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The Structural Evolution of the Qadda Area Southern Precambrian Shield of Saudi Arabia

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ABSTRACT. The Qadda area in the southern part of the Arabian Shield is composed mainly of metamorphic rocks. It can be divided into four structural subareas, 1) the Supracustal Synform, 2) the Marble Complex, 3) the North West Gneiss Dome, and 4) the North East Gneiss Dome. Two phases of deformation have effected almost all the rocks exposed throughout these four subareas. The first phase (D_1) is mainly characterised by a strong foliation and lineation (large-scale tight folding of this age is also recognized in the marble complex subarea). The second phase (D_2) is characterized by doming in the north-western and north-eastern parts, and by large-scale open folding in the areas occupied by rocks of the banded supracrustal sequence. Some parts of the North-East Gneiss Dome appear to show an older foliation which is refolded by D_1 and represent the earliest phase of deformation (D_0). A mechanism for the formation of the domes is suggested.

Introduction

The Qadah area lies in the north-eastern corner of Khaybar quadrangle between 42°55′ and 43°00E and 18°53′ and 19°00N (Fig. 1). Most rocks in this quadrangle are Precambrian in age and represent deep erosion of the Arabian Shield. The layered rocks are divided into two distinct units: (1) the basement complex (infrastructure) of Asir Mountains, and (2) younger metamorphic rocks (suprastructure) that may be part of or equivalent to the Hali or Bahaha Groups (Schmidt *et al.* 1973).

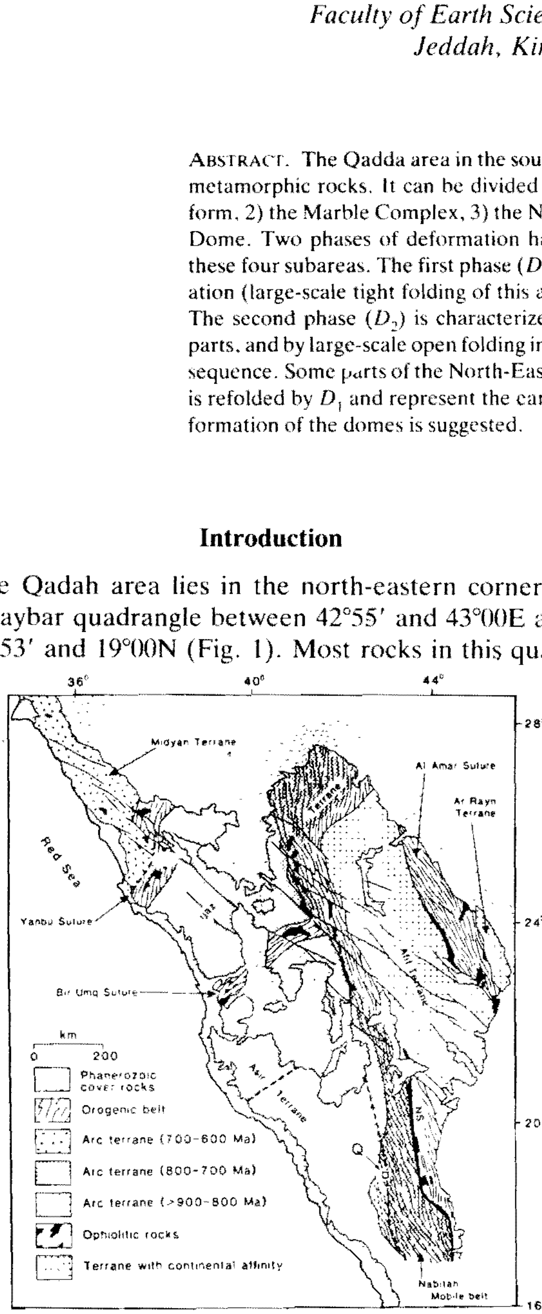

FIG. 1. Tectonic map of the Arabian Shield (after Stoeser and Camp 1985). Q= Qadda area; NS = Nabitah suture zone (published with permission of the Geological Society of America).

The basement complex consists of orthogneiss, paragneiss, migmatite, amphibolite and marble and these rocks are collectively referred to in Coleman's (1973) report as Khamis Mushayt Gneiss, which has been plastically folded and represents a very complex history of metamorphism and plutonism. Overlying it unconformably is a thick series of metamorphosed and interlayered peltic sedimentary and mafic volcanic rocks (younger metamorphic rocks). Basal conglomerates or marked angular unconformities is present along the contact between Khamis Mushayt Gneiss and these younger metamorphic rocks. The maximum grade of metamorphism is green schist facies (Coleman 1973). The studied area may be divided into four structural subareas (Fig. 2) within which the structures show a reasonably consistent pattern (Al-Filali).

1. The Synform subarea which is occupied mainly by quartzo-feldspathic schist, a variety of amphibolites, marble, calc-silicate rocks, cordierite biotite schist and post tectonic granites and gabbros,

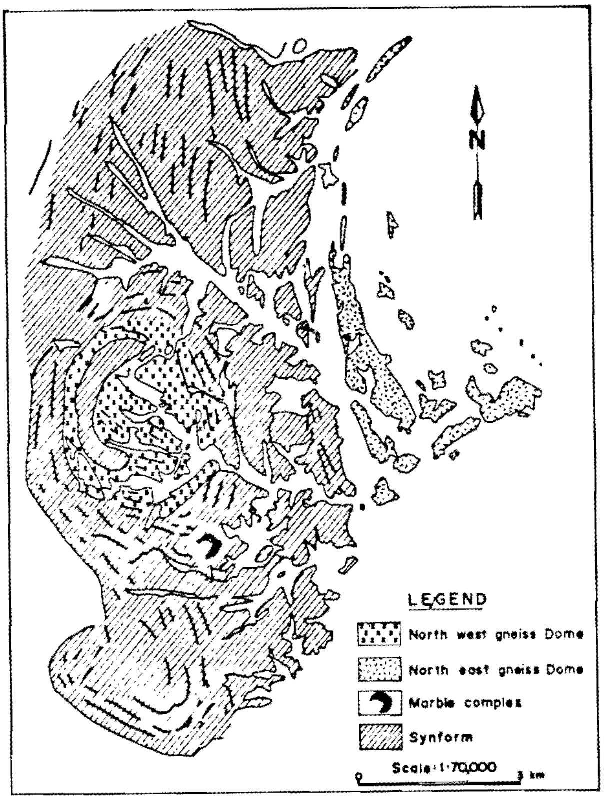

FIG. 2. Map showing main four subareas.

2. The marble complex subarea, which is occupied by marble, quartzo-feldspathic schist and amphibolite,

3. The Northwest Gneiss Dome subarea, which is occupied by granite and granodioritic gneiss, tonalitic gneiss, amphibolites and post tectonic granite, and

4. The Northeast Gneiss Dome subarea, which is occupied by granitic gneiss, garnet-silimanite gneiss, pink granitic gneiss and amphibolite.

The Synform Subarea

One of the main features of the supracrustal rocks in this subarea is the compositional banding. Individual bands tend to maintain a constant thickness (5 mm-30 m), the thicker bands commonly traceable for several hundred meters. Most lithologies (quartzo-feldspathic schist, amphibolites and calc-silicates) have, on a hand specimen scale, a strongly developed schistosity, representing the earliest planar structure of metamorphic origin recognized in this subarea, in addition to the compositional banding. Throughout this subarea, these two planar features appear to be parallel (though this is not the case in all subareas) and, where both are present, form a composite foliation. This schistosity (S_1) is most strongly developed in lithologies rich in biotite or prismatic minerals, but may also be defined partly by quartz and plagioclase shape fabrics. The schistosity is weak or absent in massive marble, biotite-poor quartzo-feldspathic schist and wollastonite free calc-silicates. Amphiboles or wollastonite grains defining S_1 commonly show a strong mineral elongation lineation which is thought to be of the same age. Small scale isoclinal folds have been found in many places (Fig. 3a). The axial planes of these isoclinal folds are parallel to S_1 schistosity, suggesting that both schistosity and isoclinal folds were produced in the same phase of deformation (hereafter called D_1). In the same places, this limbs have become so attenuated that only isolated folds hinges remain, producing quartz rodding lineation. Where thin quartzite layers within quartzo-feldspathic schist have been folded in this way, a spectacular "broom-handle" rodding has been produced. No large scale fold of D_1 age have been identified in the "Synform" subarea.

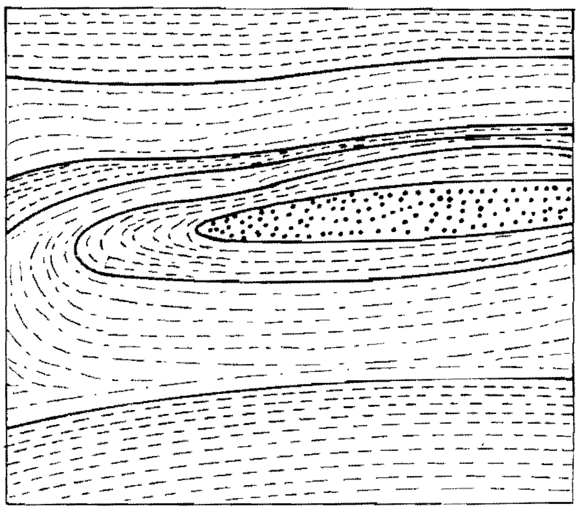

FIG 3a. Intrafolial isoclinal fold of a quartzo-feldspathic layers in the banded supra crystal sequence.

Boudins of calc-silicate rock occur locally within thinly banded amphibolite; their axes are oriented, roughly at right angles to the D_1 lineation, perhaps indicating stretching along the lineation and also that the boudinage was produced during the D_1 phase of deformation.

The "Synform" subarea also suffered from a second phase of deformation (D_2). This deformation generated the large-scale asymmetrical synform that controls the outcrop pattern of the subarea as well as a variety of locally developed minor structures such as kink folds and crenulation lineation.

The recognition of this subarea as a large synform is based on the observation that both the lithological banding and S_1 schistosity (composite foliation) are folded, and can be traced from one limb to the around the fold hinge that closes downwards. Several open and gentle minor folds have been recognized in this subarea, especially in the eastern limb of the major synform; these fold the S_1 schistosity and are, therefore, thought to be of the same age as the synform itself. The D_2 folds vary in size from a few centimeters to several meters. Some micaceous rocks with abundant quartz veins lying in S_1 have developed an axial quartz rodding lineation and were tightly crenulated by D_2 folds. Mineral elongation lineation is commonly observed to be parallel to the main D_2 synform axis, but at some localities this lineation has been folded by D_2 folds indicating that the lineation has the same age as D_1. A second generation of lineation (crenulation lineation) can be seen at the same localities at right angles to the D_1 lineation and parallel to the F_2 fold axis.

From the evidence given above, the rocks of the "Synform" subarea have clearly suffered from the two phases of deformation. The first one was evidently an extremely intense deformation, resulting in very high strain in the supracrustal rocks. The second phase of deformation (D_2) was less intense and did not produce any penetrative fabric.

The Northwest Gneiss Dome

The northwestern gneiss dome of the present study consists of granite gneiss overlain by rocks of the banded supracrustal sequence. The granitic rocks in the core of the dome are not obviously foliated, but close to the contact with the country rocks, they are strongly foliated. The foliation, the contact, the layering and schistosity in the supracrustal rocks are all parallel to one another and generally dip outward away from the gneiss dome core. In the supracrustal rocks, the foliation is essentially same as described above for the synform subarea. Boudinage is common. Amphibolites close to the margin of the dome are locally interbanded with granite gneiss on a small scale, and at some localities, these veins of granitic gneiss in amphibolite have clearly been isoclinally folded. The axial planes of these folds are parallel to the schistosity in the amphibolite, indicating that these isoclines are of the same age as those described in the synform subarea, *i.e.*, D_1. The axes of these folds are parallel to the stretching lineations described below.

In the granitic rocks, the foliation is defined by a planar arrangement of flattened quartz-feldspathic and mafic aggregates.

Several types of stretching lineations are found in this subarea. The granitic gneisses themselves carry a feldspar rodding and, parallel to it, a lineation defined by elongated streaks of hornblende and/or biotite is developed. The lineations in the supracrustal rocks resemble those described above for the synform subarea. In the abundant amphibolites close to, and within, the dome itself, the most common type of lineation is defined by an alignment of hornblende prisms. The orientation pattern of the lineation is crucial in establishing their relationship with the dome. If the stretching lineation had been produced during doming (model 1 in Fig. 3b), they should form a radially sym-

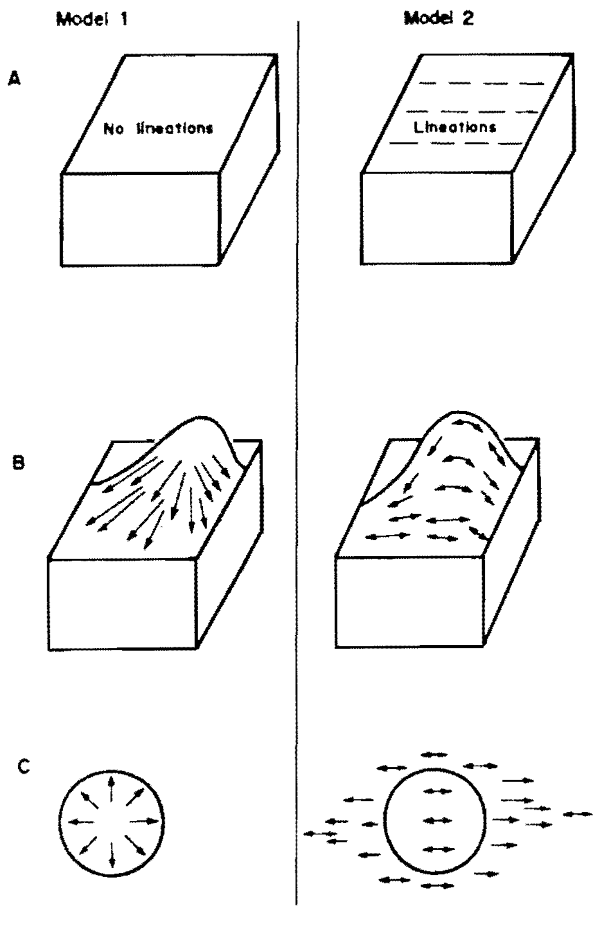

FIG. 3b. Lineation patterns in gneiss domes:
A. Block diagram showing pattern before doming
B. Block diagram showing pattern after doming
C. Plan view of pattern after doming.

metrical pattern. This is not what is observed. At the northern and southern sides of the dome, lineation plunges steeply outward, but in the core and at the eastern and western sides of the dome the lineations are subhorizontal and parallel to the dominant lineations in the synform and marble complex subareas. This pattern is not consistent with stretching during dome formation, but is consistent with the updoming of sequence of rocks already carrying a foliation and lineation (model 2, Fig. 3b). The foliation and dominant lineation almost certainly correlate with the D_1 structures of the synform subarea. The dome itself, therefore, must postdate D_1, and may be of the same age as the large D_2 synform. Two sets of lineation are visible on foliation surfaces at a few localities on the flanks of the dome. At one locality, an oblique stretching lineation is accompanied by a weaker stretching one plunging down dip. The latter is interpreted as a local D_2 lineation produced during doming.

Marble Complex Subarea

The marble complex, after which this subarea is named, is a northeastwards closing U-shaped outcrop of marble within part of the Banded Supracrustal Sequence on the southeastern side of the Northwestern Gneiss Dome (Fig. 4). The marble band encloses an outcrop of quartz-feldspathic schist and is surrounded by amphibolite. This area is considered separately from the synform and Northwestern Gneiss Dome subareas, because it contains some unusual structural features not seen elsewhere. These are as follows :

1. This subarea is the only place in the study area where angular discordance between the schistosity and the compositional banding is visible over a significant distance. This is particularly well displayed by the marble itself and the quartzo-feldspathic schist.
2. The lineation produced by the intersection of compositional banding and schistosity in the marble and quartzo-feldspathic schist is parallel to the axes of tight and open minor folds in the marble as well as the other types of lineation within this subarea. This indicates that the lineations of this subarea and minor folds are of the same age.
3. The axial planes of the minor folds are parallel to a planar fabric of lensoidal calcite grains in the marble itself and to a biotite schistosity in the quartzo-feldspathic schist. The biotite schistosity is not a strain-slip schistosity and appears to be the first foliation to have affected the schistosity.
4. The axial planar fabric in the folded marble area is parallel to the dominant composite foliation in the surrounding amphibolites, including those northeast of the closure.

From the evidence outlined above, it would appear that the Marble Complex is the nose of large scale tight or isoclinal fold of D_1 age. Small parasitic folds (Fig. 5)

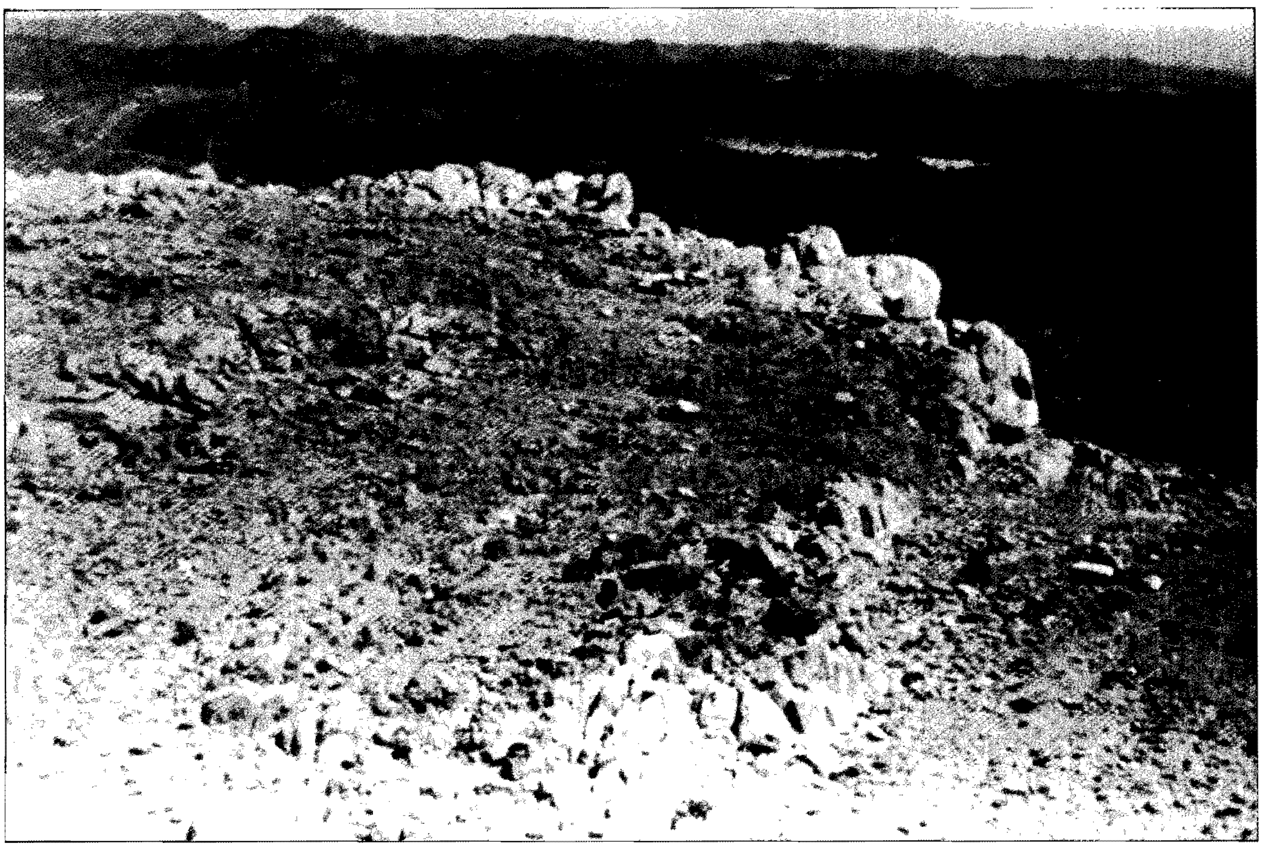

FIG. 4. U-shaped outcrop of marble, at the nose of large-scale tight fold of D_1 age.

of the same age were developed in finely banded units. An S_1 axial planar schistosity was also developed at the same time, locally at a high angle to the folded compositional banding (bedding), and is the earliest tectonic foliation in the area. The shallow southerly plunge of all the axial lineations in the marble complex suggests that the large-scale fold is a south-plunging synform. Its axial plane dips eastwards. The fold must have been in existence before the formation of the adjacent D_2 dome and must have been tilted by it.

Faulting is not very common in the study area, but to the southwest of this subarea there is a clear discordance between the schistosity trends in Fig. 6; it has northeast trend in the northeastern part, whereas it strikes northwest in the southwestern part. There must be a fault between the two trends although the narrow zone in which it must occur is not exposed. It is clear that this faulting is later than the development of the schistosity. The timing of faulting relative to the large D_2 synform and gneiss dome is not clear.

The Northeastern Gneiss Dome

This subarea was affected by three phases of deformation and faulting. The earliest deformation has been identified by a parallel alignment of amphibolite prisms producing foliation in the amphibolite xenoliths within granitic gneiss (Fig. 7). For the reason given later, this deformation is considered to be earlier than D_1 in the other subareas, and is designated D_0. The foliation of this stage of deformation has also been recognized in orthopyroxene-bearing gray gneiss and it forms a gneissic banding in this lithology. Isoclinal folds have been recognized with their axial planes parallel to this foliation, indicating that both iscoclinal folds and gneissic foliation are of the same age, *i.e.*, D_0.

The different rock types mentioned above have been intruded by pink and gray varieties of granite which are also themselves foliated.

FIG. 5. Small scale D_1 folds in banded marble.

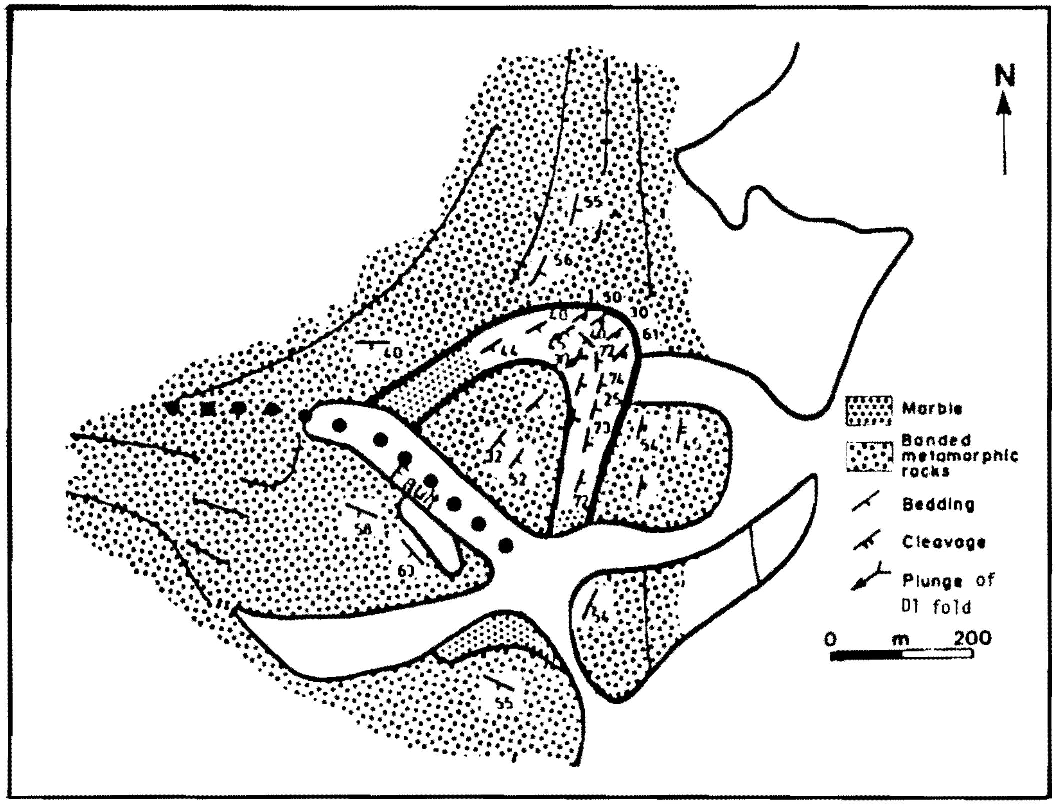

FIG. 6. Simplified structural map of the marble complex subarea.

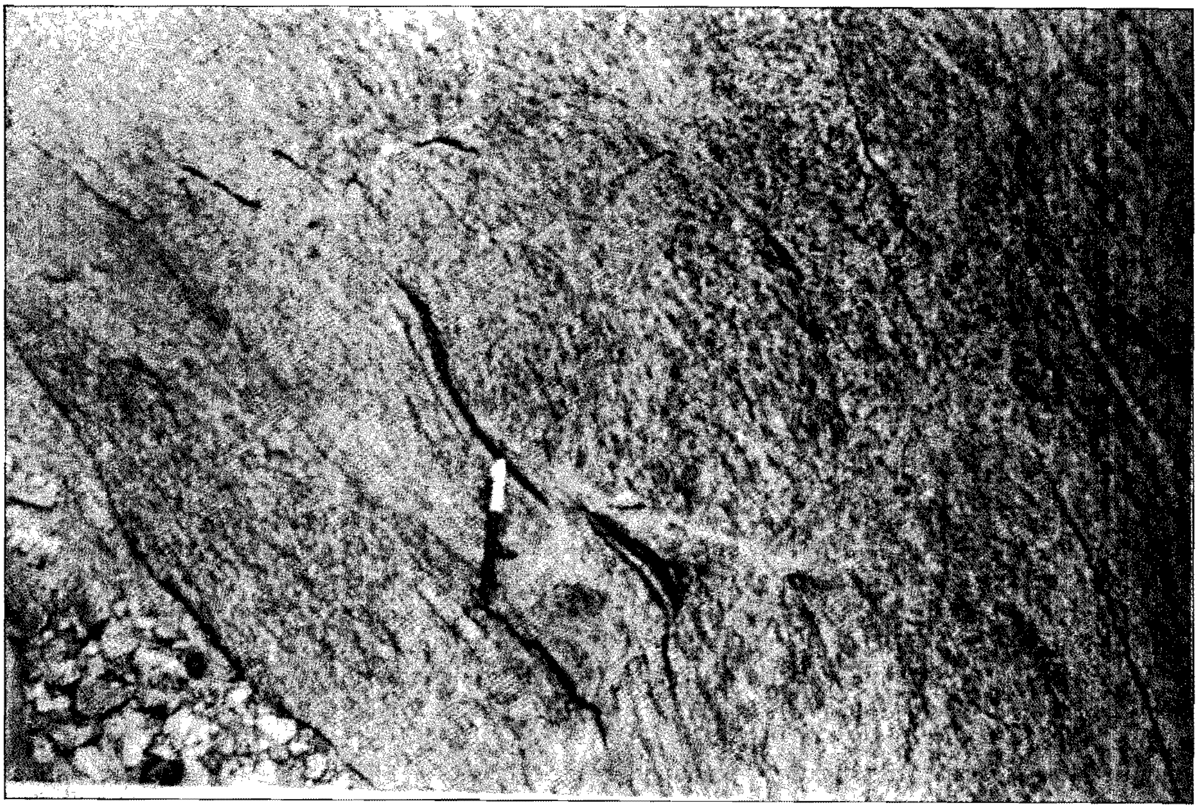

FIG. 7. Parallel alignment of amphibolite prisms defining an early foliation and lineation in amphibolite xenoliths in the N.E. Gneiss Dome.

Xenoliths of strongly foliated amphibolite and granitic gneiss have been found within the intrusive pink and gray granites and the intrusive contacts clearly truncate the foliation in the xenoliths. The second deformation in this subarea (designated D_1) is clearly shown by the following structural features :

1. Foliation

A foliation of very variable intensity has been seen in the intrusive pink and gray granites. In most cases in angular discordance with the old D_0 foliation has been rotated by the new one. The latter is defined by flattened quartzo-feldspathic aggregates and flattened biotite aggregates.

2. Lineation

Lineations are very common in the subarea. In the pink granitic gneiss, the lineation is also defined by the long axes of ellipsoidal patches of biotite (typically measuring 20 × 8 × 1 mm) which are presumably flattened pseudomorphs of an original igneous phenocryst mineral such as hornblende. Gray granites commonly carry a more penetrative biotite streaking. In sillimanite-bearing garnetiferous gneiss, this feature is parallel to a sillimanite elongation lineation. These lineations have mainly a N-S trend, and plunging northwards in the northern part of the dome, and are approximately horizontal in the east and west. This lineation pattern is similar to that observed in the NorthWest Gneiss Dome and indicates that these lineations were produced before doming. It also strongly suggests that all the stretching lineations throughout the study area are of the same age, *i.e.*, D_1, an idea which is supported by a general consistency in the lineation trend across all four subareas. If this correlation is correct, then the older gneissic foliation, which is truncated by granites now carrying this lineation, must predate D_1.

The third phase of deformation (D_2) is represented by the large dome itself which has folded both the foliation as well as lineations of the first and second deformations (Fig. 8).

Shear zones have been in some places. They are regularly spaced about 20 cm apart, and have subvertical SW-striking axial planes. They fold the gneissic banding at some localities (SW part of this subarea) and fold a relatively strong second foliation in gray granitic-gneiss at several localities. These observations suggest that they postdate D_1 and are of the same age as the doming, *i.e.*, D_2. Many of the shear zones are cored by segregations of undeformed granite, suggest-

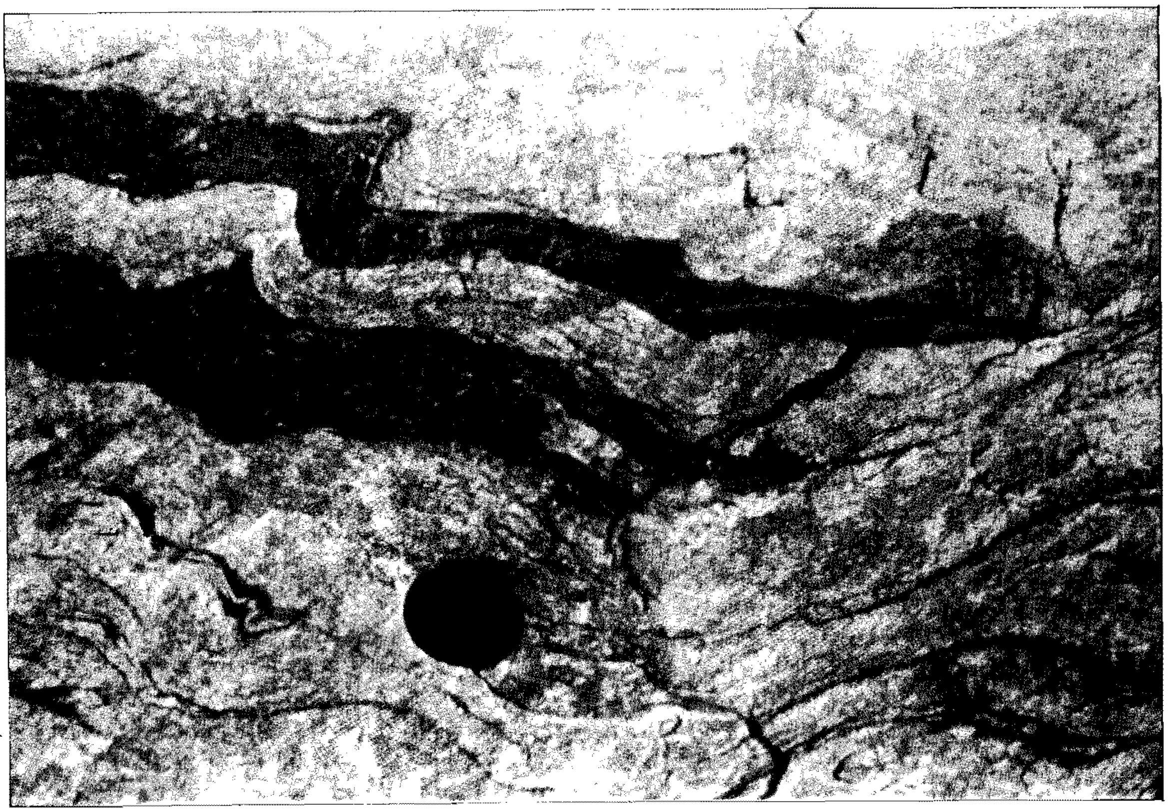

FIG. 8. Refolded D_0 folds in interbanded amphibolites and quartzo-feldspathic gneiss of the N.E. Gneiss Dome.

ing that the rocks were at a high temperature during shearing.

Several eastwest trending faults were encountered in the northwestern part of this subareas. It is clear that this faulting is post-D_1. The relative ages of the faulting and the D_2 doming is not clear. However, the different deformation phases, D_0, D_1 and D_2 are all of a ductile nature, whereas the faulting is brittle, which may indicate that the faults are post-D_2.

The Origin of the Gneiss Dome

Several models have been proposed to explain the origin of gneiss domes in various parts of the world. The models can be summarized as follows :

1. Forceful or Diapiric Intrusions Producing Domes

Granitic intrusions can occur as forceful intrusions which make a space for themselves by pushing aside the country rocks as they intrude. Such an intrusion usually crops out as a round or elongate mass with a sharp outline and a thermal aureole is typically developed. Locally, discordant veins and irregular masses of granite are usually also present (Roberts 1982). The Ardara granite of Donegal, Ireland, is probably the type example of this kind of gneiss dome. Examples have also been recognized in the Arabian Shield (Bahafzallah 1980) and the White Creek Granites in British Columbia (Roberts 1982).

2. Doming as the Result of Differential Isostatic Uplift in an Area of Tectonically Thickened Continental Crust

Domes produced in this way are likely to be found exposed within large tectonic windows in thick napped piles floored by continental basement. Such domes are likely to be large (several tens of kilometers across), elongated and arranged in a linear arrray occupying the axial part of the orogenic belt. The rocks forming the dome may belong to an underlying thrust sheet or may represent the autochthon. A good example of such a dome has been studied by Droop (1979 and 1981) and Cliff (1971) in the southeast Tauern Window, Austria.

3. Gneiss Domes Produced by the Interference of Two Fold Sets

If two sets of upright open folds intersect at a high angle, domes will be generated at the culminations of crossing anticlines. Individual domes and basins define areas where the curvature is more or less equal in all directions. It is commonly found that individual formations can be traced around these structures, dipping outwards in the case of domes and brachy-anticlines, and inwards in the case of basins and brachy-synclines if the layering has not been overturned anywhere. The formations then form a concentric series of annular outcrops, showing circular outlines in the case of domes and basins but elliptical outlines in the case of brachy-anticlines and brachy-synclines (Roberts 1982). Small scale evidence of two phases of late folding should be recognized in such structures. An example of a large scale map interference pattern is described by Park (1983), and Ramsay (1967) from the Lock Monar area of Scotland.

4. Mantled Gneiss Domes

The crystalline regions in the cores of many orogenic belts and in granitic or gneissose Precambrian Shields commonly exhibit dome-shaped areas of granitic material surrounded by a mantle of metasedimentary or metavolcanic rocks (Park 1983). Structures of this type were first described from Finland and were given the name "mantled gneiss domes" by Eskola (1949). These gneiss domes have originated in the same way as salt domes, *i.e.*, in response to gravitational instability resulting from the lower density of the "core" relative to the overlying "mantle" (Fletcher 1972). The "core" rocks in the central portions of some domes have an igneous microstructure, but near to their contact with "mantle" rocks, they are foliated. The foliation, the contact, and the layering in the "mantle" are parallel to one another and generally dip outwards, away from the gneiss "core" (Hobbs *et al.* 1976).

There appears, thus, to be four well-documented mechanisms by which gneiss domes can form. In the following discussion, field-evidence is used to constrain the mechanism of gneiss domes formation in the Qadda Area.

The Northwest and Northeast domes of the study area were clearly formed after the first deformation (D_1), since the S_1 foliation is itself updomed. The strong planar and linear D_1 fabrics in the dome orthogneisses, and the tightly folded intrusive veins indicate that $D_1$was imposed when the granites were solid *i.e.* well after intrusion. The gneiss domes of the study area are, therefore, not magmatic intrusive features, and explanation 1 is not applicable. The lack of contact metamorphism support this conclusion.

The gneiss domes are not really large enough to have been formed by differential isostatic uplift (model 2; the Northwest Gneiss Dome is only ca 3 km, and is not particularly elongated in outcrop. Furthermore, Coleman's (1973) map reveals that the Khaybar Quadrangle contains many such domes in random array. Explanation 2; is therefore also rejected here.

The absence of any regularity in the size or spacing of gneiss domes and the lack of any small-scale evidence for two phases of late folding both argue against the fold-interference model for dome formation (explanation 3).

Of the four models for gneiss dome formation outlined above, the only one which adequately satisfies the field evidence in the Qaddah Area is the "mantled gneiss dome" model. The post-D_1 density contrast required for such a mechanism could be provided by the thick "mantle" of relatively dense supracrustal rocks (containing a high proportion of mafic volcanic rocks) locally overlying deformed granitic plutons. The high post-D_1 ductility, which is also required for this mechanism, may have been induced by high peak-metamorphic temperatures which prevailed soon after D_1(*See:* Table 1).

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TABLE 1. The structural history of the Qadda region.

The supracrustal synform	The north-western gneiss dome	The marble complex	The north-eastern gneiss dome
Faulting		Faulting	Faulting
Intrusion of non-foliated granite dikes Intrusion of gabbro plugs	Intrusion of pegmatitic veins and non-foliated granites	Intrusion of non-foliated granite	Intrusion of pegmatite veins
D_2: Large scale gentle folding synform	D_2: Doming-Rotation of D_1 lineations	–	D_2: Doming (rotation of D_2 lineation) Shear zones
D_1: Schistosity – lineations – small and large isoclinal folds.	D_1: Foliation in granodioritic gneiss	D_1: Schistosity – lineations – large fold	D_1: New foliation stretching lineations
	Intrusions of granodiorite		Intrustions of pink and gray granite
			D_0: Old foliation in amphibolite and gneiss xenoliths – isoclinal folds.

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التطـــور البنـــائي لمنطقـــة القطـــة جنوب الـــدرع العربي المملكة العربيـــة السعوديـــة

عصام يحيى الفيلالي

كلية علوم الأرض ، جامعة الملك عبد العزيز ، جـــدة ، المملكة العربية السعودية

المستخلص . تتكون منطقة القطة ، الواقعة في الجزء الجنوبي من الدرع العربي ، أساسًا من الصخور المتحولة . ويمكن تقسيمها بنائيا إلى أربعة أجزاء هي : ١ - منطقة صخور القشرة العلوية ، ٢ - منطقة معقد الرخام ، ٣ - منطقة قبة النَّيس الشمالية الغربية ، ٤ - منطقة قبة النَّيس الشمالية الشرقية .

تأثرت هذه الصخور بطورين من أطوار التشوه ، حيث يمكن تلخيص صفات كل من هذين الطورين على النحو التالي :

الطور الأول (د١) : ويتميز بصفة خاصة بظاهرتي التورق والتخطط الواضحتين كما يظهر في منطقة معقد الرخام طي حاد من نفس الطور .

الطور الثاني (د٢) : ويتميز بالتقبب في المناطق الشمالية الغربية والشمالية الشرقية ، إضافة إلى الطي المفتوح في منطقة صخور القشرة العلوية . ويشاهد في بعض مناطق القبة الشمالية الشرقية ظهور تورق أقدم من ذلك المميز للطور الأول (د١) حيث حدثت له إعادة طي بوساطة التشوه الممثل للطور الأول (د١) . وبذلك ، فإن هذا التورق الأقدم يمثل أقدم طور للتشوه أثّر في المنطقة ويمكن اعتباره (د٠) .