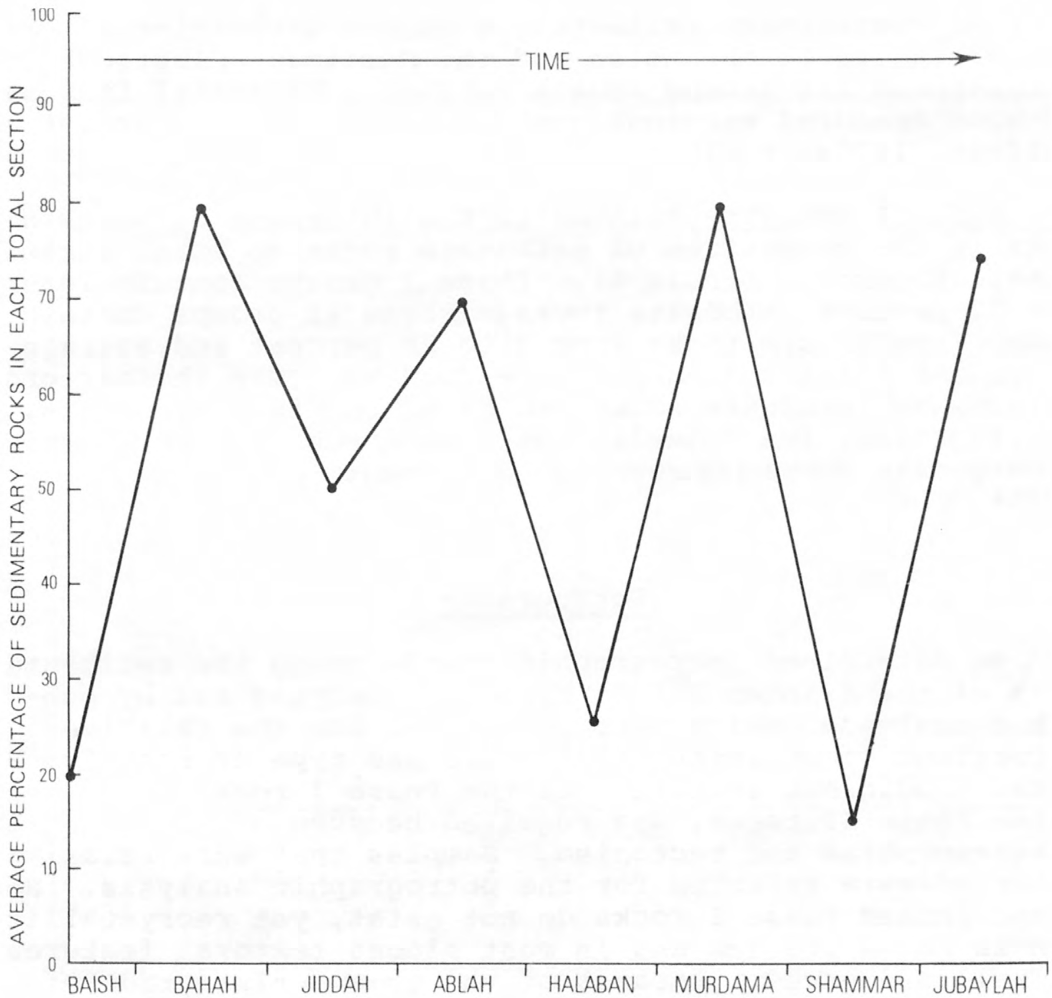


Figure 2. Average percentage of sedimentary rocks in the total stratigraphic section for each group plotted against time. Data are mostly approximate but are based on best available information.

including siltstone and coarser grained rocks (excluding graywacke), was tabulated (table 8). Phase I groups contain less than 20 percent of these rocks, and the dominantly volcanic Baish and Jiddah groups contain less than 10 percent. The proportion of the coarser-grained clastic rocks rises abruptly in the Phase II groups. For example, the Ablah and Murdama groups contain a maximum of 70 percent and 75 percent of these rocks, respectively. In contrast, however, the Halaban contains a lower proportion (40 percent) than its Phase II companions, reflecting a higher proportion of graywacke relative to the Ablah and the Murdama. Clastic rocks in the Phase III groups show a further substantial increase, and some measured sections contain as much as 95 percent (Delfour, 1970a, p. 18-19).

A final category related to the thickness of sedimentary rocks is the proportion of carbonate rocks to total stratigraphic thickness (table 8). Phase I groups contain less than 10 percent carbonate rocks. Phase II groups contain a range of carbonate rocks from 3 to 25 percent and average 18 percent for the Ablah and the Murdama. The Shammar group contains no carbonate rocks and is of continental origin. Of all groups, the Jubaylah contains the highest proportion of carbonate rocks (as much as 55 percent, Jabal Nadah; Hadley, 1974b).

Petrography

We determined petrographic trends among the sedimentary rocks of the Arabian Shield by modal analyses and by published analyses, which were reexamined for the relative proportions of constituent minerals and type of rock fragments. Judicious selection of the Phase I rocks, and some of the Phase II rocks, was required because of their degree of metamorphism and tectonism. Samples that were relatively unsheared were selected for the petrographic analysis. Nonmetamorphosed Phase I rocks do not exist, yet recrystallization is not a problem and in most places textural features are well preserved. Because of the greenschist grade of metamorphism, some Phase I rocks have a high mica content (table 5).

Ten samples of medium- to coarse-grained clastic rocks, including graywacke (especially for Phase I groups), subgraywacke, arkose, and protoquartzite, were examined for each group. Results of these analyses are summarized in tables 5 and 6 and figures 3 and 4. Potassium feldspar does not occur in sedimentary rocks older than the Halaban group, where it averages 4 percent but may be as much as 10 percent. Following deposition of the Halaban, potassium feldspar steadily increases in clastic rocks of the shield to a maximum average of 18 percent in the Jubaylah (fig. 3; table 6).

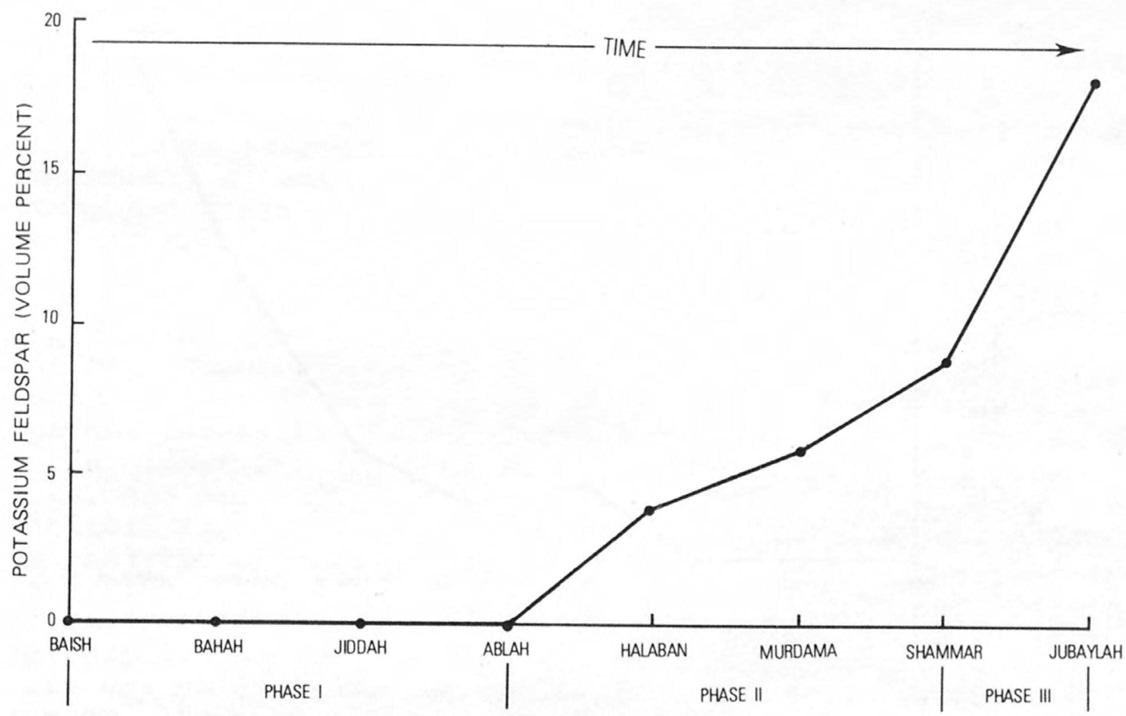


Figure 3. Potassium feldspar (volume percent) plotted against groups and time.

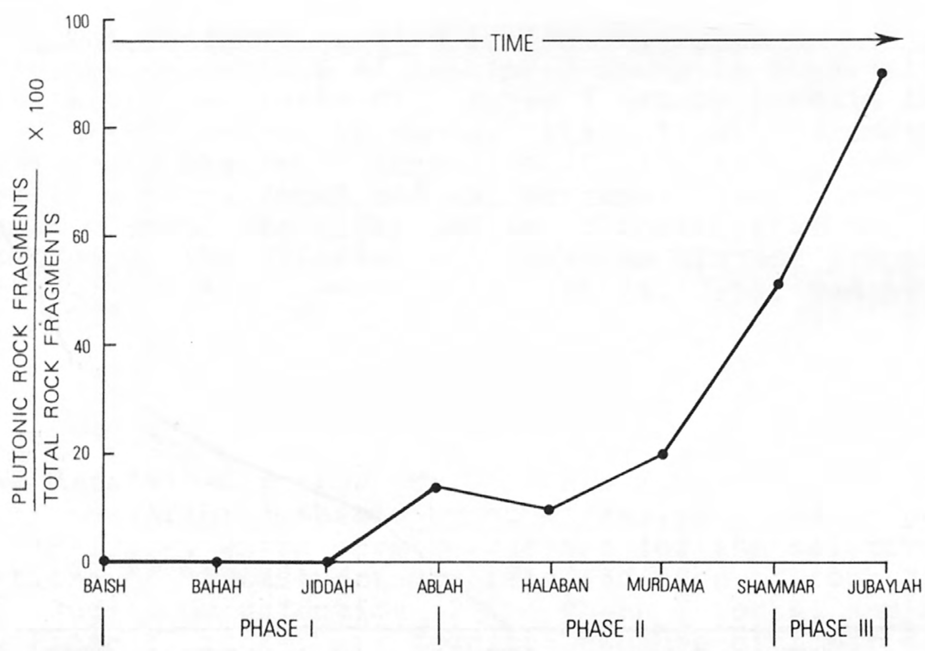


Figure 4. Maximum percentage of plutonic rock fragments as a function of total rock fragments in clastic rocks of Arabian Shield plotted against groups and time.

On the basis of the data presented herein, plutonic rock fragments (tables 5 and 6; fig. 4) first appear in the Ablah group (15 percent), fall to 10 percent in the Halaban, and then increase steadily to as much as 90 percent in the Jubaylah group. These calculations are based on percentages of the framework constituents (quartz, feldspar, and rock fragments).

EVOLUTION OF SHIELD SEDIMENTARY ROCKS AND BASINS

General

Past and current studies (this volume, for example) have focused for the most part on the plutonic, volcanic, and structural geology of the Arabian-Nubian Shield in an effort to determine its history and evolution. Models proposed for origin of the shield have indicated volcanic and sedimentary mobile belts surrounding stable cratons in an essentially continental or ensialic regime (Brown and Jackson, 1960; Ramsay and others, 1978), or evolution in an oceanic-plate tectonic environment characterized by collision orogeny and subduction (Al-Shanti, 1978; Fleck and others, 1978; Frisch and Al-Shanti, 1977; Gass, 1978; Greenwood and others, 1976; Schmidt and others, 1978). Brown and Jackson (1960) stated that "the framework of the shield is granitic". They further concluded that "one or two of these gneissoid belts have no apparent intrusive characteristics with adjoining beds, so may be the oldest exposed rocks". This implies that the oldest rocks, and hence the rocks from which the shield evolved, were granitoid in composition and that the ancestry of the shield was ensialic or continental. Shackleton (1976) concluded that the geologic evolution of Pan African domains across northern Africa, including the Nubian Shield, occurred *in situ*, that the ensialic model is consistent with the evidence, and that there was no evidence for ophiolites, sutures, or collision orogeny. However, later he postulated that the crust of the Arabian Shield formed by successive accretion of island-arc/back-arc complexes (Shackleton, 1978).

Brown and Coleman (1972) concluded that the Arabian craton was segmented by three cryptic sutures and was deformed during the Proterozoic by three orogenies that represented episodes of plate collision. This was the first proposal including a plate tectonic model for the Arabian-Nubian Shield. Jackaman (1972), using whole-rock geochemistry of basalt and andesite from the Baish and the Jiddah, postulated an island-arc origin for these rocks. Greenwood and others (1976) implied that the southern part of the Arabian Shield evolved in a plate tectonic, island-arc environment. To them, an increase in potassium feldspar of the granitic rocks eastward and northeastward suggested a northeast-dipping subduction plate. Al-Shanti and

Mitchell (1976) proposed a similar model for the eastern part of the shield and an eastward-dipping subduction plate.

The sedimentary record indicates that the Arabian Shield evolved from its inception to cratonization in both a progressive and a cyclical manner. The changes are also marked by well-defined boundaries--divisions between the phases--that is, regional unconformities.

Tables 2 and 9 summarize the principal sedimentary characteristics of the three phases described in this paper. In addition, the volcanic rock types are shown because of the consanguineous association between them and the sedimentary rocks. From this summary documentation, however, one cannot easily devise an unambiguous model for evolution of the shield. We offer a broad interpretation slanted toward current plate-tectonic concepts, but realize that many ambiguities remain and that many questions are unanswered.

Group summary

In Phase I, the Baish and Jiddah groups (tables 2 and 9) consist of graywacke, chert, graphitic argillaceous rocks, and nonstromatolitic marble. Current structures and graded bedding are generally absent in these groups. Thick, abundant intraformational conglomerates (table 3) dominated by ill-sorted angular clasts of the same composition as the associated volcanic rocks indicate contemporaneous volcanism and a near-source, submarine- slump origin for these coarse rocks. A general lack of graded bedding and bedding-plane sedimentary structures in Phase I graywackes indicates distal deposition. The associated volcanic rocks are dominated by basalt (in places showing pillow structure), andesite, and associated pyroclastic rocks. Collectively, these features indicate deposition in a deep-water flysch environment.

The sedimentary and volcanic character of the Bahah group (tables 2 and 9) contrasts sharply with the Baish and the Jiddah. It is dominated by siltstone, mudstone, quartzite, flat-pebble conglomerate, marble, and argillite, and contains minor amounts of graywacke, chert, and interlayered flow rocks. Sedimentary characteristics include crossbedding, ripple marks, mud cracks, flat-pebble chips, graded bedding, and wavy laminated (stromatolitic?) marble. Sialic components such as potassium feldspar and plutonic rock fragments have not been identified petrographically (tables 5 and 6; figs. 3 and 4). The type of sedimentary rocks and structures in the Bahah reflect deposition in a moderate to shallow-water marine environment.

Of the Phase II groups, the Ablah and the Murdama contain the same types of sedimentary rocks and structures (table 9):

Table 9.--*Sedimentary structures recorded in clastic and carbonate rocks of the Arabian Shield and the types and abundances of volcanic rocks found in each group*

	Phase I			Phase II			Phase III	
Sedimentary Structures	Baish	Bahah	Jiddah	Ablah	Halaban	Murdama	Shammar	Jubaylah
Clastic								
Crossbedding	--	C-A	--	C	S	C	S	C
Ripple marks	--	S	--	C	S-C	C-A	S	C
Ripple cross laminations	--	C	--	C-A	S-C	C-A	S-C	C-A
Mud cracks	--	S	--	C	--	C	--	S
Graded bedding	S	C-A	S	A	A	A	C	A
Rain drop imprints	--	--	--	S	S	--	--	--
Carbonate								
Stromatolite hemispheres	--	--	--	--	--	--	--	C-A
Stromatolitic algal laminites	--	S	--	C	--	C	--	A
Ripple drift laminations	--	S	--	C	--	C	--	A
Mud cracks	--	--	--	S	--	S	--	C
Volcanic Rocks								
Rhyolite-Dacite	S	--	S	S-C	C-A	C	A	--
Andesite	C	S	A	S-C	A	C	S	C
Basalt	A	--	C	--	S	--	--	--

A - Abundant; C - Common; S - Sparse; --Not recorded thick basal boulder conglomerates (recording unconformities), intraformational conglomerates, abundant arkosic and lithic (protoquartzite) sandstone, mudstone, siltstone, and marble, and subordinate amounts of pebble conglomerate and argillitic rocks. In the clastic rocks, sedimentary structures, such as crossbedding, ripple marks, ripple drift, mud cracks, and graded bedding abound, and a few rain drop imprints have been observed; in the carbonate rocks, stromatolites, and oolites have been noted at numerous localities. The sedimentary rock types and structures and the abundant potassium feldspar and plutonic rock fragments in the Ablah and Murdama groups identify nearby sialic source rocks and indicate molasse and carbonate shelf sedimentation in a moderate to shallow-water marine environment.

In contrast to the Ablah and Murdama groups, the Halaban group is dominantly volcanic. It contains a substantial thickness of sedimentary rocks, comprising boulder conglomerate (basal and intraformational), graywacke, siltstone, argillite, and marble. Plutonic rock fragments and potassium feldspar are common to abundant. Volcanic flow rocks and pyroclastic rocks ranging in composition from andesite to rhyolite dominate the group; andesite is interstratified with the sedimentary rocks and is closely interbedded with, and a contributor to, the Halaban chaotic boulder conglomerates. Sedimentary structures include graded bedding, crossbedding, ripple marks, mud cracks, and rain drop imprints. Deposition is interpreted to have been in a moderate to shallow low-energy marine environment.

Phase III sedimentary and volcanic rocks differ substantially from rocks of the two older phases. Apart from carbonate rocks in the Jubaylah, the Shammar and Jubaylah groups are dominated by terrigenous clastic rocks. Each consists of basal conglomerates (boulder-sized fragments in the Jubaylah), medium- to coarse-grained arkosic sandstone, and siltstone. The Jubaylah, in addition, contains minor amounts of mudstone and shale and abundant cherty limestone and dolomite that contain chert nodules and interbeds. Potassium feldspar and potassium feldspar-bearing plutonic rock fragments are abundant components of the clastic rocks. Both groups are nonmetamorphosed and only moderately deformed; thus, sedimentary structures are excellently preserved. Sedimentary structures consist of moderate-scale crossbedding, graded bedding, ripple drift, mud cracks, laterally linked hemisphere stromatolites, and stromatolitic algal laminates. The volcanic rocks include rhyolite, rhyolitic ignimbrite, and andesitic basalt. The sedimentary and volcanic composition and structures of the Shammar and Jubaylah groups show that they were deposited in continental-alluvial fan, fluvial, and lacustrine environments. The carbonate rocks were deposited in an intertidal-marine, or possibly a lake-bed, environment.

Discussion

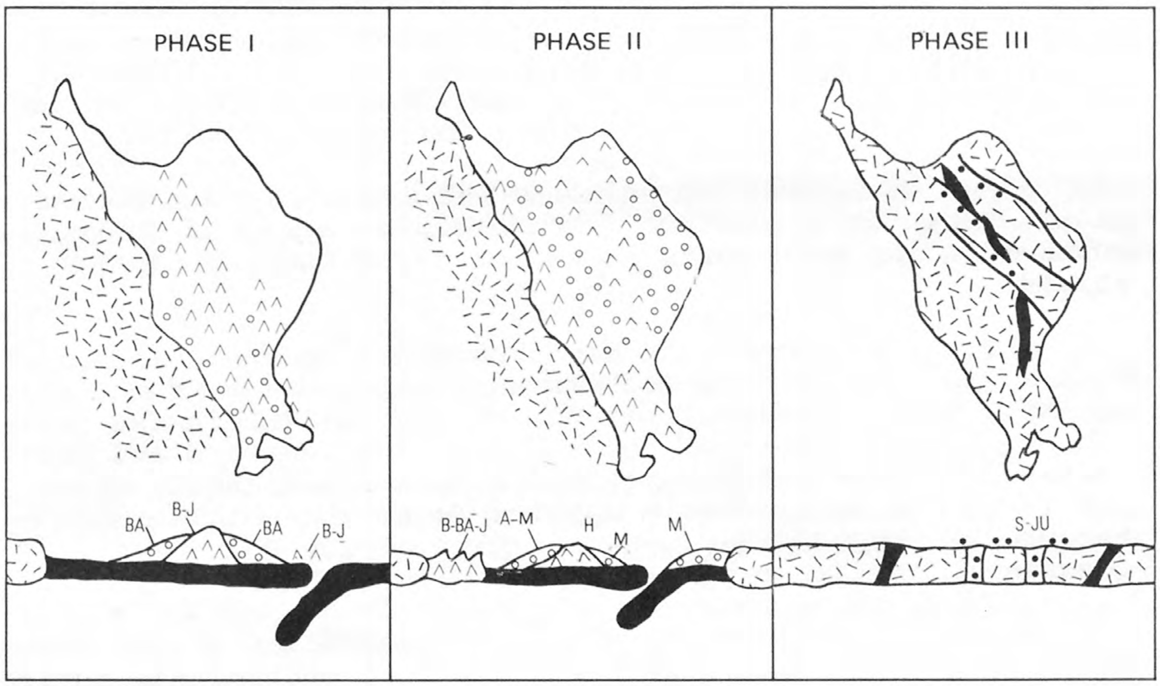
Sequential evolution of the sedimentary rocks and basins of the shield took place in three phases (table 10) schematically depicted in figure 5. Superimposed upon the phases are the cycles in the evolution that consist of volcanism followed by sedimentation repeated four times since the inception of Baish volcanism. However, with time, plutonic rocks (beginning with syn-Jiddah batholiths) assumed an ever-increasing role as a source of coarse sedimentary detritus for sedimentary units of the shield (figs. 3 and 4).

Evolution of the Arabian Shield was initiated by sea-floor volcanism during Baish time in an oceanic environment that continued through Jiddah time (fig. 5). Sedimentary basins were north trending and confined to the southern and western parts of the neo-craton. During this phase, the Bahah was deposited mainly as moderate- to shallow-water back-arc(?) products, possibly partly contemporaneous with volcanism and sedimentation of the Baish and Jiddah groups. A westward-dipping oceanic plate is envisaged because sedimentary, volcanic, and plutonic rocks of the shield decrease in age toward the east and northeast. The complex distribution of Phase II rocks (fig. 5) suggests that the groups of this phase were not deposited in a single linear basin or trough (trench?), but rather a digitate system of basins or troughs (Frisch and Al-Shanti, 1977) may have existed that were contemporaneous. A well-defined island-arc and back-arc system emerged during Baish and Jiddah time, and a second system developed during Halaban time; subsequent erosion and sedimentation continued through Murdama time (Greenwood and others, 1976; Jackaman, 1972; Fleck and others, 1978; Schmidt and others, 1978; Dodge and others, in press).

Phase II basins and sedimentary rocks (fig. 5) are also north trending, but have an apparent northwest trend that is due to subsequent rotation by faulting during Najd time (Schmidt and others, 1973; Moore and Al-Shanti, 1973, 1978). In general, Phase II basins shifted eastward and northeastward following Phase I time. Sedimentation during Phase II time was influenced by and took place on the flanks of mature island arcs (Halaban) in a moderate to shallow marine environment. The primitive Phase I oceanic and island-arc products, consumed and intruded by late Phase I collision (Phase I diorite and trondhjemite batholiths), began to feed plutonic detritus to the island-arc Phase II (Ablah) basins. During early Phase II time, as the adolescent Arabian Shield started to mature, potassium-bearing plutons evolved from Phase I dioritic to trondhjemitic batholiths and the thick volcanic piles and, during subsequent erosion, contributed potassium feldspar detritus to the Halaban and Murdama sedimentary basins. A new episode of continental collision during late Phase II and early Phase III time about 640 to 610 m.y. ago

Table 10.--*Sedimentary depositional environments and corresponding geologic-tectonic environments during evolution of the Arabian Shield*

PHASES	DOMINANT SEDIMENTARY ENVIRONMENT	GEOLOGIC/TECTONIC ENVIRONMENT
Phase I	Deep-Water Marine (Flysch)	Oceanic-Island Arc/ Subduction and Collision
Phase II	Moderate to Shallow Marine (Molasse-carbonate shelf)	Island Arc/Continental Accretion and Collision
Phase III	Continental and Shallow Marine (?)	Cratonization



EXPLANATION

CONTINENTAL ROCKS

BACK– AND FORE–ARC SEDIMENTARY ROCKS

CONTINENTAL SEDIMENTARY ROCKS

ISLAND–ARC AND OCEANIC VOLCANIC AND SEDIMENTARY ROCKS

OCEANIC CRUST

JU – JUBAYLAH
S – SHAMMAR
M – MURDAMA
H – HALABAN
A – ABLAH
J – JIDDAH
BA – BAHA
B – BAISH

Figure 5. Schematic diagram showing plate tectonic evolution of Arabian Shield.

(Fleck and others, 1978; Schmidt and others, 1978) marked the cessation of Phase II sedimentation and volcanism, terminated oceanic, and for the most part marine, sedimentation, and initiated continental deposition and the development of the Pan-African age Najd fault system (Clifford, 1967; Fleck and others, 1976). The Najd fault system formed during the 640-610 m.y. old collisional event during which the Arabian block was juxtaposed against an east-Arabian-Iranian block (Schmidt and others, 1978; Fleck and others, 1978) in the manner described by Tapponnier and Molnar (1976) for collision of the Eurasian and Indian plates. Compressional tectonics surrounding the collision swept the old island-arc volcanic rocks and arc and back-arc sedimentary rocks together into a complex array of dominantly north-trending fold belts as now observed in most of the shield.

Phase III sedimentation was confined to small local basins (Shammar) and to grabens and half-grabens produced by the Najd faults (Delfour, 1970a; Hadley, 1974b) in the northern and northeastern part of the shield. The eastward and northeastward shift of sedimentary basin axes prevalent in Phase I and II is not particularly applicable to Phase III sedimentary rocks because they were not part of the Phase I and II oceanic-island-arc regime.

Phase III sedimentary rocks were deposited unconformably on the deformed Phase I and II rocks in a continental environment. Phase III clastic material was derived primarily from the erosion of Phase I and II rocks, but a substantial portion probably come from the erosion of post-collisional granites in the 620-540 m.y. range (Fleck and others, 1976).

REFERENCES

Aldrich, L. T., and Brown, G. F., 1960, Distribution of ages in the Arabian segment of the Arabian Shield: Geological Society of America Bulletin, v. 71, p. 1813.

Al-Shanti, A. M. S., 1978, Introduction, *in* Al-Shanti, A. M. S., ed., Evolution and mineralization of the Arabian-Nubian Shield, a symposium: Precambrian Research, v. 6, p. A2.

Al-Shanti, A. M. S., and Mitchell, A. H. G., 1976, Late Precambrian subduction and collision in the Al Amar-Idsas region, Arabian Shield, Kingdom of Saudi Arabia: Tectonophysics, v. 30, no. 3-4, p. T41-T47.

Bayley, R. W., 1972, Geologic map and section of the Wadi Yiba quadrangle, Kingdom of Saudi Arabia: Saudi Arabian Directorate General of Mineral Resources Geologic Map GM-1, scale 1:100,000.

Bramkamp, R. A., Brown, G. F., Holm, D. A., and Layne, N. M., Jr., 1963a, Geologic map of the Wadi as Sirhan quadrangle, Kingdom of Saudi Arabia: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-200A, scale 1:500,000.

Bramkamp, R. A., Ramirez, L. F., Brown, G. F., Pocock, A. E., 1963b, Geologic map of the Wadi ar Rimah quadrangle, Kingdom of Saudi Arabia: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-206A, scale 1:500,000.

Bramkamp, R. A., and Ramirez, L. F., 1958, Geologic map of the northern Tuwayq quadrangle, Kingdom of Saudi Arabia: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-207A, scale 1:500,000.

Brown, G. F., 1960, Geomorphology of western and central Saudi Arabia: International Geological Congress, 21st, Copenhagen, 1960.

______, 1970, Eastern margin of the Red Sea and the coastal structures in Saudi Arabia, *in* 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 Socity of London Philosophical Transactions, ser. A, v. 267, p. 75-87.

Brown, G. F., and Coleman, R. G., 1972, The tectonic framework of the Arabian peninsula: International Geological Congress, 24th, Montreal, 1972, v. 3, p. 300-305.

Brown, G. F., and Jackson, R. O., 1958, Geologic map of the Tihamat ash Sham quadrangle, Kingdom of Saudi Arabia: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-216A, scale 1:500,000.

______, 1959, Geologic map of the Asir quadrangle, Kingdom of Saudi Arabia: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-217A, scale 1:500,000.

______, 1960, The Arabian Shield: International Geological Congress, 21st, Copenhagen, 1960, v. 9, p. 69-77.

Brown, G. F., Jackson, R. O., Bogue, R. G., and Elberg, E. L., Jr., 1963a, Geologic map of the northwestern Hijaz quadrangle, Kingdom of Saudi Arabia: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-204A, scale 1:500,000.

Brown, G. F., Jackson, R. O., Bogue, R. G., and MacLean, W. H., 1963b, Geologic map of the southern Hijaz quadrangle, Kingdom of Saudi Arabia: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-210A, scale 1:500,000.

Brown, G. F., Layne, N. L., Jr., Goudarzi, G. H., and MacLean, W. H., 1963c, Geologic Map of the northeastern Hijaz quadrangle, Kingdom of Saudi Arabia: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-205A, scale 1:500,000.

Clifford, T. N., 1967, The Damaran episode in the upper Proterozoic-lower Proterozoic structural history of southern Africa: Geological Society of American Special Paper 92, 100 p.

Cornwall, H. R., 1973, Geology of the Wadi Harjab quadrangle, Kingdom of Saudi Arabia: Saudi Arabian Directorate General of Mineral Resources Geologic Map GM-3, scale 1:100,000.

Delfour, J., 1967, Report on the mineral resources and geology of the Hulayfah-Musayna'ah region, sheet 78, zone 1 north: Bureau de Recherches Géologiques et Minières Open-File Report SG-JED-66-A-8, 139 p.

______, 1970a, Le groupe de J'Balah, une nouvelle unité du bouclier arabe (The J'Balah Group, a new unit of the Arabian Shield): Bureau de Recherches Géologiques et Minières Bulletin (ser. 2), sec. 4, no. 4, p. 19-32.

______, 1970b, Sulfide mineralization at Nuqrah and Jabal Sayid: Bureau de Recherches Géologiques et Minières Open-File Report 70-JED-22, 34 p.

______, 1976, Comparative study of mineralization in the Nubian and Arabian Shields: Saudi Arabian Directorate General of Mineral Resources Bulletin 15, 22 p.

______, 1977, Geology of the Nuqrah quadrangle, 25E, Kingdom of Saudi Arabia: Saudi Arabian Directorate General of Mineral Resources Geologic Map GM-28, scale 1:250,000.

Dodge, F. C. W., Fleck, R. J., Hadley, D. J., and Millard, H. T., Jr., in press, Geochemistry and Sr87/Sr86 ratios of Halaban rocks of the central Arabian Shield: Saudi Arabia Inst. of Applied Geol. Bull.

Earhart, R. L., 1969a, A preliminary investigation of a copper occurrenc at Jabal Sarbon, Tihamat ash Sham quadrangle, Kingdom of Saudi Arabia: U.S. Geological Survey open-file rept. (IR)SA-102, 11 p.

Earhart, R. L. 1969b, Report on exploration of the Wadi Yiba copper prospect, Tihamat ash Sham quadrangle, Kingdom of Sauid Arabia: U.S. Geological Survey open-file rept. (IR)SA-108, 11 p.

Fleck, R. J., Coleman, R. G., Cornwall, H. R., Greenwood, W. R., Hadley, D. G., Prinz, W. C., Ratte, J. C., and Schmidt, D. L., 1976, Geochronology of the Arabian Shield western Saudi Arabia: K-Ar results: Geological Society of America Bulletin, v. 87, no. 1, p. 9-21.

Fleck, R. J., Greenwood, W. R., Hadley, D. G., Anderson, R. E., and Schmidt, D. L., 1978, Age and evolution of the southern part of the Arabian Shield [abs.], *in* Al-Shanti, A. M. S., ed., Evolution and mineralization of the Arabian-Nubian Shield, a symposium: Precambrian Research, v. 6, p. A21-A22.

Frisch, W., and Al-Shanti, A., 1977, Ophiolite belts and the collision of island arcs in the Arabian Shield: Tectonophysics, v. 43, p. 293-306.

Gaskill, D. L., 1970 , Economic evaluation of a marble deposit and a Kyanite deposit notheast of Al Lith, southern Hijaz quadrangle, Kingdom of Saudi Arabia: U.S. Geological Survey open-file rept. (IR)SA-116, 19 p.

Gass, I. G., 1978, Evolutionary model for the Pan-African crystalline basement [abs.], *in* Al-Shanti, A. M. S., ed., Evolution and mineralization of the Arabian-Nubian Shield, a symposium: Precambrian Research, v. 6, p. A23.

Greenwood, W. R., 1975a, Geology of the Al Aqiq quadrangle, sheet 20/41 D, Kingdom of Saudi Arabia: Saudi Arabian Directorate General of Mineral Resources Geologic Map GM-23, scale 1:100,000.

______, 1975b, Geology of the Biljurshi quadrangle, sheet 19/41 B, Kingdom of Saudi Arabia: Saudi Arabian Directorate General of Mineral Resources Geologic Map GM-25, scale 1:100,000.

______, 1975c, Geology of the Jabal Ibrahim quadrangle, sheet 20/41 C, Kingdom of Saudi Arabia: Saudi Arabian Directorate General of Mineral Resources Geologic Map GM-22, scale 1:100,000.

______, 1975d, Geology of the Jabal Shada quadrangle, sheet 19/41 A, Kingdom of Saudi Arabia: Saudi Arabian Directorate General of Mineral Resources Geologic Map GM-20, scale 1:100,000.

Greenwood, W. R., and Brown, G. F., 1973, Petrology and chemical analysis of selected plutonic rocks from the Arabian Shield, Kingdom of Saudi Arabia: Saudi Arabian Directorate General of Mineral Resources Bulletin 9, 9 p.

Greenwood, W. R., Hadley, D. G., Anderson, R. E., Fleck, R. J., and Schmidt, D. L., 1976, Late Proterozoic cratonization in southwestern Saudi Arabia: Royal Society of London Philosophical Transactions, Ser. A, v. 280, P. 517-527.

Greenwood, W. R., Hadley, D. G., and Schmidt, D. L., 1973, Tectono-stratigrapnic subdivision of Precambrian rocks in the southern part of the Arabian Shield [abs.]: Geological Society of America Abstracts with Programs, v. 5, no. 7, p. 643.

Greenwood, W. R., Hadley, D. G., Anderson, R. E., Fleck, R. J., and Schmidt, D. L., 1975, Late Proterozoic cratonization in southwestern Saudi Arabia: Royal Society of London Symposium, Global tectonics in Proterozoic times, London, March 1975, p. 10.

Greenwood, W. R., Hadley, D. G., and Schmidt, D. L., 1974, Generalized geologic map of the Arabian Shield, Kingdom of Saudi Arabia, *in* Greenwood, W. R., Roberts, R. J., and Bagdady, A., Mineral belts in western Saudi Arabia: Arab Conference for Mineral Resources, Second, 1974, Jeddah, Saudi Arabia, Conference Documents Background Papers, Miscellaneous, p. 130-151.

Hadley, D. G., 1973, Geology of the Sahl al Matran quadrangle, northwestern Hijaz, Kingdom of Saudi Arabia: Saudi Arabian Directorate General of Mineral Resources Geologic Map GM-6, scale 1:100,000.

______, 1974a, Geologic map of the Wayban quadrangle, Kingdom of Saudi Arabia: Saudi Arabian Directorate General of Mineral Resources Geologic Map GM-7, scale 1:100,000.

______, 1974b, The taphrogeosynclinal Jubaylah Group in the Mashhad area, northwestern Hijaz, Kingdom of Saudi Arabia: Saudi Arabian Directorate General of Mineral Resources Bulletin 10, 18 p.

______, 1975a, Geology of the al Qunfudhah quadrangle, sheet 19/41 C, Kingdom of Saudi Arabia: Saudi Arabian Directorate General of Mineral Resources Geologic Map GM-19, scale 1:100,000.

______, 1975b, Geology of the Qal'at as Sawrah quadrangle, sheet 26/38 D, Kingdom of Saudi Arabia: Saudi Arabian Directorate General of Mineral Resources Geologic Map GM-24, scale 1:100,000.

Hadley, D.G., 1975c, Geology of the Wadi Hali quadrangle, sheet 18/41 B, Kingdom of Saudi Arabia: Saudi Arabian Directorate General of Mineral Resources Geologic Map GM-21, scale 1:100,000.

______, 1976, Geology of the Bir Juqjuq quadrangle, sheet 21/43 D, Kingdom of Saudi Arabia: Saudi Arabian Directorate General of Mineral Resources Geologic Map GM-26, scale 1:100,000.

Hadley, D. G., and Schmidt, D. L., 1978, Proterozoic sedimentary rocks and basins of the Arabian Shield and their evolution [abs.], *in* Al-Shanti, A. M. S., ed., Evolution and mineralization of the Arabian-Nubian Shield, a symposium: Precambrian Research, v. 6, p. A23-A24.

Hirayama, Ken, and Assad, M. Q., 1967, Types of iron deposits in Saudi Arabia: Japanese Geological Survey Saudi Arabian Mission Open-File Report, 30 p.

Hirayama, Ken, Nakazawa, Jiro, Komara, Kohjiro, Higashimoto, Sadao, Odani, Yoshitaka, Iso, Miyoji, and Kuwagata, Hisao, 1967, Report on the iron-ore deposits in the Wadi Sawawin district, northwest Saudi Arabia: Japanese Geological Survey Saudi Arabian Mission Open-File Report, 115 p.

Holmes, Arthur, 1920, The nomenclature of petrology, with references to selected literature: London, Thomas Murby and Co., 284 p.

Jackaman, Barry, 1972, Genetic and environmental factors controlling the formation of the massive sulfide deposits of Wadi Bidah and Wadi Wassat, Saudi Arabia: Saudi Arabian Directorate General of Mineral Resources Technical Record TR-1972-1, 244 p.

Jackson, R. O., Bogue, R. G., Brown, G. F., and Gierhart, R. D., 1963, Geologic map of the southern Najd quadrangle, Kingdom of Saudi Arabia: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-211A, scale 1:500,000.

Karpoff, Roman, 1957, Esquisse géologique del l'Arabie Séoudite: Société Geologique de France Bulletin, ser. 6, v. VII, p. 672-674.

Moore, J. McM., and Al-Shanti, A. M., 1973, The use of stress trajectory analysis in the elucidation of part of the Najd fault system, Saudi Arabia: Geologists' Association (London), Proceedings, v. 84, p. 383-403.

______, 1978, The Najd fault system and associated mineralization [abs.], *in* Al-Shanti, A. M. S., ed., Evolution and mineralization of the Arabian-Nubian Shield, a symposium: Precambrian Research, v. 6, p. A30-A31.

Overstreet, W. C., Whitlow, J. W., Kahr, V. P., and Ankary, Abdullah, 1972, Reconnaissance geology of the Bi'r Al Badriyah quadrangle, Kingdom of Saudi Arabia: U.S. Geol. Survey open-file rept (IR)SA-126, 47 p.

Pettijohn, F. J., 1957, Sedimentary rocks (2nd ed.): New York, Harper and Row, 718 p.

______, 1975, Sedimentary rocks (3rd ed.): New York, Harper and Row, 628 p.

Prinz, W. C., 1975, Reconnaissance geology of the Jabal 'Aya quadrangle, sheet 18/42 A, Kingdom of Saudi Arabia: Saudi Arabian Directorate General of Mineral Resources Geologic Map GM-17, scale 1:100,000.

Ramsay, C. R., Jackson, N. J., and Roobol, M. J., 1978, Structural/lithological provinces in a Saudi Arabian Shield geotraverse [abs.], *in* Al-Shanti, A. M. S., ed., Evolution and mineralization of the Arabian-Nubian Shield, a symposium: Precambrian Research, v. 6, p. A31-A32.

Ratte, J. C., and Andreasen, G. E., 1974, Reconnaissance geology and magnetic intensity map of the Jabal Sawdah quadrangle, Kingdom of Saudi Arabia: Saudi Arabian Directorate General of Mineral Resources Map GM-16, scale 1:100,000.

Richter-Bernburg, G., and Schott, W., 1954, Geological researches in western Saudi Arabia: Saudi Arabian Directorate General of Mineral Resources Open-File Report 38, 69 p.

Roberts, R. J., Greenwood, W. R., Worl, R. G., Dodge, F. C. W., and Kiilsgaard, T. H., 1975, Mineral deposits in western Saudi Arabia--a preliminary report: U.S. Geol. Survey open-file rept. 75-654 (IR)SA-201, 60 p., 1 fig., 8 tables.

Schmidt, D.L., Hadley, D. G., Greenwood, W. R., Gonzalez, Louis, Coleman, R. G., and Brown, G. F., 1973, Stratigraphy and tectonism of the southern part of the Precambrian Shield of Saudi Arabia: Saudi Arabian Directorate General of Mineral Resources Bulletin 8, 13 p.

Schmidt, D. L., Hadley, D. G., and Stoeser, D. B., 1978, Late Proterozoic crustal history in the southern Najd Province, Saudi Arabia [abs.], *in* Al-Shanti, A. M. S., ed., Evolution and mineralization of the Arabian-Nubian Shield, a symposium: Precambrian Research, v. 6, p. A35.

Shackleton, R. M., 1976, Pan-African structures, *in* Sutton, J., and others, eds., A discussion on global tectonics in Proterozoic times: Royal Society of London Philosophical Transactions, Ser. A, v. 280, p. 491-497.

Shackleton, R. M., 1978, Precambrian tectonics of northeast Africa [abs.], *in* Al-Shanti, A. M. S., ed., Evolution and mineralization of the Arabian-Nubian Shield, a symposium, Programme and Abstracts: Institute of Applied Geology Research Series no. 4, p. 105-106.

Tapponnier, P., and Molnar, P., 1976, Slip-line field theory and large-scale continental tectonics: Nature, v. 264, p. 319-324.

U.S. Geological Survey-Arabian American Oil Co., 1963, Geologic map of the Arabian Peninsula, Kingdom of Saudi Arabia: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-270A, scale 1:2,000,000.

Vail, J. R., 1978, Outline of the geology and mineralization of the Nubian Shield east of the Nile Valley, Sudan [abs.], *in* Al-Shanti, A. M. S., ed., Evolution and mineralization of the Arabian-Nubian Shield, a symposium: Precambrian Research, v. 6, p. A39-A40.

Walker, R. G., and Pettijohn, F. J., 1971, Archean sedimentation: Analysis of the Minnitaki Basin, northwestern Ontario, Canada: Geological Society of America Bulletin, v. 82, no. 8, p. 2099-2130.

D.G. Hadley and D.L. Schmidt – PROTEROZOIC SEDIMENTARY ROCKS AND BASINS OF THE ARABIAN SHIELD – IR 242