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Layering in Gabbroid Rocks from Semail Ophiolite, United Arab Emirates: Characterization, Tectonic Control on Origin and Orientation

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ABSTRACT. Layering is well pronounced in several exposures of gabbroid rocks within certain zones, subzones and horizons of the Semail ophiolite (Late-Cretaceous). From Khor Kalba Horizon - Wadi Hatta Zone, southward to Khor Fakkan Zone, and northward passing through Bathnah Zone (Al-Fujairah - Masafi road), most layered gabbros appear to have formed with their layering steeply inclined to vertical; horizontal layering is rarely observed. It is probably formed in situ on cooling walls or plated onto the walls by density or convection currents (current deposition). This mechanism, may however, not be responsible for the formation of all types of layering found in the present work.

Preferred orientations of magmatic flow structure "layering" are compatible to a large extent with the major structural trends identified in the United Arab Emirates. The NW orientation (Hatta Zone-Wadi Ham trend), the NE orientation (Dibba Zone trend) and NS orientation (overthrusted Semail ophiolite nappe) are consistent with the major tectonic trends identified in the UAE. This may lead to a better understanding of the orientation of layering that has been controlled by the regional tectonism and may be the dynamics of magma chambers at oceanic spreading center.

Introduction

The geology of the United Arab Emirates has been divided into three major rock units (Lippard *et al.* 1986 and Glennie *et al.* 1990):

1. An autochthonous succession of middle Permian to Upper Cretaceous carbonate resting unconformably on Late Precambrian to lower Paleozoic sediments, representing a part of the stable Arabian Platform.

2. Allochthonous units composed mainly of Mesozoic rocks and include the Sumeini Group (concomittent slope sediments), Hawasina Complex (basinal sediments) and the Semail ophiolite nappe (massive slice of former oceanic crust), that were emplaced as a series of thrust nappe in the Late Cretaceous.

3. An neo-autochthonous sequence of Mastrichtian and Lower Tertiary sediments. The Semail ophiolite (600 km long and up to 150 km wide) is thought by some authors (Glennie *et al.* 1990) to have been generated along a subduction-related back-arc spreading axis during the Cenomanian-Turonian and was obducted onto the Arabian continental margin during the Campanian. Others, however, consider it to represent a primitive arc-spreading center related to oblique subduction.

According to Glennie *et a1.* (1974), the Semail ophiolite includes the following rock units starting from the top:

	extrusive rocks, mainly spilites and basalts with some pelagic sediments.
	diabase dike swarms.
	a complex zone of gabbroid rocks.
Cumulus sequence	layered gabbros. transitional zone (gabbro-peridotite complex). layered peridotite
Non-cumulus sequence	metamorphic peridotite(serpentinized peridotite).

The layered gabbros in the United Arab Emirates have been mentioned very rarely in the literature (Allemann and Peters 1972; Hunting, 1979; Hassan and Al Sulaimi, 1979; El Bayoumi and Heikal, 1992 and Hassan *et al.* 1995). Allemann and Peters (1972) noted the layering in gabbros near Bathnah and estimated that the thickness of layers is not more than 1 km. Hunting (1979) stated that "layering in gabbros is a widespread feature; light and dark banding which correlates with alternating layers rich in feldspathic and ferromagnesian constituents, has often been accentuated by erosion". They also added that fine banding is a feature of many localities, individual layers less than 1 cm thick having been observed southeast of Bathnah in Wadi Ham. Hassan and Al Sulaimi (1979) explained that the origin of layers near Al Fujairah area is caused by two features; the differential settling of pyroxene and/or olivine relative to plagioclase, and the crystallization behavior of the melt. El Bayoumi and Heika1 (1992) recorded the presence of layered gabbros at Wadi Hatta. They showed that these rocks are characterized by cumulus layering of variable thickness and the presence of diffusion phenomena. Hassan *et al.* (1995) defined the layers according to the variation in the relative abundance and/or size of the three primary cumulus minerals, olivine, pyroxene and plagioclase.

A field traverse (Fig. l) was carried out across the Semail ophiolite in UAE to select the best exposures of layered gabbros. Four selected areas (435 km^2) revealed the presence of zones and horizons of layered mafic rocks (77 km^2) at Khor Kalba (Fig. 1-1), Bathnah (Fig. 1-2), Khor Fakkan (Fig. l-3) and Wadi Hatta (Fig. l-4).

The areas under consideration are accessible, where paved roads and motor tracks crosscut the main wadis and their tributaries.

The present work was carried out with the following aims: :

1. To develop a new and more realistic nomenclature based on serious as well as systematic field mapping using colored aerial photographs (scale 1:25,000) of the layered gabbros using the North American Stratigraphic Code (1983).

2. To emphasize the main characteristic features of the layering and the petrography of the gabbros, with respect to the tectonic stresses which may provide the principal control on the development and orientation of the layering.

Geological Setting

Gabbro Terminology

The terminology of igneous cumulates proposed by Irvine (1982) was formulated on the concept that the rocks were concentrations of minerals accumulated by crystal settling. **A Cumulate** is defined as an igneous rock characterized by a framework of touching mineral crystals and grains that evidently were concentrated through fractional crystallization of the parental magmatic liquids. **A layer** is sheetlike unit of cumulate that is a distinctive entity in its compositional and/or textural features. **A lamina** is a thin (2-5 cm), sharply defined layer. **Layering** represents the overall structure and fabric manifest through combinations of layers, laminae and lamination. The **layer contacts** can essentially be described according to one or more of the four modifiers, 'grain size', 'modal', 'textural' and 'cryptic', where the last refers to cumulus-mineral compositions. Layered units may be ranked as **series, zones, subzones** and horizons and the prominent unit's members, **rhythmic units and cyclic units.**

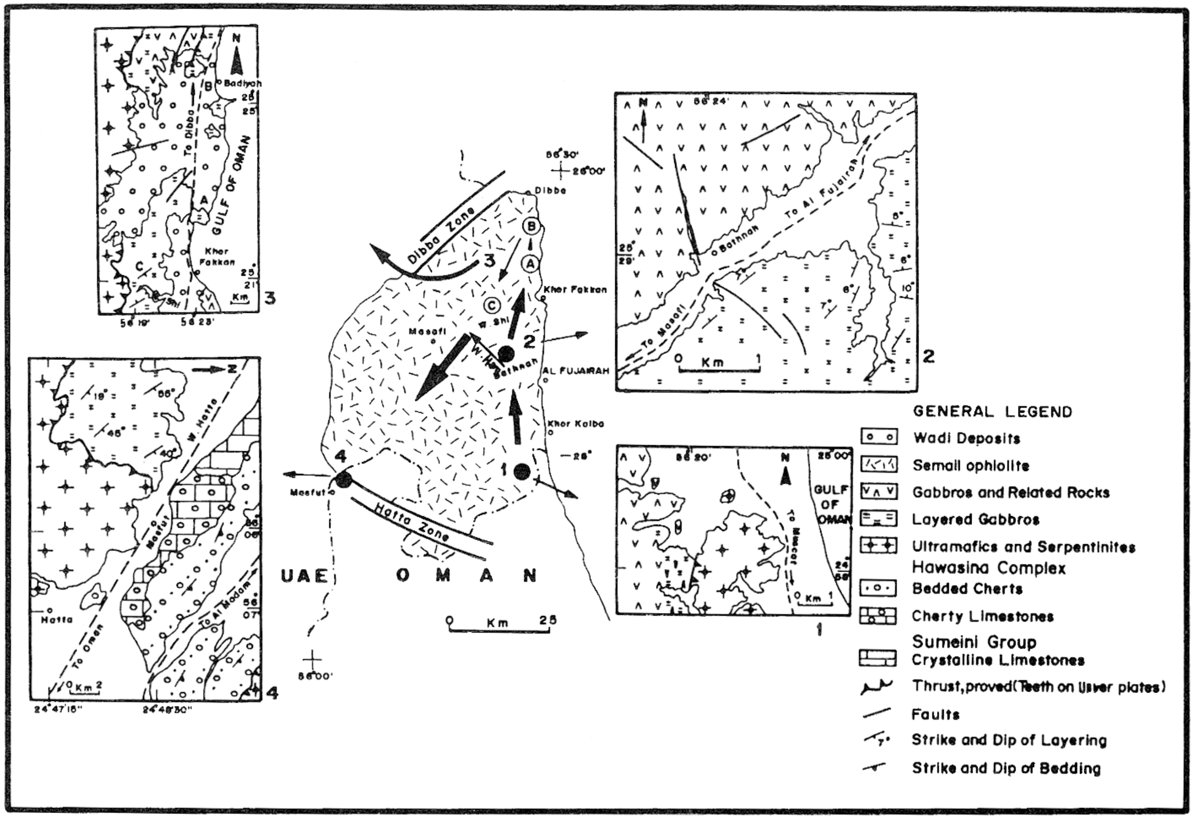


FIG. 1. Field-Traverse map in Semail ophiolite showing the locations of four selected areas under study. (1:A part of geologic map of Khor Kalba area ; 2: Geologic map of Bathnah area across Al Fujairah-Masafi highway ; 3: Geologic map of Khor Fakkan. A & B : Khor Fakkan-Dibba road and C: Wadi Shi : 4: Wadi Hatta area across Masfut-Oman highway).

In the present work, 'Zone' and 'horizon' are probably the most common names used for the formal subdivisions of layered gabbros. It is the first attempt to apply standardized stratigraphic nomenclature to layered gabbros of Semail ophiolite in UAE.

The characteristic features of layers; and layering (Irvine, 1982), include thickness, form, internal constitution, contacts, lithology, demarcation, regularity, structure, repetition, distribution and continuity and mode of origin.

Field Relationships

Khor Kalba layered Gabbros Horizon

In the Khor Kalba area (Abu El Ela and Heikal, l996), a new mappable microrhythmic unit (Fig. l-l) has been defined and named as "Khor Kalba Layered Gabbros Horizon" (North American Stratigraphic Code, 1983 and Bates and Jackson, 1980). A part of the Khor Kalba area (34.5 km^2, Fig. l-l) comprises non-cumulus ultramafic rocks (mainly harzburgite and dunite), massive gabbroid rocks, and a cumulus sequence of layered gabbros (3 km^2). Pegmatoidal gabbros and pyroxenite form vertical dykes and veins, few meters thick, cross-cut all the lithologic units.

The ultramafics are commonly fractured and variously serpentinized. They are bounded on the west by a thrust fault dipping east against the layered and massive gabbros. The massive gabbroic rocks comprise different rock types, whereas the layered gabbros, mainly troctolite and olivine gabbro, likely form microrhythmic unit and are ranked as a 'Horizon'. The phase contact is easily seen in the field (abrupt appearance and/or disappearance of cumulus min).

The layering is mostly isomodal and of a microrhythmic type (Fig. 2A) of very limited distribution and is restricted to the vicinity of thrust contacts (Fig. l-l). On the other hand, the massive-layered gabbros contact is inconspicuous and disturbed by minor faults and fractures. Also igneous lamination (turbulence layering) is well defined (Fig. 2B). Most layers maintain a dip ranging from almost horizontal to gently inclined (20-40ºNE). Evidence for magmatic flow is well recognized in the linear fabric and the preferred orientation of elongated minerals parallel to the flow direction.

The main characteristic features of layers and layering for Khor Kalba Layered gabbros Horizon are summarized in Table 1.

Bathnah Layered Gabbros Zone

Bathnah area (12.5 km^2) is located at 12 km from Al Fujairah (Al Fujairah-Masafi highway) (Fig. l-2). The ophiolitic slices in Bathnah area constitute non-

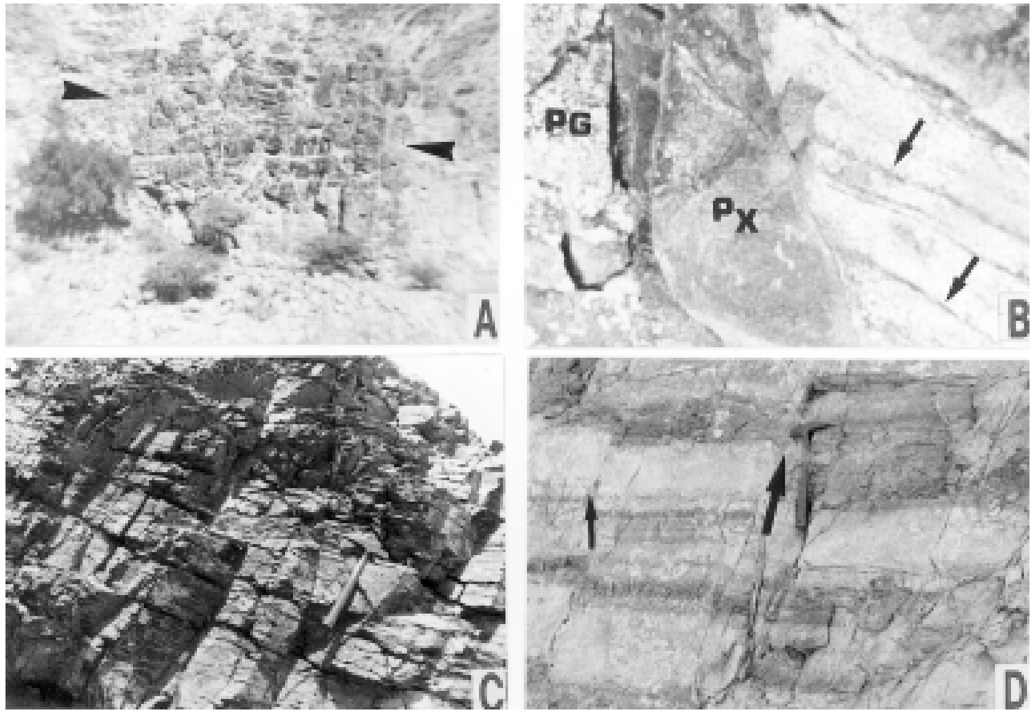


FIG. 2 – A. General view of microrhythmic layering (alternative bands of troctolite at the bottom and olivine gabbro at the top) "arrows". Khor Kalba Layered Gabbros Horizon: Note the disturbance and fragmentation of layers.
B. Modal lamination (inch-scale layering) striking NW and dipping N40ºE in gabbroid rocks invaded by Pyroxenite (PX) and pegmatoidal gabbro (PG) dikes, near ultramafic-mafic thrust contact, Khor Kalba area.
C. Cryptic layering striking N15ºW in gabbroid rocks at Bathnah area.
D. Continuous mineral rhythmic layering from olivine-and pyroxene rich (weathered dark colored bands) to light colored feldspar-rich bands. Faulting is indicated by arrows, Bathnah Layered gabbros zone.

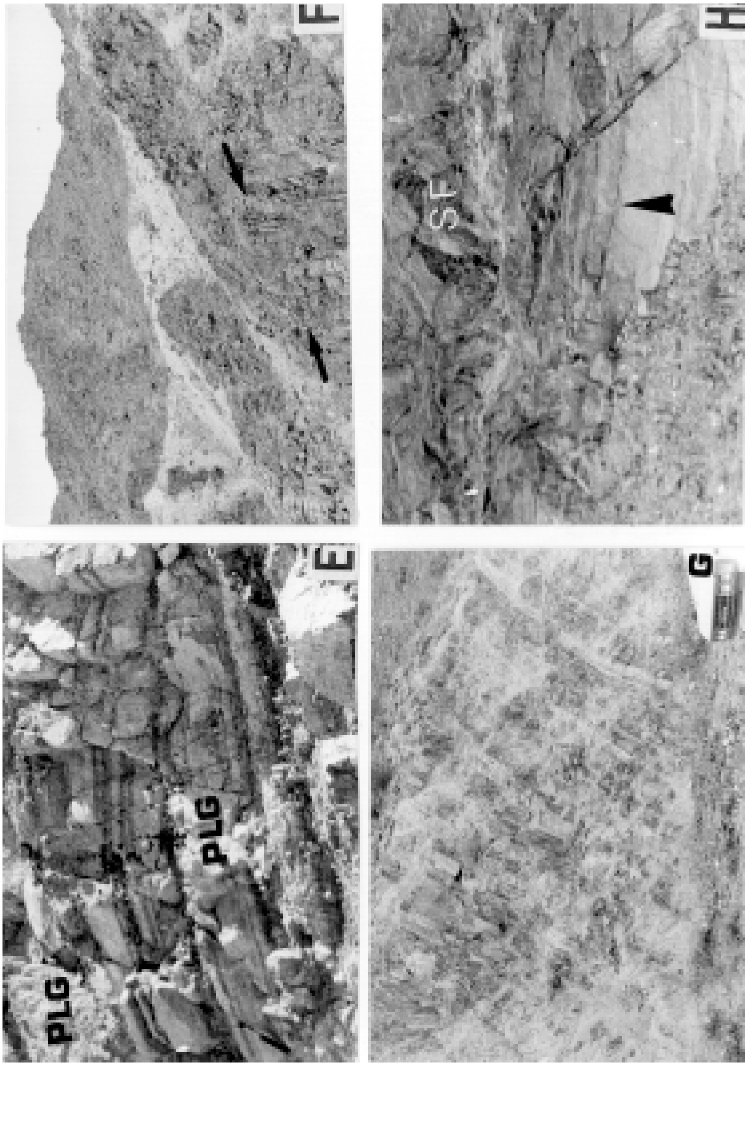


FIG. 2 – (Continued)

E. A sequence of modally-graded rhythmic layers, approximately 10 cm thick, invaded by plagiogranite pockets (PLG). 5 km SE Bathnah area.

F. Graded fragmental layer in gabbroid rocks, Khor Fakkan-Dibba highway. The inclined layering is largely restricted to the lower part "arrows". Khor Fakkan Layered Gabbros Zone.

G. Graded fragmental layers, dipping 55ºNE. The Same locality.

H. Cross-cutting layered gabbros, strongly deformed. Note a sheath fold (SF) and strong lineation "arrows", near Dibba town.

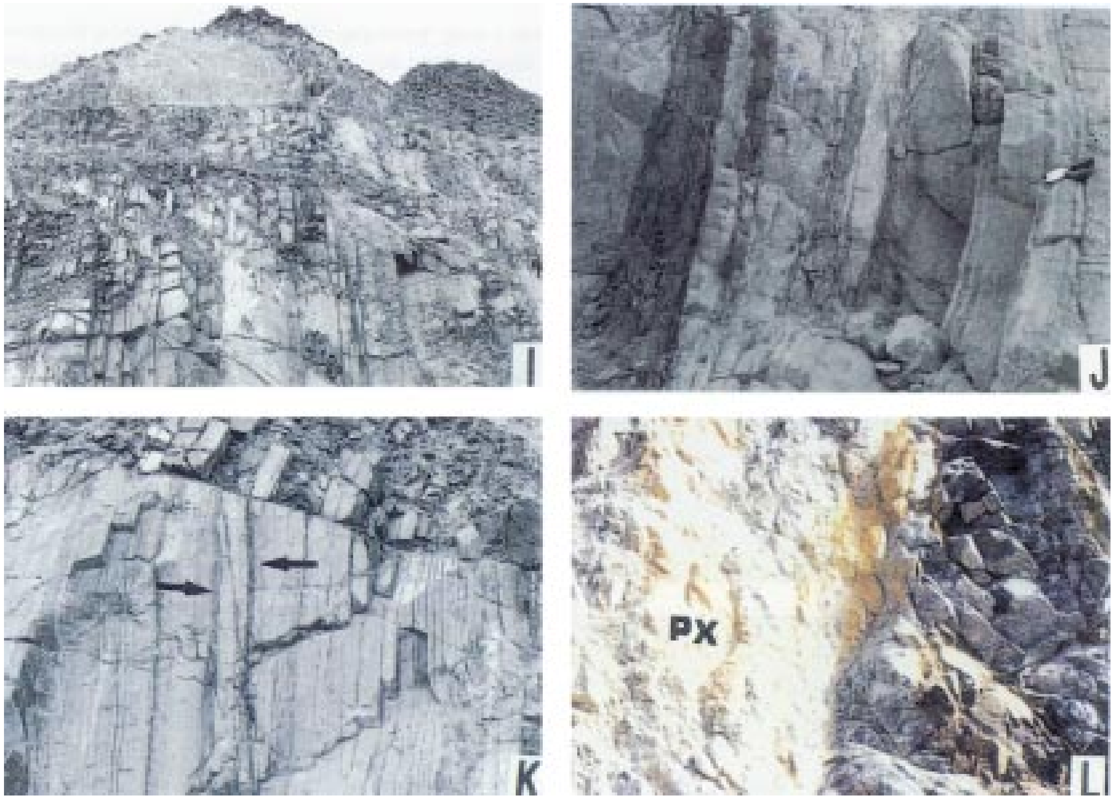


FIG. 2 – (Continued)

I. The layering with very steep dips of about 86º SE at Wadi Shi .

J. Inclined layers of variable thickness resembling a current deposited structures at Wadi Shi.

K. Graded layers (090º) from olivine gabbro (dark bands) to light anorthosite bands crosscut by pyroxenite veinlets "arrows". Wadi Shi.

L. Highly weathered pyroxenite dike (PX) crosscutting massive gabbros at Wadi Shi.

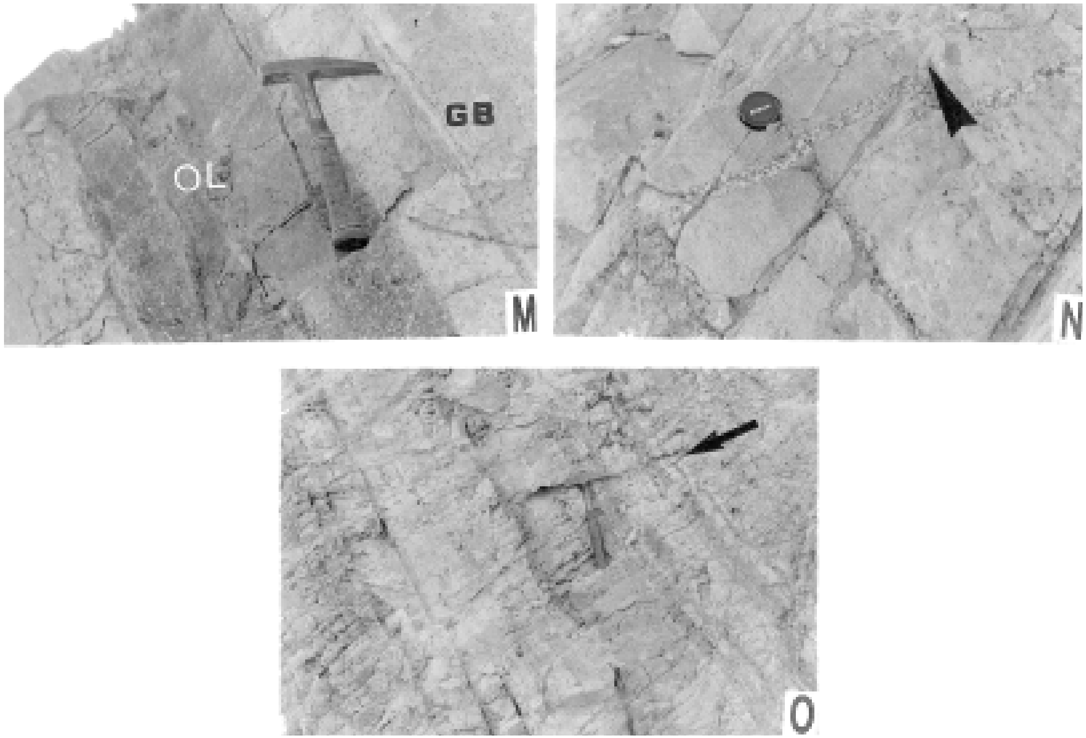


FIG. 2 – (Continued)

M. Phase contact between uniform troctolite cumulate thick layer (OL) and laminated gabbro (GB) near Masfut town. Wadi Hatta Layered Gabbros Zone.

N. Demarcation and flanking of joint sets filled with pyroxenite thin bands in leucogabbro layer. Note the irregular faulted pegmatoidal gabbros "arrows" at Wadi Hatta.

O. A sequence of modally-graded rhythmic layers (10 cm thick) is indicated by arrows. Note the irregular truncation and dying-out of the layers at the left of the photograph. Musfut town.

cumulus and cumulus gabbros. The first type of gabbro is dominantly massive and altered, where uralitization is commonly observed. Uralitized and non-uralitized gabbros are the main rock types therein. Faults trending NNE, NW and NE dissect these rocks (Fig.1-2). The cumulate "layered" gabbros (5 km) are best exposed along drainage channels and mountain slopes across the highway, where artificial and natural cuts are present. According to Wager and Deer (1939) and Irvine (1980), two main types of layering can be recognized in the outcrop; (a) cryptically- graded layering and (b) modally-graded rhythmic layering, therefore. The author suggests a proper name for these rocks as "cryptic-rhythmic unit".

TABLE 1. Characterization and field aspects of layers and layering for Khor Kalba Horizon.

Characterization	Field aspect
1. Layers:	
1.1 Thickness	thin (2-5 cm)
1.2 Form	planer to arched
1.3 internal constitution	uniform "isomodal", leuco and melanocratic variants, fragmental and pegmatitic
1.4 Layer contacts	phase" change in cumulus assemblage "and planar form
2. Layering:	
2.1 Lithology	modal lamination
2.2 Demarcation	prominent, rudely developed and faint
2.3 Regularity	irregular
2.4 Structure	slumped and deformed
2.5 Repetition	microrhythmic
2.6 Distribution and continuity	local and laterally continuous
2.7 Mode of origin	crystallization layering

(a) Cryptically-graded layering is defined petrographically as cumulus-mineral composition variations comprising troctolite, olivine gabbro and mesocratic gabbro. Its normal and continuous grading is remarkable (Fig. 2C). The contacts of the internal layers are gradational and individual layers cannot be followed for long distances because they pinch out after a few tens of meters and give way to rhythmic layering .

(b) Rhythmic layering with phase contacts (Figs. 2D&E) is defined by a conformable alternation between dark colored, olivine-pyroxene rich bands (norite and olivine gabbros), and light colored, plagioclase-rich bands (anorthosite). The former layers vary in thickness from 7 cm to 50 cm, whereas the latter ones vary in thickness from 5cm to 40 cm. The contacts of the internal layers are mostly sharp. The gradation of layering is also common in both directions.

Most layering strikes NNE, NW and NE with the vector mean (mean azimuth computed from field data) being 7 degrees (Fig. 3), and the confidence interval (true population mean direction) is 10.5 degrees. The dip ranges from 3-15º NW&NE. Some faults trending NW dissect these rocks. Pockets and veins of plagiogranite also invade the layered gabbros (Fig. 2E). The main characteristic features of the layers and layering in Bathnah area are summarized in Table 2.

TABLE 2. Characterization and field aspects for layers and layering of Bathnah Layered Gabbros Zone.

Characterization	Field aspects
1. Layers	
1.1 Thickness	cryptic to medium thick (5-50cm)
1.2 Form	planar to trough
1.3 Internal constitution	stratigraphically variable, leucocratic to melanocratic
1.4 Layer contacts	cryptic cumulus appearance and phase contact, planar form
2. Layering:	
2.1 Lithology	cryptic and modal
2.2 Demarcation	prominent
2.3 Regularity	mostly regular
2.4 Structure	deformed
2.5 Repetition	cryptic to rhythmic
2.6 Distribution and continuity	intermitted to stratigraphically variable
2.7 Mode of origin	crystallization-current layering

Khor Fakkan layered Gabbros Zone

Khor Fakkan area (Fig. 1-3) represents a part of Dibba Zone (Fig. 1) which is a transition between Late-Paleozoic-Mesozoic continental margin and an ocean basin. This critical area links a continental-ocean boundary to the SE in the Gulf of Oman (Robertson *et al.,* 1990a). The area under study covers about 106 km^2, out of which some 44 km^2 is occupied by layered gabbros. In the present mapped area, three lithologic units are well defined from top to bottom as follows :

Massive gabbros

Layered gabbros

Ultramafics (mainly tectonite peridotite and cumulate serpentinites)

The ultramafic-layered gabbros contact forms a large northwesterly thrust sheet (Fig. l-3) bounded to the east by Wadi Shi fault zone. A much-faulted, smaller allochthonous of layered gabbros lies to the north and south and partly

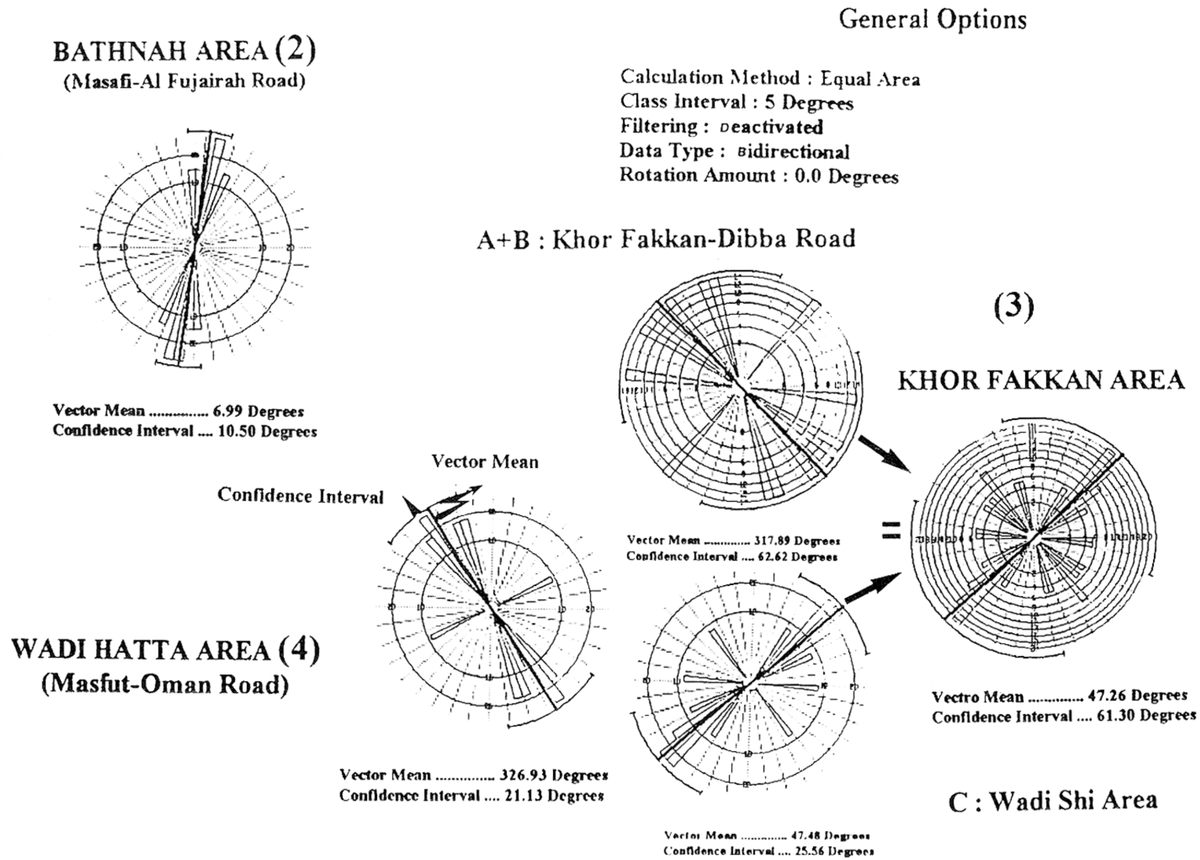


FIG. 3. Rose diagrams are based on orientation data collected from the field for the layering in gabbroid rocks of three selected areas. Data plotting are base on Rose 2-D Orientation Analysis and Plotting (Rockworks Application, Ver. 1, 1991).

beneath the mean ultramafic mass. Mafic cumulate of layered gabbros conformably overlie the ultramafics. Most of the sequence displays stratiform features ranging, on gross to small-scale from troctolite, olivine gabbro, gabbronorite, uralitized gabbro at the base to anorthosite at the top. The attitude of layers vary from northeastward dips (roughly parallel to the massif) to northwestward dips. Minor exposures of non-cumulus "massive" gabbros cover about 6 km^2. They form scattered and discontinuous outcrops exhibiting varying degrees of alteration and deformation along Khor Fakkan-Dibba road (Fig. l-3).

Khor Fakkan layered gabbro zone could be subdivided into two subzones: the Khor Fakkan-Dibba Road Subzone (marked by A&B in Fig. l) and Wadi Shi Subzone (marked by C in Fig. 1).

1. Khor Fakkan-Dibba Road Subzone

Excellent examples of well-preserved layering (19 km^2) are found along the paved road between Khor Fakkan and Dibba towns forming scattered and discontinuous exposures (Fig. l-3). A graded-fragmental rhythmic layering (Figs. 2-F-H) is remarkable that the fragments indicate that the layering is a current layering and that the rock is a depositional cumulus (Irvine, 1982), a "graded-rhythmic unit".

Jackson (1967) proposed that such graded layers be classified as 'size graded', 'mineral graded' or 'chemical graded' depending on the grading in the grain size, modal abundance or chemical composition of the cumulus minerals. The present layered subzone constitutes a typical rhythmic grain-size layer featuring grain-size graded layers and sharply defined grain-size laminae. On the other hand, the graded fragmental layers, nearly vertical (Figs. 2F & G) exhibit grading which is largely restricted to the granular upper part of the layer, so called "delayed grading" (Irvine, 1982). Cross-cutting oblique layers of gabbros, near Dibba town (Fig. 2H) are strongly deformed and magmatic lineation may be dispersed on the same outcrop from one layer to the next.

The layering trends to the NW and less commonly to the NE, the vector mean being 317.89 degrees (Fig. 3) and the confidence interval is 62.63 degrees. The attitude of dips vary from 20º to 70º NE. The characteristic features of the layers and layering for Khor Fakkann- Dibba road Subzone are given in Table 3.

2. Wadi Shi layered Gabbros Subzone

Wadi Shi Subzone covers an area of about 25 km^2 (Fig. l-3). It constitutes a large masses and bodies of layered gabbro (alternating bands of troctolite, olivine gabbro, gabbronorite and anorthosite) as well as minor exposures of massive, highly altered and uralitized gabbro. Layering is generally of NE strike and dips steeply (75º-90º) to the NW (Fig. 3); the mean vector being 47.49 degrees and the confidence interval is 25.58 degree. The nature of the layering in Wadi Shi is quite similar to that of the Khor Fakkan-Dibba road subzone. Some layers are steeply oriented (Figs. 2 I, 2J and 2K). Also many pyroxenite veins and dykes of variable thickness, a few centimeters to some meters, invaded both layered gabbros (Fig. 2K) and massive gabbros (Fig. 2L). Disturbance, slumping and fragmentation of layering are also reported along Wadi shi fault zone. Layering in the Khor Fakkan area strikes mainly NE, NNE and less commonly NW, with a vector mean of 47.26 degrees and a confidence interval of 61.30 degrees (Fig. 3).

TABLE 3. Characterization and field aspects for layers and layering of Khor Fakkan-Dibba Road Subzone.

Characterization	Field aspects
1. Layers :	
1.1 Thickness	medium-thick (5-30cm)
1.2 Form	trough to planar
1.3 Internal constitution	uniform, leuco-melanocratic, fragmental.
1.4 Graded layers	grain-size graded, texturally graded, normal, continuous and recurrent grading
1.5 Layer contacts	grain size and planar form
2. Layering :	
2.1 Lithology	grain-size
2.2 Demarcation	prominent
2.3 Regularity	mostly regular
2.4 Structure	slumped and deformed
2.5 Repetition	graded rhythmic
2.6 Distribution and continuity	intermittent
2.7 Mode of origin	crystallization -current layering

Wadi Hatta Layered Gabbros Zone

Wadi Hatta area (Fig. 1-4) covers about 282 km^2 and represents a part of the Hatta Zone (Fig. 1). This zone was interpreted as 50 km long left lateral of the north Oman passive continental margin that was generated by right-lateral transform faulting during spreading of Neo-Thyses ocean (Robertson *et al.* 1990 b). El Bayoumi and Heikal (1992) studied the geology of south Wadi Hatta, NE of the present area. This area can be considered as an ideal zone exhibiting the contact between ophiolitic Rocks with the underlying Hawasina basinal sediments.

The area under study constitutes three distinct units (Fig. l-4) as follows from top to bottom:

Semail ophiolite

- Massive gabbros (unmappable at the present scale)
- Layered gabbros
- Ultramafics (mainly harzburgite and serpentinites)

Hawasina Complex (basinal sediments)

- Bedded radiolarian cherts
- Cherty limestones

Sumeini Group (slope sediments)

- Crystalline limestone

The ophiolitic rocks are found either as mountainous blocks or as fragments incorporated in melange mixture. The ultramafics are composed of harzburgite representing the refractive residue of the crystallized original magma as well as serpentinites, which constitute the main bulk of the ultramafic masses. Signs of slumping, deformation and tectonic metamorphism are common.

The layered gabbros of the Wadi Hatta zone (25 km^2) are found as separate mountainous blocks crossed by the Masfut-Oman highway at the southern end of the mapped area (Fig. l-4). Thrust contact dipping towards the ultramafics is distinct, where a disturbed and discordant layering is notable. Modally-graded rhythmic layering is the main rock type (Figs. 2M&O) "graded-rhythmic unit". This type of layering is well developed, where light-rich bands alternating with dark-rich bands are well observed from a distance. The thickness of both felsic layers representing leucogabbros and anorthosite as well as mafic layers representing troctolite, olivine gabbros and norite is variable. Generally speaking, the felsic bands are thicker than the mafic ones. A modally-graded rhythmic layering constitutes a conformable alternation between light-colored bands (10 cm - 1 m thick) and dark-colored bands (7 - 90 cm). This contact is mostly phase (Fig. 2M) and sometimes modal (Fig. 2O). Individual layer can be followed for long distance, more than 200 meters, especially near Masfut town, where the mode of preservation and attitude of the layering are distinguished. The orientation of the layering is mostly NW (Fig. 3). The mean vector being 326.93 degrees and the confidence interval is 21.31 degrees. The dip ranges from 19º to 55º NE & SE. Some layers at the tectonized and alteration zones die out and show irregular and weak lineation. The gabbros are invaded by plagiogranite veinlets and pyroxenite as well as pegmatoidal gabbro dykes (Fig. 2N). Deformation effects such as fractures, joints and minor faults are approximately parallel to the layers.

The main characteristic features of the layers and layering for Wadi Hatta layered gabbro across Masfut-Oman highway are summarized in Table 4.

TABLE 4. Characterization and field aspects of layers and layering of Wadi Hatta area (Masfut-Oman Highway) Layered Gabbros Zone.

Characterization	Field aspects
1. Layers:	
1.1 Thickness	medium-thick (7 cm - 1 m)
1.2 Form	trough to planar
1.3 Internal constitution	uniform, leuco to melanocratic, pegmatitic
1.4 Graded layers	modally graded, normal, continuous and sometimes interrupted grading
1.5 Layer contacts	phase and modal, planar form
2. Layering:	
2.1 Lithology	modal
2.2 Demarcation	prominent
2.3 Regularity	mostly regular
2.4 Structure	slumped and deformed
2.5 Repetition	rhythmic
2.6 Distribution and continuity	laterally variable
2.7 Mode of origin	current layering

Petrography

The petrographic characteristics of the layered gabbros are used to interpret the mode of origin of the layering. The following rock types are distinguished throughout the four zones of layered gabbros starting from top:

1. Anorthosite
2. Leucogabbro
3. Gabbronorite & norite
4. Olivine gabbro
5. Troctolite

The cumulus minerals are listed in decreasing order of abundance in Table 5.

TABLE 5. Conventional rock names for common of gabbroic cumulates.

Cumulate type	Conventional rock name
Plagioclase	Anorthosite
Plagioclase-augitic clinopyroxene	Gabbro
Plagioclase-orthopyroxene-clinopyroxene	Gabbronorite
Plagioclase-olivine	Troctolite

The petrographic characteristics of the gabbroic cumulates are summarized as follows:

1. Anorthosite unit in the rhythmically layered interval contains 98-99% plagioclase (An_{80}) with 1-2% intercumulus clinopyroxene, mainly bronzite (Fig. 4A). The average of grain size of both plagioclase and clinopyroxene ranges are 1.3 to 0.9 mm respectively. Petrographic evidences for deformation of some samples include spindle-shaped twin lamellae in plagioclase and gently to strongly bent cleavage traces in pyroxene.

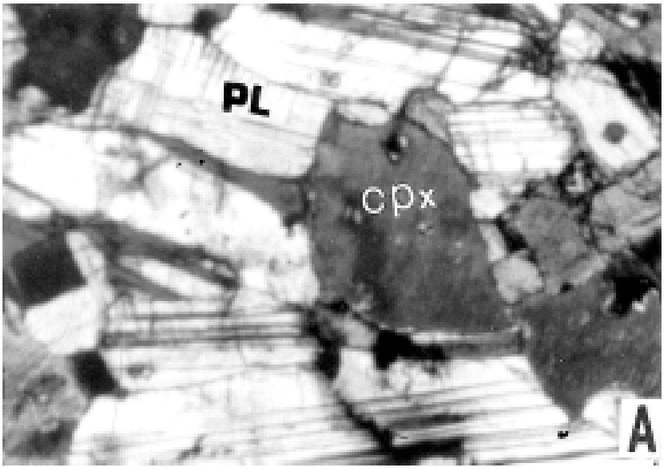
2. Leuco-normal gabbro unit has sharp contact with overlying anorthosite layers. Gabbro contains a framework of cumulus plagioclase of labradorite composition (An_{55}) (Fig. 4B), augitic clinopyroxene and minor olivine with intergranular spaces filled by small xenomorphic grains of orthopyroxene, mainly enstatite. The pattern of association of essential minerals reflects a typical cumulate texture. Deformation effects upon all mineral constituents indicate plastic squeezing, generating the apparent draping features.

3. Gabbronorite unit (plagioclase, hypersthene, augite, bronzite ± olivine ± hornblende) is rhythmically layered. Texture is mostly cumulate, where plagioclase (An_{60}) defines a strong lamination and occurs as interstitial post-cumulus material (Fig. 4C), whereas hypersthene, augite and olivine occur as nucleated crystals. Olivine occurs as flattened, elongated grains due to deformation.

4. Olivine gabbro-Troctolite unit (olivine, augitic clinopyroxene and plagioclase in addition to enstatite, magnetite cumulus minerals). Plagioclase (An_{65}) is cumulus, whereas olivine and pyroxene are to be nucleated crystals (Fig. 4D). Small percentage of late interstitial orthopyroxene is common, and occasionally constitutes small oikocrysts. The grain size is generally few millimeters (1 × 3 mm for typical plagioclase and CPx cumulus crystals), it may be larger in troctolite (approximately 5 mm) and even more in the recrystallized pegmatitic parts occurring throughout the sequence.

Discussion

The origin of layering has been attributed to several different processes, including current deposition (Wager and Deer, 1939; Wager and Brown, 1968; Irvine, 1980, Jaupart and Brandeis; 1986 and Conrad & Naslund, 1988), rhythmic nucleation events (Maaloe, 1978) and in situ crystallization (McBirney and Noyes, 1979; McBirney & Russell, 1986). These theories imply significantly different modes of crystallization for the layered intrusions. The following is a brief summary of these theories.



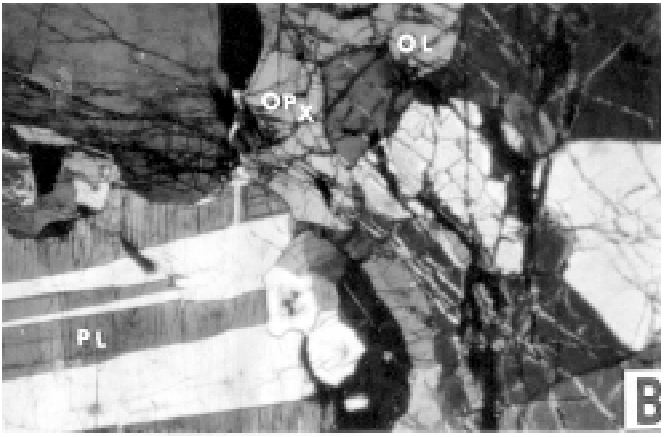
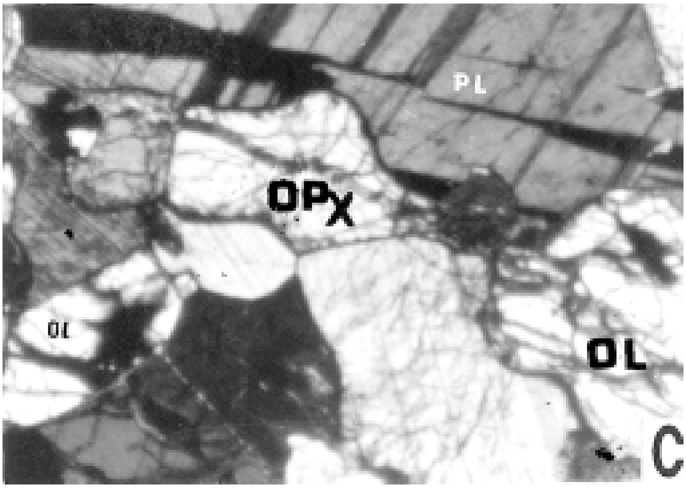


FIG. 4 – A. Cumulus plagioclase (PL) with very minor intercumulus clinopyroxene (CPx), anorthosite, Khor Fakkan area. C.N., × 30.
B. Gabbroic cumulate showing cumulus labradorite (PL) and clinopyroxene (CPx), normal gabbro, Wadi Hatta area. C.N., × 30.



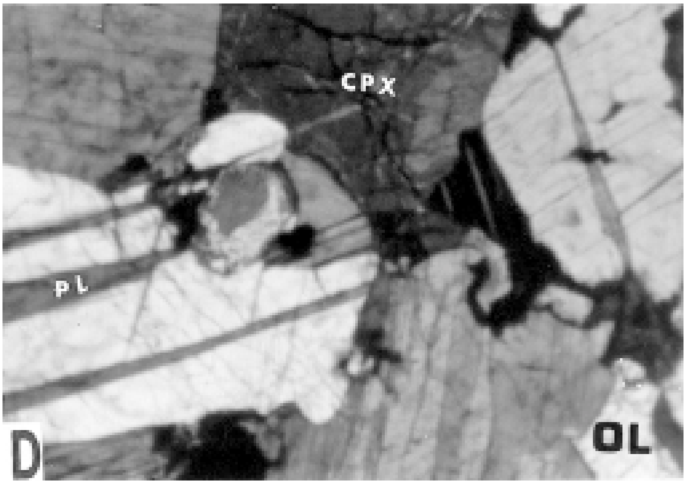


FIG. 4 – C. Cumulate gabbronite showing irregular crystals of orthopyroxene (OPx) intergrown with plagioclase and olivine (OL), Wadi Shi, C.N., × 30.

D. Cumulus labradorite (PL) and olivine nucleated (OL) attached to augitic clinopyroxene (CPx), olivine gabbro, Khor Kalba area, C.N., × 30.

Current deposition: Wager & Deer (1939) originally postulated that the layers were the result of convection currents winnowing the upper part of the crystal pile to produce gravity-stratified layers. Wager & Brown (1968) later suggested that the layers were formed by density currents which periodically detached from the roof and walls of magma chamber and deposited as layers on the floor of the chamber.

Rhythmic nucleation: Maaloe (1978) suggested that this process for gross and small-scale modally-graded rhythmic layers of the Skaergaard intrusion. In this theory, crystal nucleation occurs in periodic bursts followed by episodes of rapid crystal growth during which denser crystals settle to the bottom of the magma chamber faster than less dense crystals.

In situ crystallization: McBirney & Noyes (1979) postulated in situ crystallization after demonstrating that the plagioclase was lighter than the Skaergaard magma throughout most of the crystallization history of the intrusion. They suggested that crystallization occurred in a static zone around the margins of the intrusion and proposed two different processes by which the layers could have formed. The first process involves heat diffusing downward from the overlying magma. It also involves chemical components diffusing upward from the crystallization front which lead to oversaturation with respect to different minerals at different levels in the static zone. The second process involves the development of vertically stacked double diffusive convection cells within the static zone, which result in layering as the magma crystallizes.

The origin of layering in Oman "Semail" ophiolite was discussed by few workers; Coleman (1977), Hassan and Al Sulaimi (1979), Gass, (1982) and Reuber (1990).

Coleman (1977) assumed that the layering in the gabbros developed as a result of gravity settling, and that the overlying sheeted dikes representing filled fractures developed at spreading ridge and the layered gabbros (steeply inclined) were contemporaneous. He also reported that the layering in the Semail ophiolite indicates cyclic events. Hassan & Al Sulaimi (1979) proposed a model of origin for layering in NW Al Fugairah based on rhythmic nucleation and in situ crystallization theories. Reubeer (1990) proposed a model for the generation of the cumulate sequence in the northern Oman ophiolite by inflation of the transition zone: Tholeiitic magma generated at depth infiltrates the uppermost mantle and induces supplementary partial melting until this zone becomes unstable and bulges upwards. The feeder zone of these magma bodies could be traced to massive gabbros showing a vertical fabric, whereas large amounts of magma intrude sideways into pre-existing more or less solidified cumulus as sills, thereby creating the most frequent type of layering.

In the present work, rhythmic layering constitutes the main type with respect to cryptic layering in Bathnah Zone. The idea of a rhythmic unit was first applied by Brown (1956) to a layered succession that is repeated ten times in the Rhum intrusion.

As far as the author is aware, no such characterizations of layering in gabbroid rocks have been reported in literature of Semail ophiolite in United Arab Emirates.

The cumulate gabbroic rocks are well exposed in four areas and display stratiform features such as planar lamination (2-5 cm thick) of microrhythmic unit in the Khor Kalba horizon; cryptic layering (sequence of troctolite, olivine gabbro and mesocratic gabbro) with mineralogical variations and rhythmic layering (5-50 cm thick) with phase contacts in the Bathnah Zone; graded-fragmental rhythmic layering (3-30 cm thick) of graded- rhythmic unit in the Khor Fakkan Zone; and madally-graded rhythmic layering (7 cm - 1 m thick) in the Wadi Hatta Zone.

In normal cases, layers originate in horizontal or near horizontal planes as seen in the Khor Kalba and the Bathnah areas, where layers are mostly horizontal to gently inclined. However, igneous layering is not necessarily in an initially horizontal position, where inclination being steep in the upper layered gabbros, decreasing to small angles in the transition zone and ultramafic cumulate (Komer and Elthon, 1990). These geometric relationships suggest that the upper-level layered cumulates formed by in situ crystallization along the walls of the magma chamber rather than by crystal settling or current deposition (Casey and Karson, 1981). In Wadi Shi layered gabbro subzone (Khor Fakkan area), the layers appear to have formed with their steeply inclined and vertical positions (Fig. 2I, 2J and 2K), also some layered facies crosscut or deformed the earlier ones (Fig. 2H). Sheeted dykes are found to the SW of Wadi Shi; their trends are quite similar to the layering trend of Wadi Shi.

The author suggests that the crystals in the steep layers were formed in situ on cooling walls or they were plated onto the walls by density of convection current. Also steep inclination of layering are of early origin. They were steepened by consecutive magma intrusions or occasional vertical magmatic flow (Coleman,1977 and Reuber, 1990).

The field and petrographic data indicate that other origins may apply to the layering :

1. Layers with sharp phase contacts, often with contrasting composition and intensity of preferred mineral orientation parallel to the flow line as recognized in the Khor Kalba horizon, indicate crystallization layering due to in situ crystallization processes.

2. Layers exhibiting grain size and modal variation with gradual or sharp contacts are likely related to current layering. Elsewhere, the layers are more or less modally-graded with plagioclase concentrated at the top of the layer and pyroxene above the base and olivine and iron oxide minerals at the base of the layers. These characteristic could be the result of gravitational sorting mechanism for the formation of the layers. Also some layers exhibit a number of distinctly sedimentary-like structure including trough-shaped layers and laterally graded layers. The author suggests that these layers are the result of periodic interaction between convection or density currents in the magma and a zone of crystallization on the floor of the magma chamber. This suggestion provides a mechanism, which could have produced gravity-stratified layers with sedimentary-like structures in the intrusions where crystallization occurred essentially on the floor of the magma chamber.
3. The most common small-scale rhythmic layered units consist of an olivine-rich base grading up to an olivine-free plagioclase-clinopyroxene upper part as shown in Bathnah area. The texture can be explained as a concentration of olivine by gravity settling or continued growth of nuclei (Khor Kalba area). Moreover, the nucleation and growth of clinopyroxene and plagioclase in the upper part is best explained by in situ crystallization .
4. Irregular layers of relatively minor occurrences in different layered zones can be explained as segregation of interstitial liquid during compaction (Reuber, 1990).

The author proposes that the studied layers result from periodic disruption of a static zone of crystal growth on the floor of the magma chamber by convection or density currents. This mechanism, however, is almost certainly not responsible for the formation of all types of layering found in the Semail ophiolite.

Church (personal communication, 1997) stated that "it is conceivable that in ophiolite layered sequences a substantial part of the mineral crystallization and fractionation takes place in the conduit through which magma passes from the mantle into the spreading zone magma chamber. First order crystallization is therefore gradational but confined to the conduit. Within the magma chamber crystallization takes place at the roof which is growing downwards, and the roof gabbros so-formed are heterogeneous, only very crudely layered, and pass upwards into the sheeted diabase unit. Periodically, the crystals in the magma conduit are flushed out into the magma chamber and settle again under the action of gravity to form phase and size-layered units. He added that the layered units may subsequently be subject to metasomatism as well as deformation during sea-floor spreading and obduction subject to all processes, the layering in ophiolite gabbro bodies may be very complex".

On the basis of the analysis of layering orientation, the recognized major trends are consistent and compatible with the major tectonic framework of United Arab Emirates (Dunne *et al.* 1990). Layering in Wadi Hatta trends NW (Hatta zone), whereas in the Khor Fakkan zone trends NE (Dibba zone). To the Bathnah zone, the layering trends NNE (N-S obducted fault Semail ophiolite). Benn and Allard (1989) claim that the lineation and foliation in layered gabbros from the lower crustal section of Oman ophiolite are oblique with respect to the compositional layering and result from magmatic shearing. Layering in Khor Fakkan zone is however steep to vertically dipping and varies in strike from N42W to N48E (Fig. 3). The vertical layering has been interpreted by Murphy and Hynes (1990) to be result of progressive and multiple injection of appinitic magma from either an interstitial liquid or a subjacent body of magma into fracture. The present work demonstrates that the orientation of the gabbroic layering has been controlled by the regional tectonism.

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الطباقية في صخور جابروية من أفيوليت سمائل ، الإمارات العربية المتحدة : الخصائص ، التحكم التكتوني في النشأة والتوجيه

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المستخلص . يتواجد الجابرو الطباقي بصورة واضحة في أماكن متعددة في أفيوليت سمائل (الكريتاسي المتأخر) خلال نطاقات معينة . وطبقا للدراسة الحقلية و المجهرية لتلك الصخور أمكن تحديد خصائصها ومميزاتها الطباقية المتنوعة شكلا ووفرة وسلوكا . وقد أوضحت الدراسة أن معظم الصخور الطباقية تميل بشدة لدرجة الرأسية وقليلا منها يكون التطبق أفقيا .

وترجع نشأة تلك الطباقات إلى ثلاثة عوامل : التبلور في موضعه الأصلي ، الترسيب التياري أو كلاهما معًا ، علمًا بأن العامل الأول هو الرئيسي لتلك النشأة . وقد أوضحت الدراسة أيضًا أن اتجاهات الطباقية متوافقة إلى حد كبير مع الاتجاهات التركيبية لدولة الإمارات العربية المتحدة .