Precambrian evolution of the Salalah crystalline basement from structural analysis and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology

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PRECAMBRIAN EVOLUTION OF THE SALALAH CRYSTALLINE
BASEMENT FROM STRUCTURAL ANALYSIS AND $^{40}$Ar/$^{39}$Ar
GEOCHRONOLOGY

by

Hanadi Abulateef Al-Doukhi

A DISSERTATION
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Approved
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ABSTRACT

The Salalah Crystalline Basement (SCB) is the largest Precambrian exposure in Oman located on the southern margin of the Arabian Plate at the Arabian Sea shore. This work used remote sensing, detailed structural analysis and the analysis of ten samples using $^{40}$Ar/$^{39}$Ar age dating to establish the Precambrian evolution of the SCB by focusing on its central and southwestern parts. This work found that the SCB evolved through four deformational events that shaped its final architecture: (1) Folding and thrusting event that resulted in the emplacement of the Sadh complex atop the Juffa complex. This event resulted in the formation of possibly N-verging nappe structure; (2) Regional folding event around SE- and SW-plunging axes that deformed the regional fabric developed during the N-verging nappe structure and produced map-scale SE- and SW-plunging antiforms shaping the complexes into a semi-dome structure; (3) Strike-slip shearing event that produced a conjugate set of NE-trending sinistral and NW-trending dextral strike-slip shear zones; and (4) Localized SE-directed gravitational collapse manifested by top-to-the-southeast kinematic indicators. Deformation within the SCB might have ceased by $752.2\pm2.7$ Ma as indicated by an age given by an undeformed granite. The thermochron of samples collected throughout the SCB complexes shows a single cooling event that occurred between about 800 and 760 Ma. This cooling event could be accomplished by crustal exhumation resulting in regional collapse following the prolonged period of the contractional deformation of the SCB. This makes the SCB a possible metamorphic core complex.
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1. INTRODUCTION

The Neoproterozoic is an important time for the formation and deformation of a significant portion of the crust. One of the important regions where a large amount of new crust was added during the Neoproterozoic is the Arabian-Nubian Shield which is dominantly exposed in the western part of the Arabian Peninsula and the eastern part of Africa (Fig. 1.1). Pre-Red Sea configuration suggests that the total area of the Arabian-Nubian Shield is over 2.7 million square kilometers. In the Arabian Plate, the Arabian Shield extends from south to north into Yemen, Saudi Arabia, and Jordon (Fig. 1.1).

To the east, the Neoproterozoic rocks of the Arabian Shield are covered by Paleozoic-Mesozoic sedimentary rocks. However, a number of small outcrops of Neoproterozoic age are found in Oman east of the sedimentary cover. The largest of these is the Salalah Crystalline Basement (SCB; Figs. 1.1 and 1.2). Although this complex has

![Figure 1.1. Digital Elevation Model (DEM) of the Arabian peninsula and northern Africa showing the location of the Arabian-Nubian Shield and the Salalah Crystalline Basement.](image)
been studied to establish its lithological units and its metamorphic history, it has remained poorly known in terms of the nature and age of the structural and tectonic events that ultimately led to shaping it.

The main purpose of this study is to establish the deformational history of the SCB using remote sensing, field studies and $^{40}$Ar/$^{39}$Ar geochronology. Results of this study are presented in parts II and III of the dissertation. Both sections are manuscripts prepared for submission to peer-reviewed journals. These are: (1) Al-Doukhi, H.A., and Abdelsalam, M.G. In Review. Structural evolution of the western part of the Neoproterozoic Salalah Base-
2. STRUCTURAL ANALYSIS OF THE WESTERN PART OF THE NEOPROTEROZOIC SALALAH CRYSSTALLINE BASEMENT, SULTANATE OF OMAN

2.1. ABSTRACT

The Salalah Crystalline Basement (SCB) is the largest Precambrian exposure in Oman located on the southern margin of the Arabian Plate at the Arabian Sea shore. It is thought to represent one of the eastern-most exposures of the Arabian-Nubian Shield. This work used remote sensing and detailed structural analysis to establish the deformational history of the SCB by focusing on its central and southwestern parts. This part of the SCB is dominated by the Juffa complex (820 ± 10 Ma) made-up of two-mica gneisses, amphibolite and ultramafic lenses, and the Sadh complex (816 ± 12 Ma) which constitutes biotite and amphibolite gneisses. This work found that the SCB evolved through four deformational events that shaped its final architecture: (1) Folding and thrusting event that resulted in the emplacement of the Sadh complex atop the Juffa complex. This event resulted in the formation of possibly N-verging nappe structure. Associated with this event was the development of mesoscopic asymmetrical tight folds and thrusts with various orientations because of folding during subsequent events. However, the dip of these structures fluctuates between SE and SW, suggestive of an initial N-vergence; (2) Regional folding event around SE- and SW-plunging axes that deformed the regional fabric developed during the N-verging nappe structure. This event produced map-scale SE- and SW-plunging antiforms, resulting in shaping the Juffa and Sadh complexes into a semi-dome structure; (3) Strike-slip shearing event that produced a conjugate set of NE-trending sinistral and NW-trending dextral strike-slip shear zones. The NW-trending
dextral strike-slip shear zones dissected the northeastern part of the Juffa-Sadh semi-dome whereas the NE-trending sinistral strike-slip shear zones deformed its southwestern part. Strong mylonitic fabric, stretching lineation and associated kinematic indicators were developed during this event; and (4) Localized SE-directed gravitational collapse manifested by top-to-the-southeast kinematic indicators and the development of stretching lineation in the form of stretched amphibole crystals overprinted on older planar fabric. This is particular apparent in the hinge of the map-scale SE-plunging antiform.

2.2. INTRODUCTION

The Precambrian rocks of the Arabian-Nubian Shield crop out along the Red Sea coasts and extend from Saudi Arabia and Yemen in western Arabia to Egypt, Sudan, Eritrea, and Ethiopia in east Africa (Fig. 2.1; Abdelsalam and Stern, 1996; Abdelsalam, 2010). Phanerozoic sedimentary rocks cover the Precambrian crystalline rocks in the eastern part of the Arabian Peninsula. However, small inliers of Precambrian crystalline rocks are exposed in Oman (Fig. 2.1). The largest of these inliers is the Salalah Crystalline Basement (SCB) that covers an area of ~750 km2 and is situated on the southern margin of the Arabian Peninsula along the Arabian Sea. The SCB is bounded in the north by a ~30 km long and ~1 km high fault escarpment extending WNW-ESE parallel to the shore of the Arabian Sea. This escarpment is made-up of ~1 km thick retaceous and Tertiary sedimentary rocks. In the south, the SCB is limited by the Arabian Sea (Fig. 2.2).
Figure 2.1. Tectonic map of the Arabian-Nubian Shield showing the location of the Salalah crystalline basement in the easternmost part of the shield. After Abdelsalam (2010).

Figure 2.2. Geologic map of the Salalah Crystalline Basement. Modified from Mercolli et al. (2006).
Regardless of the extensive exposures of different gneissic units suggestive of Archean-Paleoproterozoic ages, geochronological data have shown that the SCB rocks are Neoproterozoic (830-750 Ma) in age and are therefore chronologically similar to the juvenile Neoproterozoic rocks of the Arabian-Nubian Shield (Gass, 1981; Worthing, 2005; Mercolli et al., 2006). Although many geoscientific studies have been carried out in the SCB, the structural evolution of this region has not been established. This study represents the first detailed examination of the deformational history of the SCB through the analysis of structural data to reveal its architecture and to attempt to understand its evolution within the regional tectonic framework. Thus, the objectives of this work include: (1) Deciphering the nature of the contacts between different rock units, and examining whether these contacts are depositional, intrusive or they are tectonic contacts developed during major contraction tectonic event resulting in crustal thickening or they evolve during the final stages of orogen extension resulting in orogenic gravitational collapse; (2) Documenting the deformation history that led to the current architecture of the SCB; and (3) Investigating the role of strike-slip shear zones in the evolution of the SCB. This contribution will facilitate the regional correlation between the SCB and other regions of the Arabian-Nubian Shield.

2.3. REGIONAL SETTING

2.3.1. Previous Studies. Previous studies have established the lithological units, the geochemistry, and the regional geochronology of the SCB. In 1981, the Metal Mining Agency of Japan (MMAJ) and the Japanese International Cooperation Agency (JICA)
presented the first comprehensive geological map of the SCB. The Ministry of Petroleum and Minerals of the Sultanate of Oman presented in 1987 a geological map for the same area with a scale of 1:100,000. During this study, the SCB was divided into the Juffa and the Sadh complexes (dominantly gneissic units) which are intruded by a large batholith in the east. This batholith was subsequently divided by Hauster (1992) and Hauster and Zurbriggen (1994) into the Fusht and Hadbin complexes (Fig. 2.2). The first geochronological study on the SCB was conducted by Gass et al. (1990) who obtained a whole-rock Rb/Sr isochron age of 706 ± 40 Ma for the gneissic rocks, and an age of 640 ± 24 Ma for mafic dike swarms that extensively intrude the gneissic rocks in a NW direction (Fig. 3; Schonberg, 1996; Worthing, 2005). These dikes also gave a whole-rock K/Ar age of 490 ± 21 Ma (Gass et al., 1990). Hauser and Zurbriggen (1994) focused on studying the lithology of the Hadbin area, and interpreted the structure dominating this part of the Sadh complex as due to it being squeezed between the Fusht and the Hadbin complexes during the intrusion of the two igneous bodies (Fig. 2.2). Kellerhals (1993) studied the petrography of the western part of the Sadh complex and referred to it as the Marbat complex after the nearby city of Marbat (Fig. 2.2). Würsten (1994) further sub-divided the Sadh complex into the Sadh and Mahalla complexes, hence establishing the SCB as constituting three different complexes (Juffa, Sadh, and Mahalla) and two intrusive bodies (Fusht and Hadbin). Würsten (1994) also gave a general overview of the SCB with special emphasis on the Juffa complex, and proposed two possible tectonic models for the evolution of the SCB. These models are discussed in a subsequent section. Adler (1996), Johner (1996), Kilchmann (1996), Remund (1996) and Schonberg (1996) produced detailed geological maps and petrographic descriptions of the area between the cities of
Sadh and Hadbin (Fig. 2.2). Briner (1997) conducted a regional study of the SCB. Al-Doukhi and Divi (2001) investigated the region and produced a structural map of the eastern part of the SCB. The Hasik area, which lies at the eastern-most part of the SCB was investigated by Al-Kathiri (2001). Worthing (2005) presented geochemical and geochronological data from the NW-trending dikes and suggested that they are tholeiitic in composition, formed in supra-subduction environment, and were intruded during a period of crustal extension. These dikes gave a whole-rock Sm/Nd isocron age of 757 ± 61 Ma and a whole-rock Rb/Sr isochron age of 655 ± 89 Ma. Mercolli et al. (2006) summarized a number of unpublished master theses completed between 1996 and 1997 and proposed a new lithostratigraphic subdivision for the SCB based on lithology as well as U/Pb and Sm/Nd geochronology. In this study, Mercolli et al. (2006) divided the SCB into the 820 ± 10 Ma Juffa group, the 816 ± 12 Ma Sadh group, the 799 ± 5 Ma Mahalla complex, and the synchronous Fusht and Hadbin complexes intruded between 790-780 Ma.

2.3.2. Tectonic Models. Two models have been suggested to explain the evolution of the SCB within the tectonic framework of the Arabian-Nubian Shield and the Pan-African Orogeny (Würsten, 1994). The first model relates the formation of the Juffa and Sadh complexes to arc magmatism associated with two contemporary subduction zones forming arcs systems which eventually collided together to form the SCB. The first subduction-related magmatism was related to an oceanic island-arc, portions of which were eroded and deposited as clastic sedimentary rocks within fore-arc and back arc basin. These sedimentary rocks were intercalated with theoleiitic basaltic rocks, ultimately metamorphosed to form the Juffa complex. The second subduction-related magmatism
developed in association with an active continental margin forming the origin of the Sadh complex.

In the second model, Würsten (1994) suggested that the Sadh complex was formed as sub-crustal plutonic roots of an Andean-type arc and that the protolith of the Juffa complex is sedimentary rocks deposited in front of the continental crust. Mercolli et al. (2006) suggested that the source of these sedimentary rocks is more than 1300 Ma old. Subsequently, subduction of these sedimentary rocks brought them to a deeper level where they were metamorphosed under upper amphibolite facies metamorphic condition to form the Juffa complex. Subsequently, the Juffa complex collided with the Sadh complex to produce the SCB.

Mercolli et al. (2006) suggested that crustal accretion and amalgamation of the entire SCB took place between 880 and 780 Ma. They also suggested that the amphibolite facies metamorphism took place between 815 and 790 Ma. The SCB was intruded by calc-alkaline igneous bodies at 830-780 Ma and pegmatitic complexes at 770-700 Ma, respectively (Würsten, 1994; Ronny, 1996; Mercolli et al., 2006). The deposition of the oldest sedimentary rocks overlaying the SCB (Marbat Formation) at 630-542 Ma marks the exhumation time of the SCB (Gass et al., 1990; Mercolli et al., 2006).

2.4. DESCRIPTION OF THE SALALAH CRYSTALLINE BASEMENT COMPLEXES

Previous studies have established the SCB as constituting three gneissic complexes (Juffa, Sadh and Mahalla) and two intrusive rock complexes (Fusht and Hadbin). Only the Juffa, Sadh and Mahalla complexes are present in the study area (Fig. 2.2).
2.4.1. The Juffa Complex. The 820 ± 10 Ma Juffa complex (Fig. 2.2) is the oldest of the three complexes (Adler, 1996) and forms the central part of the SCB. Rocks belonging to the Juffa complex are divided into three units. These are two-mica gneisses, amphibolite rocks, and ultramafic rocks. The contacts between these three units is sharp and do not show any lithological gradation. The two-mica gneisses can either be biotite-rich or muscovite-dominant giving the Juffa complex a distinctive sheen appearance. The biotite-rich gneisses consist of up to a meter scale bands of fine grained biotite and coarser feldspar-rich bands, with less abundant coarse grained leucocratic layers (Hawkins et al., 1981). The muscovite-rich gneisses contain coarse-grained muscovite with small amounts of sericite and chlorite indicating retrograde metamorphism. Both gneisses have abundant leucocratic veins that have been produced by partial melting. The two-mica gneisses are highly weathered especially at the center of the complex resulting in subdued topography compared to other parts of the SCB. The amphibolite rocks are inter-layered with the two-mica gneisses, especially close to the contact between the Sadh and the Juffa complexes. They are usually found as long thick and continuous (ten of meters) bands concordant with the foliation of the two-mica gneisses or as several meter thick units forming large inhomogeneous bodies of black amphibolite (Johner, 1996). The ultramafic rocks occur as lenses which are found only where the two-mica gneisses are intercalated with the amphibolite rocks (Ronny, 1996).

Based on mineral norm calculations, Würsten (1994) suggested a sedimentary origin for the two-mica gneisses and an upper mantle magmatic origin for the amphibolite rocks. Further, Würsten (1994) suggested a sedimentary affinity close to the greywacke for the two-mica gneisses and a tholeiitic island arc tectonic setting for the amphibolite rocks.
Briner (1997) proposed that the two-mica gneisses were either deposited in a fore-arc or a back-arc basin. Both Würsten (1994) and Briner (1997) interpret the protolith of the two-mica gneisses of the Juffa complex to be a thick clastic sequence deposited in a magmatic arc setting and was originated from an older intermediate-composition igneous province. Mercolli et al. (2006) assigned an age of >1.3 Ga for the two-mica gneisses protolith. Würsten (1994) and Briner (1997) agreed that the protolith of the amphibolite rocks is volcanic material related to a marginal island arc.

The ultramafic rocks of the Juffa complex interleave concordantly with the two-mica gneisses and the amphibolite rocks. Although these rocks are highly metamorphosed and intensely metasomatized, Briner (1997) suggested that they might be of sub-oceanic mantle-origin, mainly harzburgite.

2.4.2. The Sadh Complex. The 816 ± 12 Ma Sadh complex is the most extensively exposed by area in the SCB (Fig. 2.2). This complex, also referred to as the banded gneiss complex, is composed of banded biotite gneisses, biotite-hornblende gneisses, hornblende gneisses, amphibolite rocks and rarely thin bands or nodules of calc-silicates (Mercolli et al., 2006). The most distinct characteristic of the Sadh complex is its heterogeneity, in a way that not all rock types are found evenly distributed within the complex. Rather, these rock types are found either as lenses or bands and sometime the only difference between them lies in their texture. Rocks of the Sadh complex are more intensively foliated compared to the Juffa and the Mahalla complexes. Most of the foliation occurs as preferred orientation of the platy minerals but also as spaced cleavage. The gneissic layering is parallel to the penetrative foliation and concordant to the contacts with other complexes. Occasionally localized discordant gneissic layering is observed. Ronny (1996)
explained the discordance in the gneissic layering as indicating two high-grade metamorphic events within the Sadh complex.

Würsten (1994) proposed a magmatic arc origin as a protolith for the Sadh complex and related the presence of the biotite-hornblende gneisses and the amphibolite rocks to an upper amphibolites facies anatectic melting and fractionation of dioritic to tonalitic intrusive bodies. Kilchmann (1996) interpreted the calc-silicate rocks within the biotite gneisses to be of a sedimentary origin indicating partly sedimentary protolith of this unit. However, Briner (1997) argued that fractionation processes or metasomatism processes could have produced the calc-silicate rocks. Thus, Briner (1997) considered the origin of the Sadh complex to be intrusive bodies contaminated with metasomatic fluids of sedimentary source and these intrusive bodies were affected by intense anatectic melting shortly after their emplacement.

2.4.3. Mahalla Complex. The 799 ± 5 Ma Mahalla complex occupies the coastal regions of the SCB (Fig. 2.2). The contacts of this complex are well defined in the eastern and central parts of the complex, whereas the contacts of the complex at its western part are relatively poorly known (Loosveld et al., 1996). This complex was derived from dioritic to tonalitic intrusive bodies that have been deformed and recrystallized into amphibolite, biotite-hornblende gneisses, and leucocratic biotite gneisses (Remund, 1996). The complex is highly foliated at its contact with the Sadh complex. The rock units of the Mahalla complex have the same composition as those of the Sadh complex. Although the foliation is concordant between the two complexxes, their contact is discordant. This is taken to indicate an intrusive relationship where the Mahalla complex was intruded into the Sadh complex.
Thus, the Mahalla complex was interpreted as representing the last intrusive bodies sourced from the same magma chamber that sourced the Sadh complex. Hence, the age of the Mahalla complex is taking to represent the oldest possible age for the onset of the main tectonic events that formed the regional penetrative foliation of the SCB (Mercolli et al., 2006).

2.5. STRUCTURAL ANALYSIS

2.5.1. Regional Structural Features. It is apparent from the 7-3-1 Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) image that the regional structural grain is defined by linear features and sometimes stripes of different intercalated colors (Fig. 2.3A). These linear and stripe features define fold closures as well as strike-slip shear zones that offset the regional fabric (Fig. 2.3A). These are distinctive from the consistently NW-trending linear features which define the NW-trending mafic dikes (Fig. 2.3A). Also, distinctive in this image is the difference in the appearance of the Juffa and Sadh complexes.

The Sadh complex is defined by more massive and almost continuous outcrops surrounding the more eroded Juffa complex (Fig. 2.3A). The following regional structural features are established based on the interpretation of the 7-3-1 ASTER image and field studies (Fig. 2.3B), (1) The Ayn sub-dome in the southwest and the Said sub-dome to the northeast. The core of these sub-domes is occupied by the Juffa complex and their rims are defined by the Sadh complex. (2) The Ayn-Said thrust which is a folded thrust separating
Figure 2.3. (A) 7-3-1 Advanced Spacemorne Thermal Emission and Reflection Radiometer (ASTER) of the central and southwestern and parts of the Salalah crystalline basement. Numbers and letters inside the red ellipses show the location of field photographs in figures 4, 7, 9 and 11. (B) Structural interpretation of the 7-3-1 ASTER image supported by field data showing major structural elements of the central and southwestern parts of the Salalah crystalline basement.
the Juffa complex from the Sadh complex. (3) NW-trending dextral strike-slip shear zones represented by the Shaat, Bayt Said, Aingalf and Ayn shear zones. The Aingalf and Ayn shear zones dissecting a once continuous dome into the Ayn and Said sub-domes. (4) NE-trending sinistral strike-slip faults represented by the Wadi Anshayer and Wadi Baqlat shear zones.

2.5.2. Deformational History. The deformational history of the southwestern and central parts of the SCB is divided into four stages based on style and orientations of folds and thrusts, planar and linear fabric, kinematic indicators, and cross-cutting relationship, these will be referred to as stage I (N-verging nappe structure), Stage II (folding around SE- and SW-axes), Stage III (NW-trending dextral and NE-trending sinistral strike-slip shearing), and Stage IV (localized SE-directed gravitational collapse). All deformational events are observed affecting the gneissic layering developed within the complexes of the SCB. Hence, it is assumed here that the gneissic layering was developed in deformation and metamorphic events that have occurred in mid-crustal levels (as indicated by the dominance of the amphibolite facies metamorphism) and that these events preceded the N-verging nappe structure.

2.5.2.1 Stage I, N-verging nappe structure. This deformation event resulted in the development of a nappe structure, possibly N-verging where the Sadh complex was thrust atop the Juffa complex along the Ayn-Said thrust which was folded during the subsequent event (Fig. 2.3B). This nappe is characterized by sub-horizontal planar fabrics close to the contact between the Sadh and the Juffa complexes and this planar fabric becomes steeper to the south. It is observed that the intensity of deformation (in terms of
Numerous mesoscopic folds and thrust structures are associated with the N-verging nappe structure (Figs. 2.4 and 2.5). These mesoscopic structures deform the gneissic layering of the Juffa and Sadh complexes with various degrees of intensity. One of these mesoscopic structures is the development of a thrust duplex in the western part of the Ayn sub-dome close to the Ayn-Said thrust (Figs. 2.3A and 2.4A). This thrust duplex is characterized by the presence of a horse made-up of the hornblende gneisses from the Sadh complex surrounded by the two-mica gneisses of the Juffa complex. The thrust horse is bounded by a SW-dipping roof thrust and a NW-dipping sole thrust (Fig. 2.4A). In some places close to the contact between the Sadh and Juffa complexes, mesoscopic thrusts are also found where slices of the two-mica gneisses of the Juffa complex are thrust over each other (Figs. 2.3A and 2.4B). These imbricated thrust planes create numerous schuppen-like structures with mesoscopic thrusts dipping to the northwest (Fig. 2.4B). In other places, the contact between the Juffa and Sadh complexes is marked by steep mesoscopic thrusts (Figs. 2.3A and 2.4C). Away from the thrust contact between the Juffa and Sadh complexes, evidence of early thrusting is still preserved, either as macroscopic verging folds that are usually found within the Juffa complex or as mesoscopic thrusting. Mesoscopic isoclinal folds are dominant in the Ayn-Said thrust and these folds are characterized by elongated hinges and stretched limbs that sometimes develop into rod like lineation. These folds are usually found within and concordant to the gneissic layering (Figs. 2.3A and 2.4D).
Type II fold interference patterns are also common. Hook interference patterns resulting from the refolding of earlier folds around a SW-plunging axis is found in the Sadh complex (Figs. 2.3A and 2.5A). Such interference pattern indicates the superimposition of co-axial, but non co-planar folding events possibly associated with
pulses of N-S shortening. The axial planar cleavage associated with these folds is not well developed regionally. However, penetrative foliation and spaced cleavages are preferentially developed in different lithological units and these are dominantly dipping to the southwest in the southwestern part of the Ayn sub-dome and to the southeast in the southeastern part of the Said sub-dome (Figs. 2.3A and 2.5B).

Although stretching lineation associated with this early stage of thrusting is rarely preserved, sub-horizontal S-plunging stretching lineation is sometimes observed within the biotite-hornblende gneisses of the Sadh complex at the southwestern part of the Ayn sub-dome (Figs. 2.3A and 2.5C). Boudin structure, observed within the gneisses of the Sadh complex change orientation from sub-horizontal at the central part of the sub-domes (Figs. 2.3A and 2.5D) to sub-vertical further south. The orientation of the mesoscopic thrusts and the axial surfaces of the mesoscopic folds associated with the nappe structure vary significantly because of refolding during subsequent event as will be discussed below. However, we estimate here that the initial vergence of these structures was to the north. This is because the dip of the mesoscopic thrusts and the axial surfaces of the mesoscopic folds fluctuate between southeast and southwest.

2.5.2.2 Stage II, Folding around SE and SW-plunging axes. Analysis of the planar fabric from the Ayn sub-dome in π-diagrams shows that the gneissic layering, the fold axial surfaces and the mesoscopic thrusts associated with the N-verging nappe structure, are all folded about SW-plunging axis (Figs. 2.6A-E). The fold depicted by the gneissic layering indicates an asymmetrical SW-plunging antiform, with the northern limb dipping 39° to the northwest and the southern limb dipping 56° to the southeast and that the fold axis has a trend and plunge of 227/32° (Fig. 2.6A and B).
Figure 2.5. Mesoscopic structure associated with Stage I - N-verging nappe structure. For location see Figure 2.3. (A) Type II hook interference pattern within the two-mica gneisses of the Juffa complex close to its thrust contact with the Sadh complex at the northeastern part of the Said sub-dome. (B) Steep NNW-verging (70°/60° SE) axial planar cleavage within the Sadh complex close to its thrust contact with the Juffa complex at the western part of the Ayn sub-dome; (C) SW-plunging (220°/40°) stretching lineation from the Sadh complex at the thrust contact with the Juffa complex at the northeastern part of the Ayn sub-dome defined by parallel alignment of biotite and hornblende minerals and stretched quartz crystals; (D) Sub-horizontal S-plunging (173°/18°) boudinage structure within the two-mica gneisses of the Juffa complex close to the core of the Ayn sub-dome indicating the horizontal nature of the fold-related lineation at the structural upper-part of the N-verging nappe.
Figure 2.6. (A) Geologic map of the fold-related fabrics in the Ayn sub-dome. (B-E) Geometrical analysis of the Ayn sub-dome using plot of poles to planar fabric and trend and plunge of fold-related lineations in equal area stereonet. Contouring is at 1% per unit area: (B) $\pi$-diagram of the regional foliation ($\pi$-axis = 235°/33°) with a total number of reading (n) = 472; (C) $\pi$-diagram of the axial planner cleavage and axial surfaces associated with stage I, N-verging nappe ($\pi$-axis = 238°/13°), n = 53; (D) $\pi$-diagram of mesoscopic thrust associated with stage I, N-verging nappe ($\pi$-axis = 249°/51°); n = 13; (E) Stereoscopic plot of trend (mean = 238°) and plunge (mean = 38°) of fold-related lineation; n = 61.
Similarly, π-diagrams show that the fold axial surfaces and axial planar cleavage (Fig. 2.6A and C) and mesoscopic thrusts (Fig. 2.6A and D) are folded about axes with trend and plunge of 238/13° and 249/51°, respectively.

Differently, in the Said sub-dome (Fig. 2.3B) the gneissic layering, the fold axial surfaces and planar cleavage, and the mesoscopic thrusts developed during the early N-verging nappe event are all folded about SE-plunging axis as shown by the analysis of these planar fabric in π-diagrams (Figs. 2.7A-E). The folded gneissic layering indicates a SE-plunging antiform, with the northern limb dipping 6° to the northeast and the southern limb dipping 68° to the southeast (Fig. 2.7A and B) and that the fold axis has a trend and plunge of 109/21°. Similarly, π-diagrams show that the fold axial surfaces and axial planar cleavage (Fig. 2.7C) and mesoscopic thrusts (Fig. 2.7D) are folded about axes with trend and plunge of 125/22° and 147/46°, respectively.

Fold-related lineation including intersection lineation and fold axes developed during this folding event, are dominantly plunging to the southeast (Fig. 2.7A and E). Stereoscopic projection of these fold-related lineations shows them being clustered around a mean trend of 109° and a mean plunge of 21° (Fig. 2.7E). This orientation closely coincides with the π-axes obtained from the π-diagrams for the folded gneissic layering, the early fold axial surfaces and axial planar cleavage, and the mesoscopic thrusts (Figs. 2.7B-E).
Figure 2.7. (A) Geologic map of the fold-related fabrics in the Said sub-dome. (B-E) Geometrical analysis of the Said sub-dome using plot of poles to planar fabric and trend and plunge of fold-related lineation in equal area stereonet. Contouring is at 1% per unit area; (B) $\pi$-diagram of the regional foliation ($\pi$-axis = 119°/23°), $n = 309$; (C) $\pi$-diagram of the axial planner cleavage and axial surfaces associated with stage I, N-verging nappe ($\pi$-axis = 125°/22°), $n = 28$; (D) $\pi$-diagram of mesoscopic thrust associated with stage I, N-verging nappe ($\pi$-axis = 147°/46°, $n = 42$; (E) Stereoscopic plot of trend (mean = 109°) and plunge (mean = 21°) of fold-related lineation, $n = 45$. 

Well-developed axial planar cleavage associated with the SE- and SW-plunging antiforms is particularly apparent in the hinge zones of these folds. Intersection lineation between these axial planar cleavages and the early planar fabric are hence observed. The planar fabrics at the core of the Ayn and the Said sub-dome are predominantly horizontal to sub-horizontal and depict a broad dome and basin structure (Figs. 2.3A and 2.8A). Early generation mesoscopic folds encountered in the core of the Ayn and the Said sub-domes are also sub-horizontal with their axial surfaces vary slightly from dipping southeast to dipping southwest (Figs. 2.3A, 2.8B and C). However, away from the core of the sub-domes towards the limbs of the SE- and SW-plunging antiforms, folds become gradually steeper. Most of these mesoscopic folds are not present in the Mahalla complex. Rather, the Mahalla complex is dominated by sub-vertical cleavage deforming the amphibolite and the meta-diorite rocks of this complex.

2.5.2.3 Stage III, NE-trending sinistral and NW-trending dextral strike-slip shearing. The 7-3-1 ASTER image clearly show a set of parallel NW-trending strike-slip shear zones within the eastern part of SCB affecting the Said sub-dome (Fig. 2.3A and 2.9A). These structures are represented by the Shaat, the Bayt Said, the Aingalf, and the Ayn shear zones (Fig. 2.3B). These dextral strike-slip shear zones are indicated by the map-scale offset of the gneissic layering of the Juffa and the Sadh complexes. Associated with these dextral strike-slip shear zones is well-developed NW-trending, steeply-dipping mylonitic fabric characterized by the presence of SC structure (Figs. 2.9B and 2.10A) and well-developed, moderately-plunging to the southeast stretching lineation sometimes forming L-tectonite, where both mafic and felsic minerals are stretched (Figs. 2.9C and 2.10B).
Stereoscopic analysis along the Ayn shear zone show the mylonitic fabric is very steep and strike 298° whereas the stretching lineation trend and plunge is 112/45° (Figs. 2.9B and C). The sense of shearing in these shear zones is indicated by numerous mesoscopic kinematic indicators. One of these kinematic indicators is the σ-type rotated clast made-up of feldspathic gneisses surrounded by the biotite gneisses of the Sadh complex.
Figure 2.9. (A) Geologic map of fabric related to strike-slip shear zones. (B-E) Geometric analysis of the NE-trending sinistral and the NW-trending dextral strike-slip shear zones using plot of poles to mylonite fabric and trend and plunge of stretching lineation in equal area stereonet. Contouring is at 1% per unit area: (B) Poles to mylonite fabric (n = 8) and (C) stretching lineation (n = 7) from the NW-trending dextral strike-slip shear zone. The mylonite fabric has a mean strike of 298° and it is almost vertical. The mean trend of the stretching lineation is 112° and the mean plunge is 45°. (D) Poles to mylonite fabric (n = 16) and (E) stretching lineation (n = 6) from the NE-trending sinistral strike-slip shear zone. The mylonite fabric has a mean strike of 15° and a mean dip of 58°. The mean trend of the stretching lineation is 192° and the mean plunge is 34°.
Figure 2.10. Planar and linear fabric associated with NE-trending sinistral and NW-trending dextral strike-slip shear zones. (A) NNE-trending (020°/65°E) mylonitic fabric from the Wadi Anshayer shear zone; (B) SE-plunging (110°/40°) stretching lineation from the Bayt Said shear zone. (C) σ-type rotated clast from the Aingalf shear zone indicating dextral strike-slip shearing. The clast is made-up of feldspathic gneisses and is surrounded by the biotite gneisses of the Sadh complex. (D) Secondary NW-trending (119°/70°) shear zone from the Ayn shear zone indicating sinistral strike-slip shearing. (E) NE-trending (042°/32°SE) ultra-mylonitic fabric from the Wadi Anshayer shear zone. For location see figure 2.3A.
complex (Fig. 2.10D). The feldspatic gneissic clast was rotated $65^\circ$ anticlockwise indicative of dextral strike-slip shearing. The orientation of the gneissic layering within the clast clearly indicates that the gneissic layering was formed before the strike-slip shearing. The dextral strike-slip sense of shearing combined with the moderately-plunging to the southeast stretching lineation indicate that the Ayn is dominantly strike-slip shear zone with a minor top-to-the-southeast reverse dip-slip component. Field observations indicate the presence of additional NE-trending set of strike-slip shear zones in the western side of the SCB affecting the Ayn sub-dome (Figs. 2.3B and 2.9D). This set is not obvious in the 7-3-1 ASTER image (Fig. 2.3A). These structures are represented by the Wadi Anshayer and the Wadi Baqlat shear zones (Fig. 2.3B). These NE-trending strike-slip shear zones have sinistral sense of movement. This sense of shearing is obvious from kinematic indicators present in the gneisses of the Juffa complex where mesoscopic shear zones are documented with sinistral ductile offset of the gneissic layering forming mesoscopic S-type drag folds with new localized foliation parallel to the shear plane and perpendicular to fold hinge zone (Fig. 2.10D). In these NE-trending shear zones mylonite fabric is well-developed (Fig. 2.10E) especially along the Wadi Anshayer and Wadi Baqlat shear zones (Fig. 2.3). Within regions of intense deformation, localized zones of ultra-mylonite were developed (Fig. 2.10E). Stereographic analysis of the mylonite fabric indicates that it has a mean strike of $15/58^\circ$ SE (Fig. 2.9D), whereas the stretching lineation has a mean trend and plunge of $192/34^\circ$ (Fig. 2.9E). The stretching lineation is sub-parallel to strike direction of the mylonite fabric indicating a strong strike-slip component accompanied by a minor reverse dip-slip component.
2.5.2.4 Stage IV, Localized gravitational tectonic collapse. Normal-slip shearing was locally observed in the eastern part of the SBC within the southeastern hinge of the Said sub-dome suggesting a localized gravitational tectonic collapse through the reactivation of parts of the Ayn-Said folded thrust into low-angle normal-slip shear zone (Figs. 2.11A). This interpretation is based on the following observations: (1) The gneissic layering in the southeastern part of the Said sub-dome is folded about SE-plunging axis (Figs. 2.7B and 2.11B); (2) Measurement of stretching lineation represented by the development of amphibolite crystals shows consistent SE-plunge (Figs. 2.11C and 2.12A) sub-parallel to the fold axis of the SE-plunging antiform. It is important to note that the stretching lineation represented by the elongated amphibolite crystals developed after the development of the gneissic layering and subsequent folding about SE-plunging axis; and (3) Kinematic indicators such as normal faults are also observed indicating top-to-the-southeast normal-slip displacement(Figs. 2.12B). Stereoscopic analysis of the stretching lineation indicates a mean trend and a mean plunge of 113/40° (Fig. 2.11C) similar to the π-axis of the folded planar fabric obtained from the π-diagram (Figs. 2.7B and 2.11B). The consistency in the orientation of the stretching lineation (113/40°) suggests that the SE-directed localized gravitational tectonic collapse is the last tectonic event in the SCB.
Figure 2.11. (A) Geologic map of fabric related to localized gravitation collapse. (B) $\pi$-diagram of the regional foliation from the southeastern part of the Said sub-dome ($\pi$-axis = 171°/20°), n = 14. (C) Stereoscopic plot of trend (mean = 113°) and plunge (mean = 40°) of stretching lineation, n = 12.
Structural Evolution. The overall structural architecture of the SCB must have started with deformation and metamorphic events that resulted in the formation of the extensive gneissic layering of the Juffa, Sadh, and Mahalla complexes. This event was likely occurred at middle crustal levels as evidenced from the regional upper amphibolite facies metamorphism that dominated the SBC. This was followed by the emplacement of the Sadh complex atop the Juffa complex. Field observations suggest N-S directed shortening as the Sadh complex was thrust over the Juffa complex forming N-verging nappe structure. This deformational event seems to have brought deeper crustal level rocks that were metamorphosed under upper amphibolite facies condition to a shallower crustal level. The presence of type II fold interference patterns indicates the internal folding of the nappe structures through the superimposition of co-axial but non co-planar strain. This might be due to change in strain accommodation from pure translation (thrusting without internal deformation of the thrust sheets) to translation and distortion (internal folding of...
the thrust sheets) because of locking of the nappe structure in the north with the continuation of the N-directed shortening.

Figure 2.13 is a three-stage three-dimensional (3D) diagram illustrating the evolution of the southwestern and central part of the SCB as a dome structure dominated by the Ayn and the Said sub-domes. The figure does not illustrate the early N-verging nappe structure. Rather, the diagram starts with the folding event that was superimposed on the structures developed during earlier deformation events. The first stage represents the SE- and SW-plunging folding event (Fig. 2.13A). The event formed a doubly-plunging antiform forming a dome structure with the Juffa complex occupying the core of the dome rimmed by the Sadh complex. The southwestern part of the dome is SW-plunging, while the southeastern part is SE-plunging. Such structure can be formed from a single pulse of N-S directed shortening, and resulted in folding of all previous planar fabric (gneissic layering, fold axial surfaces and axial planar cleavage, and mesoscopic thrusts) into SW-plunging antiforms in the southwest and SE-plunging antiforms in the southeast (Fig. 2.13A).

The once continuous Ayn-Said dome was dissected through sets of NW-trending dextral and NE-trending sinistral strike-slip shear zones (especially the Ayn and Aingalf shear zones) into the Ayn and the Said sub-domes (Figs. 2.3B and 2.13B). The southwestern part of the dome was deformed by a set of NE-trending sinistral strike-slip shear zones (Figs. 2.3B and 2.13B).
Figure 2.13. Structural evolution of the Ayn-Said dome after stage I, N-verging nappe event. (A) Refolding of earlier structure associated with the N-verging nappe around SE- and SW-plunging axes the Ayn-Said dome. The accompanied stereonets illustrates the π-circles and π-axes of regional foliation (blue lines and open circles), axial planar cleavage and axial planes of minor folds (black lines and open circles), and mesoscopic thrusts (red lines and open circles) from the Ayn sub-dome (upper left) and the Said sub-dome (lower right). (B) The dissection of the Ayn-Said dome into the Ayn and Said sub-domes by NE-trending sinistral and NW-trending dextral strike-slip shear zones. The accompanied stereonets illustrates the great circles defining the mylonite fabric (pink lines) and the lines defining stretching lineation (pink arrows) of the NE-trending (upper left) and the NW-trending (lower right) shear zones. (C) Localized SE-directed gravitational collapse. The accompanied stereonet illustrates the π-circles and π-axes of regional foliation (blue lines and open circles) and the line defining stretching lineation (pink arrow).
The orientation and the opposite sense of shearing in the two sets of the strike-slip shear zones is appealing to consider the two sets of the strike-slip shear zones as formed as conjugate sets of high shear strain that accompanied an overall N-S directed shortening.

The orientation and the structural style of the N-verging nappes, the SE-plunging and SW-plunging antiforms, and the NE-trending sinistral and NW-trending dextral strike-slip shear zones suggest that all these structures were formed in response to an overall N-S directed crustal shortening. This in turn suggests that these structures were formed through a single tectonic pulse that produced a prolonged N-S directed shortening in the SCB.

The prolonged period of crustal shortening through N-verging nappe structure and SE-plunging and SW-plunging antiforms might have created regions within the SCB with dynamic instability that triggered localized gravitational collapse through the reactivation of thrusts planes into low-angle normal faults as in the case of the southwestern part of the Ayn-Said thrust at southwestern part of the Said sub-dome (Fig. 2.13C).
2.6. DISCUSSION

2.6.1. Terrane Correlation of the SCB and the Arabian-Nubian Shield.

Correlating the tectonic evolution of the SCB to that of the Arabian-Nubian Shield is challenging and should only be approached with the following considerations: (1) The Arabian-Nubian Shield is the exposed remnants of a vast orogen which underwent complex tectonic, structural and metamorphic histories and different regions might have underwent different tectonic histories. (2) The SCB has a small Precambrian exposure compared to other regions of the Arabian-Nubian Shield. (3) The SCB is located ~800 km to the east of the closest exposure of the Arabian-Nubian Shield (Fig. 2.1). The region in-between is covered by Phanerozoic sedimentary rocks.

Phanerozoic sedimentary cover separates the SCB from the Asir, Afif, Ad Dawadimi and Ar Rayn terranes in Saudi Arabia and Abbas, Al Bayda, Al-Mukalla and Al Mahfid in Yemen (Fig. 2.1). The 820 ± 10 Ma Juffa complex of the SCB has been correlated to the rocks of the Afif, Abas, or Al Mahfid terrane (Whitewhouse et al., 2001; Johnson and Woldehaimanot, 2003; Mercolli et al., 2006). Also, the 830-780 Ma calc-alkaline magmatism of the SCB has been correlated with the igneous activities in the Asir terrane (Stoeser and Camp, 1985; Mercolli et al., 2006; Johnson et al., 2011).

The Al-Mukalla terrane in Yemen is the closest terrane in the Arabian-Nubian Shield to the SCB (Fig. 2.1), located ~800 km to the east. This terrane has been considered a continuation of the Al Bayda terrane (Whitehouse et al., 1998, 2001). The terrane is composed of greenschist facies metamorphic island-arc type tuffs, rhyolites, basalts and lava breccias of an unknown age. This lithology and grade of metamorphism is very different compared to those in the SCB.
Hence, it is difficult to correlate the SCB to the Al-Mukalla terrane. Also, it is difficult to correlate the Al-Bayda terrane to the SCB because of significant age difference where the Al Bayda terrane is much younger (700-600 Ma) than the SCB.

It seems that the Al-Mahfid terrane (Windley et al., 1996; Whitehouse et al., 1998; Mercolli et al., 2006) might be the closest candidate to be correlated to the SCB because of lithological, structural and geochronological resemblance. The Al-Mahfid terrane consists of 900-750 Ma amphibolite facies orthogenesises and supra-crustal rocks, but older gneisses (2.9-2.55 Ga) are also present (Whitehouse et al., 2001). This terrane has also been correlated with the Qarib Bahar-Mora terranes in Somalia which consists of 845-710 Ma para-gneisses and ortho-gneisses (Whitehouse et al., 1998). The Qarib Bahar-Mora terranes has also been considered to be the most accepted terrane to be correlated to the SCB in terms of lithology, structure and geochronology (Collins and Windley, 2002).

2.6.2. Correlation Between SCB Structures and Dominant Structures in the Arabian-Nubian Shield. The western part of the Arabian Shield in Saudi Arabia is dominated by regional structural grains that is either an older N-trending (parallel to arc-arc sutures such as Hulayfah-Ad Dalinah and Al Amar) or a younger NW-trending of the Najd Fault System as observed from surface outcrops and aeromagnetic data (Nehlig et al., 2002; Stern and Johnson, 2010). The older N-trending structure is highly oblique to the NE-trending structures that dominate the early phases of structural evolution of the SCB represented by the N-verging nappes and subsequent folding about SE and SW-axes. Additionally, these structures seems to be much younger that those of the SCB.

It is tempting to correlate the NW-trending dextral strike-slip shear zones of the SCB to structures related to the Najd fault system. Johnson and Woldehaimanot (2003)
suggested that the sub-surface structure of the Najd fault system, under the Phanerozoic sedimentary cover, extends into Oman in the southeast. Moreover, Loosveld et al. (1996) proposed that the N-trending folds and thrust belts as well as the NE-trending salt basins seen in the subsurface of Oman are associated with the rejuvenation of the Najd fault system. Johnson and Woldehaimanot (2003) highlighted that structures associated with the Najd fault system generally have a common tectonic setting, but have significant differences in age of activity and structural style. The orientation and kinematics of NW-trending shear zone of the SCB resemble the early phase of the Najd fault system evolution in which strike-slip shearing was dextral (Moore, 1979; Johner, 1996; Nehlig et al., 2002). However, it seems that activities along the NW-trending dextral strike-slip shear zones of the SCB might have started earlier (prior to ~760 Ma; the oldest age of the dikes that cut the shear zones) than the shearing activities along the Najd fault system that was suggested to have started ~640 Ma (Stern and Johnson, 2010).

In the southern part of the Arabian Shield in Yemen, the regional structural grain is NE-trending (Whitehouse et al., 2001) similar to that of the early structures in the SCB. This, combined with the lithoglical and geochronological resemblance, makes the correlation between the SCB and the Al Mahfid terrane more realistic.

2.7. CONCLUSIONS

The final structural architecture of the SCB was shaped by four structural events. The first event resulted in the emplacement of the Sadh complex atop the Juffa complex during N-verging nappe translation deformation. Hence, this event developed the contact
between the two complexes as a major thrust (the Ayn-Said thrust) that was subsequently deformed by younger deformation events. The second event re-folded the previous structure and the associated planar and linear fabrics around SE- and SW-axes producing a doubly-plunging antiform, the hinge zones of which plunges toward the southwest and southeast forming an E-W elongated dome (the Ayn-Said dome). The doubly-plunging antiform shows asymmetry with the southern limb being steeper than the northern limb, and the core of this dome is flat and a flat. The third event is manifested by the development of a conjugate set of NE-trending sinistral and NW-trending dextral strike-slip shear zones that dissected the Ayn-Said dome into the Ayn and the Said sub-domes. The last event in the evolution of the SCB is marked by a localized gravitational collapse. It is possible that the first three events in the evolution of the SCB originated from a single tectonic pulse characterized by N-S directed shortening. This shortening was first accommodated as N-verging nappes which were subsequently refolded about SE- and SW-plunging axes leading to the accommodation of the N-S shortening into NE-trending sinistral and NW-trending dextral strike-slip shear zones. The SCB might be correlated with the Al Mahfid terrane in Yemen on the bases of lithological, structural and geochronological resemblance.
3. TIMING OF DEFORMATION EVENTS IN THE NEOPROTEROZOIC SALALAH CRYSALLINE BASEMENT IN SULTANATE OF OMAN FROM 40AR/39AR GEOCHRONOLOGY

3.1. ABSTRACT

The Salalah Crystalline Basement (SCB) is the largest Precambrian exposure in Oman located on the southern margin of the Arabian Plate at the Arabian Sea shore. It is thought to represent one of the eastern-most exposures of the Arabian-Nubian Shield. It is composed of three complexes: Juffa (820±10 Ma), Sadh (816±12 Ma), and Mahalla (799±5 Ma) all metamorphosed to amphibolite facies. The SCB structural architecture was shaped by four structural events which affected the well-developed regional fabric defined by gneissic layering. The first event resulted in the emplacement of the Sadh complex atop the Juffa complex to develop the contact between the two complexes as a major thrust. This thrust contact was subsequently deformed by younger events re-folding the previous structure around SE- and SW-axes producing an E-W elongated doubly-plunging antiform referred to as the Ayn-Said dome. The third event is manifested by the development of a conjugate set of NE-trending sinistral and NW-trending dextral strike-slip shear zones that dissected the Ayn-Said dome into the Ayn and the Said sub-domes. The last event in the evolution of the SCB is marked by a SE-directed localized gravitational collapse. 

Dating technique was used on ten samples representing these deformation events to bracket the age of deformation and the cooling history, and hence establishing the exhumation history of the basement. The oldest ages ranging between 828 Ma and 814 Ma was obtained from two samples with well-developed gneissic layering but devoid of any subsequent deformation because they are situated away from the thrust contacts and the
strike-slip shear zones. Hence, this age was interpreted as the timing of the development of gneissic layering. Three samples located along the thrust contact gave ages ranging between 802 Ma and 795 Ma. Hence, this age was interpreted as the age of thrusting event. Three samples with well-developed mylonitic fabric from along the NW-trending shear zones gave ages ranging between 783 Ma and 764 Ma indicating that this deformation event shortly followed the thrusting event. One sample from a region of SE-directed low-angle normal fault with well-developed stretching lineation defined by amphibolite crystal gave an age of 787 Ma. There is no clear distinction in ages between the shearing event and the gravitational collapse. Indicating synchronous events occurred between 783 Ma and 764 Ma. A thermochron T-t plot indicates an inconsistency cooling rate. The basement was exhumed rapidly in its earliest stage pre-dates most of the major deformation events in the Arabian-Nubian shield. However, its exposure above sea level coincides with the crustal thinning of the Arabian Shield about 540 Ma.

3.2. INTRODUCTION

The Arabian plate originated ∼25 Ma ago by rifting of the northeastern part of the African plate leading to the opening of the Gulf of Aden and the Red Sea. This plate is one of the smallest and the youngest of the Earth's lithospheric plates. The upper part of its continental crust consists of Precambrian crystalline rocks of the Arabian-Nubian Shield (Stern and Johnson, 2010). The Precambrian rocks of the shield crop out all along the Red Sea coast and extend eastwards in Saudi Arabia and Yemen and westwards in Egypt, Sudan, Eritrea, and Ethiopia (Abdelsalam and Stern, 1996). Phanerozoic rocks cover the
crystalline rocks in the eastern part of the Arabian Shield (Fig. 2.1). However, small inliers of Precambrian crystalline rocks are exposed in the Sultanate of Oman. These exposures are in Jabal Ja’Alan, Salalah region, and Qalhat and Hausi-Huqf area. The Salalah crystalline basement (SCB) is the largest among these inliers. It covers an area of 750 km² and situated on the southern margin of the Arabian Peninsula along the Arabian Sea. The SCB is bounded in the north by a ~30 km long and ~1 km high fault escarpment extending WNW-ESE parallel to the shore of the Arabian Sea. This escarpment is made-up of ~1 km thick Cretaceous and Tertiary sedimentary rocks. In the south, the SCB is limited by the Arabian Sea (Fig.2.2).

Many geoscientific studies were carried out on the SCB covering lithology, geochemistry, structural and geochronology (Gass et al., 1990; Hauster and Zurbriggen, 1992 and 1994; Würsten, 1994; Al-Doukhi and Divi, 2001; Worthing, 2005; Mercolli et al., 2006). However, most of these studies were dedicated to the eastern part of the SCB. Previous geochronological studies in the SCB were devoted mainly to define the crystallization age of different complexes in the basement. Recently, from detailed field-oriented structural geology study, AlDoukhi and Abdelsalam (in review) established the relative chronological order of the deformational history of the western and central part of the SCB allowing for detailed geochronological study to constrain the ages of deformation.

This study focusses on establishing the ages of deformation associated with the different structural events of the SCB. Using $^{40}\text{Ar}/^{39}\text{Ar}$ radiometric dating of amphibole, biotie and muscovite mineral, ten samples from different rock types that have been affected by different phases of deformation were analyzed. This absolute dating is aimed to bracket the age of different deformation events associated with the SCB. Hence,
understanding evolution of the SCB within the regional tectonic framework of the Arabian Shield including its emplacement, deformation, and exhumation.

3.3. REGIONAL SETTING

3.3.1. Proposed Tectonic Models. Two models are suggested to explain the evolution of the SCB within the tectonic framework of the Arabian-Nubian Shield and the Neoproterozoic Pan-African Orogeny (Würsten, 1994). The first model relates the formation of the Juffa and Sadh complexes to arc magmatism associated with two contemporary subduction zones forming arc systems which eventually collided together to form the SCB. The first subduction-related magmatism was related to an oceanic island-arc, portions of which were eroded and deposited as clastic sedimentary rocks within fore-arc and back arc basin. These sedimentary rocks were intercalated with theoleiitic basaltic rocks, ultimately metamorphosed to form the Juffa complex. The second subduction-related magmatism developed in association with an active continental margin forming the origin of the Sadh complex.

In the second model, Würsten (1994) suggested that the Sadh complex was formed as sub-crustal plutonic roots of an Andean-type arc and that the protolith of the Juffa complex is sedimentary rocks deposited in a fore-arc continental setting. Mercolli et al. (2006) suggested that the source of these sedimentary rocks is more than 1300 Ma old. Subsequently, subduction of these sedimentary rocks brought them to a deeper level where they were metamorphosed under upper amphibolite facies metamorphic condition to form
the Juffa complex. Afterward, the Juffa complex collided with the Sadh complex to produce the SCB.

Mercolli et al. (2006) suggested that crustal accretion and amalgamation of the entire SCB took place between 880 and 780 Ma. Mercolli et al. (2006) also suggested that the amphibolite facies metamorphism took place between 815 and 790 Ma. The SCB was intruded by calc-alkaline igneous bodies at 830-780 Ma and pegmatitic complexes at 770-700 Ma, respectively (Würsten, 1994; Ronny, 1996; Mercolli et al., 2006). The deposition of the oldest sedimentary rocks overlaying the SCB (Marbat Formation) at 630-542 Ma marks the exhumation time of the SCB (Gass et al., 1990; Mercolli et al., 2006).

3.3.2. Description of the Salalah Crystalline Basement Complexes. Previous studies have established the SCB as constituting three gneissic complexes (Juffa, Sadh and Mahalla) and three intrusive rock complexes (Fusht, Hadbin and Hasik). Only the Juffa, Sadh and Mahalla complexes are affected by the main deformations events that shape the final architecture of the SCB and thus they will only presented in this study. The other three complexes (Fusht, Hadbin and Hasik) are considered to be post-deformational intrusive bodies.

3.3.2.1 The Juffa complex. The 820 ± 10 Ma Juffa complex (Fig. 3.1) is the oldest of the three complexes (Adler, 1996) and forms the central part of the SCB. Rocks belonging to the Juffa complex are divided into three units. These are two-mica gneisses, amphibolite rocks, and ultramafic rocks. The contacts between these three units is sharp and do not show any lithological gradation. The two-mica gneisses can either be biotite-rich or muscovite-dominant giving the Juffa complex a distinctive sheen appearance. The biotite-rich gneisses consist of up to a meter-scale bands of fine grained biotite and coarser
feldspar-rich bands, with less frequent coarse grained leucocratic layers (Hawkins et al., 1981). The muscovite-rich gneisses contain coarse-grained muscovite with small amounts of sericite and chlorite indicating retrograde metamorphism. Both gneisses have abundant leucocratic veins that have been produced by partial melting. The two-mica gneisses are highly weathered especially at the center of the complex resulting in subdued topography compared to other parts of the SCB. The amphibolite rocks are inter-layered with

the two-mica gneisses, especially close to the contact between the Sadh and the Juffa complexes. They are usually found as long thick and continuous (ten of meters) bands concordant with the foliation of the two-mica gneisses or as several meter thick bands.

Figure 3.1. Spatial distribution of previous and current geochronologic data from different rock types of the Salalah Crystalline Basement using different isotope systematics. See table 3.1 for data source. The base geological map is modified after Mercolli et al. (2006).
units forming large inhomogeneous bodies of black amphibolite (Johner, 1996). The ultramafic rocks occur as lenses which are found only where the two-mica gneisses are intercalated with the amphibolite rocks (Ronny, 1996).

The ultramafic rocks of the Juffa complex interleave concordantly with the two-mica gneisses and the amphibolite rocks. These rocks are highly metamorphosed and intensely metasomatized.

3.3.2.2 The Sadh complex. The 816 ± 12 Ma Sadh complex is the most extensively exposed by area in the SCB (Figure 3.1). This complex, also referred to as the banded gneiss complex, composed of banded biotite gneisses, biotite-hornblende gneisses, hornblende gneisses, amphibolite rocks and rarely thin bands or nodules of calc-silicates (Mercoli et al., 2006). The most distinct characteristic of the Sadh complex is its heterogeneity, in a way that not all rock types are found evenly distributed within the complex. Rather, these rock types are found either as lenses or bands and sometime the only difference between them lies in their texture. Rocks of the Sadh complex are more intensively foliated compared to the Juffa and the Mahalla complexes. Most of the foliation occurs as preferred orientation of the platy minerals but also as spaced cleavage. The gneissic layering is parallel to the penetrative foliation and concordant to the contacts with other complexes. Occasionally localized discordant gneissic layering is observed. Ronny (1996) explained the discordance in the gneissic layering as indicating two high-grade metamorphic events within the Sadh complex.

3.3.2.3 The Mahalla complex. The 799 ± 5 Ma Mahalla complex occupies the coastal regions of the SCB (Fig. 3.1). The contacts of this complex are well defined in the eastern and central parts of the complex, whereas the contacts of the complex at its western
part are relatively poorly known (Loosveld et al., 1996). This complex was derived from
dioritic to tonalitic intrusive bodies that have been deformed and recrystallized into
amphibolite, biotite-hornblende gneisses, and leucocratic biotite gneisses (Remund, 1996).
The complex is highly foliated at its contact with the Sadh complex. The rock units of the
Mahalla complex have the same composition as those of the Sadh complex.

Although the foliation is concordant between the two complexes, their contact is
discordant. This is taken to indicate an intrusive relationship where the Mahalla complex
was intruded into the Sadh complex.

3.3.3. Description of the Salalah Crystalline Basement Structural Framework.
The final architecture of the SCB was shaped by four structural events (Al-Doukhi and
Abdelsalam, in review). All these four deformational events have affected the gneissic
layering developed within the SCB complexes (Fig. 3.2). The overall structural must have
then started with deformation and metamorphic events that resulted in the formation of the
extensive gneissic layering of the Juffa, Sadh, and Mahalla complexes. This event was
likely occurred at middle crustal levels as evidenced from the regional upper amphibolite
facies metamorphism that dominated the SBC.

The first event resulted in the emplacement of the Sadh complex atop the Juffa
complex during N-verging nappe translation deformation event developing the major
thrust (the Ayn-Said thrust) contact between the two complexes. This deformational
event brought deeper crustal level rocks that were metamorphosed under upper amphibolite facies condition to a shallower crustal level. The intensity of deformation (in terms of the development of nappe-associated planar fabric) increases systematically in the Sadh complex as the thrust contact with the Juffa complex is approached.

The second event re-folded the previous structure and the associated planar and linear fabrics associated with the N-verging nappe around SE- and SW-plunging axes. This produced doubly-plunging antiform forming a dome structure (the Ayn-Said dome) with the Juffa complex occupies the core of the dome rimmed by the Sadh complex. This doubly-plunging antiform shows asymmetry with the southern limb being steeper than the
northern limb, and the core of this dome is flat. We did not attempt to date this event with $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology since it does not involve any crystallization and/or recrystallization of minerals to reset the isotopic systematics.

The third event is manifested by the development of a conjugate set of NE-trending sinistral and NW-trending dextral strike-slip shear zones. The once continuous Ayn-Said dome has been dissected by the conjugated strike-slip shear zones set into the Ayn and the Said sub-domes. Associated with these dextral strike-slip shear zones is well-developed NE- and NW-trending, steeply-dipping mylonitic fabric characterized by the presence of SC structure and well-developed, moderately-plunging to the southeast stretching lineation sometimes forming L-tectonite, where both mafic and felsic minerals are stretched. The sense of shearing in both sets of shear zones is obvious from kinematic indicators present in the gneisses of the Juffa complex where mesoscopic shear zones are documented offsetting the gneissic layering forming mesoscopic Z- and S-type drag folds with new localized foliation parallel to the shear plane and perpendicular to fold hinge zone. Within regions of intense deformation, localized zones of ultra-mylonite were developed.

The last event in the evolution of the SCB is marked by a localized gravitational collapse. The prolonged period of crustal shortening through N-verging nappe structure and SE-plunging and SW-plunging antiforms might have created regions within the SCB with dynamic instability that triggered localized gravitational collapse through the reactivation of thrusts planes into low-angle normal faults as in the case of the southwestern part of the Ayn-Said thrust at southwestern part of the Said sub-dome. The normal-slip shearing was locally observed in the eastern part of the SBC within the southeastern hinge of the Said sub-dome. Kinematic indicators such as normal faults and
strecthing lineation of amphibolite crystals indicate top-to-the-southeast normal-slip displacement. The consistency in the orientation of the stretching lineation suggests that the SE-directed localized gravitational tectonic collapse is the last tectonic event in the SCB.

3.4. PREVIOUS GEOCHRONOLOGICAL STUDIES

Results of previous geochronological studies in the SCB are summarized in table 3.1. The first geochronological study on the SCB was conducted by Gass et al. (1990) who obtained a whole-rock Rb/Sr isochron age of 706 ± 40 Ma for the gneissic rocks of the whole basement, and an age of 640 ± 24 Ma for N-trending mafic dike swarms that extensively intrude the gneissic rocks (Fig. 3.2; Schonberg, 1996; Worthing, 2005). These dikes also gave a whole-rock K/Ar age of 490 ± 21 Ma (Gass et al., 1990). These dikes gave a whole-rock Sm/Nd isocron age of 757 ± 61 Ma and a whole-rock Rb/Sr isochron age of 655 ± 89 Ma (Worthing, 2005). Based on U/Pb and Sm/Nd geochronology, Mercolli et al. (2006) divided the SCB into the 820 ± 10 Ma Juffa complex, the 816 ± 12 Ma Sadh complex, the 799 ± 5 Ma Mahalla complex, and the synchronous Fusht and Hadbin complexes intruded between 790-780 Ma. Table 1 summarizes previous geochronological studies of the SCB.
Table 3.1. Summary of previous and current geochronological studies in the Salalah Crystalline Basement.

<table>
<thead>
<tr>
<th>Complex</th>
<th>Rock name</th>
<th>Sample No.</th>
<th>Isotope method</th>
<th>Dated mineral</th>
<th>Age (Ma)</th>
<th>Error</th>
<th>Temp</th>
<th>Author</th>
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<td>2-mica gneiss</td>
<td>OS 1178</td>
<td>U/Pb</td>
<td>Zr</td>
<td>812</td>
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<tr>
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<td>K/Ar</td>
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<td>Mus60</td>
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<td>5</td>
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<td>Mercelli et al., 2006</td>
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<td>8</td>
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<td>Pb/Pb</td>
<td>Zr</td>
<td>799</td>
<td>7</td>
<td>825</td>
<td>Mercelli et al., 2006</td>
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<tr>
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<td>OS 1170</td>
<td>Sm/Nd</td>
<td>Wh.R</td>
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<td>800</td>
<td>825</td>
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<tr>
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<td>K/Ar</td>
<td>Bi</td>
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<td>300</td>
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<td>Pigmatitic dikes</td>
<td>OS 014</td>
<td>K/Ar</td>
<td>Mus2</td>
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<td>7</td>
<td>350</td>
<td>Adler thesis, 1996</td>
</tr>
</tbody>
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3.5. GEOCHRONOLOGY

3.5.1. Samples Description. Ten samples from different rock types that have been affected by different phases of deformation are obtained to bracket the age of these deformation events (Table 3.2). Below is a description of the samples grouped on the basis of the deformation events that affected them.

Table 3.2. Description of the samples from the Salalah Crystalline Basement used in the geochronological study.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Location</th>
<th>Complex</th>
<th>Rock type</th>
<th>Deformation event</th>
</tr>
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<tr>
<td>Sc 7-6</td>
<td>16°59'17.63&quot;N 5°45'15.94&quot;E</td>
<td>Juffa complex</td>
<td>Garnet quartz-feldsparic gneiss</td>
<td>Gneissic layering</td>
</tr>
<tr>
<td>Sc 9-1</td>
<td>17°22'9.11&quot;N 5°45'10.68&quot;E</td>
<td>Juffa complex</td>
<td>Amphibole quartz-feldsparic gneiss</td>
<td>Gneissic layering</td>
</tr>
<tr>
<td>Sc 6-3</td>
<td>17°36'0.04&quot;N 5°58'14.55&quot;E</td>
<td>Sadh complex</td>
<td>Hornblende gneiss</td>
<td>Ayn-Said thrust</td>
</tr>
<tr>
<td>Sc 7-3</td>
<td>17°21'5.67&quot;N 5°49'58.29&quot;E</td>
<td>Juffa complex</td>
<td>Amphiboleite</td>
<td>Ayn-Said thrust</td>
</tr>
<tr>
<td>Sc 9-6</td>
<td>16°59'50.46&quot;N 5°49'25.00&quot;E</td>
<td>Sadh complex</td>
<td>Hornblende gneiss</td>
<td>Ayn-Said thrust</td>
</tr>
<tr>
<td>SC 4-3</td>
<td>17°24'1.28&quot;N 5°56'17.96&quot;E</td>
<td>Juffa complex</td>
<td>Mylonitic</td>
<td>NW-trending shear zone</td>
</tr>
<tr>
<td>Sc 7-2</td>
<td>17°45'3.04&quot;N 5°57'12.00&quot;E</td>
<td>Sadh complex</td>
<td>Mylonite</td>
<td>NW-trending shear zone</td>
</tr>
<tr>
<td>Sc 11-4</td>
<td>17°04'8.12&quot;N 5°55'53.39&quot;E</td>
<td>Sadh complex</td>
<td>Mylonite</td>
<td>NW-trending shear zone</td>
</tr>
<tr>
<td>SC 4-4</td>
<td>17°23'1.02&quot;N 5°55'24.13&quot;E</td>
<td>Sadh complex</td>
<td>Hornblende schist</td>
<td>Gravitational collapse</td>
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<td>SC 6-2</td>
<td>17°35'6.08&quot;N 5°52'22.96&quot;E</td>
<td>Juffa complex</td>
<td>Red-pegmatite</td>
<td>Undeformed dike</td>
</tr>
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</table>

3.5.1.1 Samples from the gneissic layering. Samples Sc 7-6 and Sc 9-1 are from the Juffa complex in a region that is 7 to 8 km away from the thrust contact between this complex and the Sadh complex and is not affected by strike-slip shearing (Fig. 3.2). Sample Sc 7-6 is a garnet quartz-feldspathic gneiss with small amount of biotite (Fig. 3.3A and B). It composed only of four minerals: quartz, plagioclase, biotite and garnet.
Quartz is the dominant mineral constituting about 50% of the rock bulk composition (Fig. 3.3A). The plagioclase makes about 30% of the rock. Because of the small amount of mafic minerals, gneissic layering is less obvious in the hand-specimen. In thin section biotite has a preferred orientation within the ground mass of the rock, and sometimes forms aggregates that warp around the garnet porphyroblasts (Fig. 3.3B). Garnet is abundant in this rock. Two distinctive garnet sizes can be easily observed in photomicroscope. The larger than 500µm grains seems to be

Figure 3.3. Samples collected from the Juffa complex that have not been affected by subsequent deformation: (A) A close-up photograph of sample Sc 7-6 (Garnet quartzofeldspathic gneiss). (B) A cross-polarized micro-photograph of sample Sc 7-6 showing preferred orientation of biotite crystals wraps around garnet porphyroblast. C) A close-up photograph of sample Sc 9-1 (hornblende quartzofeldspathic gneiss). (D) Cross-polarized micro-photograph of sample Sc 9-1 showing the 40Ar/39Ar dated amphibole crystals at an angle to the preferred orientation of the biotite crystals.
the older, with large quartz crustal replacement at the rim of the grains and smaller in the center. The smaller than 500µm is fresh, unbroken, and lack mineral replacement.

Sample Sc 9-1 is located to the north of sample Sc 7-6 within the Juffa complex (Fig. 3.2). The rock is medium grained amphibole quartzofeldspathic gneiss composed of quartz, biotite, and green amphibole (Fig. 3.3C and D). The planar fabric is obvious in both the hand specimen and under the microscope. It is defined by the alignment of small needle like biotite crystals (Fig. 3.3D). Less than 100µm biotite crystals are found enclosed inside recrystallized quartz pseudo-morphs (Fig. 3.3D). Quartz crystals are small in size and completely recrystallized. Larger quartz crystals seem to have replacing garnet minerals. Remnants of small garnet grains and its original shape are still preserved in the center of many quartz grains (Fig. 3.3D). The amphibole crystals are oriented at an angle to the biotite crystals, and almost all the grain shows an overgrowth of the amphibole lattice (Fig. 3.3D).

3.5.1.2 Samples from Ayn-Said thrust contact. Three samples were collected from different complexes along the Ayn-Said thrust contact to represent this major event (Fig. 3.2). Sample Sc 6-3 is from the eastern part of the thrust contact and belongs to the hornblende gneiss of the Sadh complex. It composed of hornblende, plagioclase, and muscovite (Fig. 3.4A and B). All minerals show strong preferred orientation parallel interpreted by AlDoukhi and Abdelsalam (in review) to be developed as a planar fabric associated with to the thrust contact between the Juffa and the Sadh complexes. In thin section, the preferred orientation is slightly noticed (Fig. 3.4B). Minerals are fresh and without any sign of alteration. There is no distinctive difference in grain size among different minerology.
Figure 3.4. Samples collected from different complexes along the Ayn-Said thrust contact: (A) A close-up photograph of sample Sc 6-3 representing the hornblende gneiss of the Sadh complex. (B) A cross-polarized micro-photograph of sample Sc 6-3 showing the preferred orientation of the hornblende crystals. (C) A close-up photograph of sample Sc 7-3 representing the amphibolite component of the Juffa complex. (D) A cross-polarized micro-photograph of sample Sc 7-3 showing preferred orientation of amphibole crystals at an angle to micro-crack filled with calcite minerals. (E) A close-up photograph of the hornblende gneiss (sample Sc 9-6) of the Sadh complex. (F) A cross-polarized micro-photography of sample Sc 9-6 showing the 40Ar/39Ar dated hornblende.
Sample Sc 7-3 is situated in the northwestern western end of the thrust contact (Fig. 3.2). The sample belongs to the amphibolite component of the Juffa complex (Fig. 3.4C and D). It is foliated with a noticeable mineral lineation defined by elongated amphibolite crystals. The amphibole is the main constituent of the rock, making about 80% of the bulk composition (Fig. 3.4D). Quartz makes about 5% of the rock and they are mostly strained and seem to grow at the expense of other minerals. About 10% alteration is affecting the rock. The dark spots scattered along the whole thin section represent opaque mineral (Fig. 3.4D). Many micro-cracks are noticed within the rock following no specific orientation. The cracks are filled with calcite minerals and with serpentinization encase the wall of the cracks and extended out like fathers in the rock body (Fig. 3.4D).

Sample Sc 9-6 is situated at the Ayn-Saide thrust contact in the hinge zone of the SW-plunging antiform (Fig. 3.2). It represents the hornblende gneiss of the Sadh complex. The sample is a medium grain foliated rock composed mainly of plagioclase, quartz, and hornblende (Fig. 3.4E and F). In thin section, alteration is covering the matrix while the three main components of the rock are fresh lacking any type of alteration. The gneissose fabric is manifested mainly by the preferred orientation of the tabular euhedral hornblende crystals (Fig. 3.4F).

3.5.1.3 Samples from the strike-slip shear zones. Three samples from different complexes in the SCB were collected along the more pronounced NW-trending dextral strike-slip shear zones (Fig. 3.2). Sample Sc-4-3 within the Bayt Said shear zone and it represents a sheared gneissic rock from the Juffa complex. Although it falls along the Ayn-Said thrust, the dominant planar and linear fabric manifests NW-trending strike-slip shearing (Fig. 3.5A and B). The sample is composed of medium grain highly-sheared mica
schist, with 85% medium grain mica, sericite, and chlorite alteration, and 15% quartz and feldspars mylonitic porphyroblast. In thin section, biotite is the main phyllosilicate mineral. It is usually altered into chlorite and sericite especially in the high strain zones (Fig. 3.5B). Feldspars are usually > 500 µm in diameter, and commonly represent mylonitic porphyroblasts and rarely found in the matrix. Quartz is found in two sizes; the > 400µm and more often as < 300 µm grains. The smaller quartz grains occur either as broken grains in the ground mass of the rock or in the pressure shadow area of the mylonitic porphyroblasts (Fig. 3.5B). Garnet represents about 3% of the total rock composition (Fig. 3.5B). Two types of garnet are easily recognized, a relatively large and deformed garnet with the fabric-related minerals penetrate the grains following the regional fabric orientation, and a smaller garnet with the foliation related minerals wraps around the grain forming the mylonitic fabric. The mylonitic fabric in this rock is defined by the preferred orientation of the muscovite and chlorite minerals (Fig. 3.5B).

The second sample (Sc 7-2) was collected from the Shaat shear zone which is located in the easternmost part of the Said-Ayn dome (Fig. 3.2). This sample is characterized by mildly-developed mylonitic fabric superimposed on originally biotite-muscovite gneiss of the Sadh complex (Fig. 3.5C and D). It composed mainly of fine to medium grain quartz, biotite and some feldspar. In thin section the quartz represents about 60% of the total rock composition. Biotite represents 25% of the bulk composition. The sample shows zones of discrete shearing. It has no signs of alteration and strain is very obvious in the biotite crystals. Biotite shows a preferred orientation parallel to the
Figure 3.5. Samples collected along different complexes along the NW-trending strike-slip shear zones: (A) A close-up image of the mylonitic fabric within the highly-sheared mica schist sample Sc 4-3 of the Sadh complex. (B) A cross-polarized microphotography of sample Sc 4-3 showing the preferred orientation of the muscovite crystals wraps around the garnet porphyroblast. (C) An image for the mildly-developed mylonitic fabric in biotite-muscovite gneiss (sample Sc 7-2) of the Sadh complex. (D) A cross-polarized micro-photography of sample Sc 7-2 showing the orientation of 40Ar/39Ar dated biotite crystals. (E) A close-up image of the mylonite (sample Sc 11-4) within the Sadh complex. (F) A thin section image of sample Sc 11-4 showing the crushed and recrystallized quartz crystals in the pressure shadow region of the feldspar porphyroclast.
shear plane, while muscovite minerals show a lineation at an angle to the biotite direction. The mylonitic porphyroblast is represented mainly by deformed quartz crystals that are highly strained in thin section.

Sample Sc 11-4 is from the Ayngalf shear zone (Fig. 3.2) and has the well-developed mylonitic fabric compared to the other samples representing the strike-slip shearing event (Fig. 3.5E and F). It is located within the Sadh complex. The rock is made-up of porpohyroclasts of feldspar and quartz crystals within quart, feldspar and biotite matrix. In thin section, the feldspar porphyroclasts are K-Na rich microperthite (Fig. 3.5F). The edges of these porphyroclasts are irregular and surrounded by small recrystallized quartz grain and Na-rich feldspars indicating dynamic recrystallization. The mylonitic fabric is defined by the alignment of the biotite crystals (Fig. 3.5F).

3.5.1.4 Sample from the gravitational collapse contact. This sample (Sc 4-4) was collected the hinge of the SE-plunging antiform close to Ayn-said thrust and the Bayt Said shear zone (Fig. 3.2). It is mica hornblende schist from the Sadh complex and contains muscovite and biotite representing a matrix with well-developed schistosity enclosing quartz porphyroblasts (Fig. 3.6A and B). The hornblende defines mineral mineral lineation over-growing on the planar fabric. The rock show luster sheen due to its high muscovite content. It exhibits over growth of amphibole mineral in one prefer orientation (Fig. 3.6A) due to the SE-directed gravitational collapse locally reactivating thrust planes. In thin section, the rock composed of 40% strained quartz grains and 20% biotite and muscovite, with the amphibole forming the rest of the rock (Fig. 3.6B). The planar fabric is exhibited due to the preferred orientation of the platy minerals.
Recrystallization of quartz is observed in the thin section with the quartz being replaced by other minerals.

### 3.5.1.5 Undeformed sample.

An undeformed sample (Sc 6-2) was collected from the core of the Ayn-Said dome and it represents a post-kinematic pinkish feldspar-rich pegmatite dike (Fig. 2). The rock composed of 95% orthoclase with quartz and biotite forming the rest. There is no evidence of any deformation related fabrics or preferred orientation of any mineral. In thin section, the pegmatitic phenocrysts are made-up of the cross-hatched orthoclase, and muscovite and quartz aggregates (Fig. 3.7A and B).

![Image](image.jpg)

Figure 3.6. Sample collected from the localized gravitational collapse zone: (A) A close-up of the hornblende mineral overgrowth within the mica hornblende schist (sample Sc 4-4) of the Sadh complex. (B) A thin section of sample Sc 4-4.

### 3.5.2. Analytical Method.

The samples were analyzed in New Mexico Geochronology Research Laboratory (NMGRL). Each sample was crushed in a jaw crusher and ground in a disc grinder and then sized. The size fraction used generally corresponds to the largest size possible, which will permit obtaining a pure mineral
separate. Following sizing, the sample is washed and dried. Crystals are separated using standard heavy liquid, Franz magnetic and hand-picking techniques (McIntosh et al., 2003). All of the minerals were analyzed by the incremental step-heating method with 75Wphoton-machines and the samples were heated using a defocused 810 nm diode laser. The Argon gas extracted by CO2 laser heating, the CO2 laser is a Synrad 50W laser equipped with a He-Ne pointing laser (Peters, L., 2011). The laser chamber is constructed from a 3-3/8” stainless steel conflat and the window material is ZnS. The extraction line is a two-stage design. The first stage is equipped with a SAES GP-50 getter operated at 450°C, whereas the second stage houses two SAES GP-50 getters operated at room temperature and the tungsten filament is operated at ~2000°C. Gases evolved from samples heated in the furnace are reacted with the first stage getter during heating. Following heating, the gas is expanded into the mass spectrometer through a cold finger.
operated at -140°C for analysis. The J-factor determined to a precision of ±0.02% by CO2 laser-fusion of 6 single crystals (Peters, L. 2011). The mass spectrometer is operated with a resolution ranging between 450 to 600 at mass 40 and a sensitivity= 1E-16 mole/fA. Final isotopic intensities are determined by linear regression to time zero of the peak height versus time following gas introduction for each mass. Each mass intensity is corrected for mass spectrometer baseline and background and the extraction system blank.

3.5.3. Results. Results of the geochronological study of the tens samples are summarized in table 3.3.

3.5.3.1 Gneissic layering. $^{40}\text{Ar}/^{39}\text{Ar}$ dating was carried out on biotite crystals in both samples Sc 9-1 (garnet quartz-feldspathic gneiss) and Sc 7-6 (hornblende quartz-feldspathic gneiss) taken from the Juffa complex away from zones of thrusting or strike-slip shearing. The biotite crystals in both samples are small needle-like idioblastic crystals that found scattered in the ground mass of the sample and are only noticed under microscope (Fig. 3.3 B and D). These small biotite crystals show one preferred orientation parallel to the regional gneissic layering. In sample Sc 7-6 larger biotite crystals are observed with the same preferred orientation. However, sometimes the biotite crystals occur in aggregates that wraps around garnet porphyroblasts. An age of 828.9±2.4 Ma is obtained from sample Sc 7-6 with MSWD=43 (Table 3.3, Figure 3.8A) making it the oldest cooling age affects the SCB. Sample Sc 9-1 gave an age of 814.1±1.4 Ma with a MSWD=192 (Table 3.3, Figure 3.8B).
Table 3.3. 40Ar/39Ar isotopic data and age results for the ten dated samples representing the different deformations events acted on the Salalah Crystalline Basement.

<table>
<thead>
<tr>
<th>Sample</th>
<th>L#</th>
<th>min</th>
<th>Plateau</th>
<th>TGA</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Age ± MSWD 39Ar n</td>
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<tr>
<td>SC-4-3</td>
<td>61394-01</td>
<td>M</td>
<td>783.14 ± 0.71 27 98.3 8</td>
<td>781.38 ± 0.25 9</td>
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<td>SC-4-4</td>
<td>61396-01</td>
<td>H</td>
<td>787.6 ± 2.5 96 93.9 3</td>
<td>782.87 ± 0.45 6</td>
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<td>SC-7-2</td>
<td>61392-01</td>
<td>B</td>
<td>779.38 ± 0.78 847 96.9 9</td>
<td>777.14 ± 0.15 10</td>
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<tr>
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<td>M</td>
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<td>SC-7-3</td>
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<td>H</td>
<td>802.90 ± 0.28 2.8 94.2 5</td>
<td>801.16 ± 0.25 8</td>
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<td>B</td>
<td>828.9 ± 2.4 43 38.7 4</td>
<td>790.66 ± 0.28 8</td>
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<td>B</td>
<td>814.1 ± 1.4 192 67.5 7</td>
<td>796.79 ± 0.26 9</td>
</tr>
<tr>
<td>SC-9-6</td>
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<td>H</td>
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<td>793.63 ± 0.56 9</td>
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<td>B</td>
<td>784.6 ± 1.3 12 52.8 7</td>
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</tr>
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</table>

L# = Lab number
min = mineral dated. H=hornblende, B=Biotite, M=Muscovite
n = number of steps for plateau or TGA calculation.
% 39Ar = percentage of total 39Ar comprising the plateau.
TGA = total gas age.
All errors at 1σ
Age in box is preferred cooling age.

Figure 3.8. An 40Ar/39Ar age spectra diagrams for the biotite dated mineral: (A) in sample Sc 7-6 and (B) in Sample Sc 9-1 obtained from the gneissic layering event.
3.5.3.2 Thrusting event. Samples Sc 6-3 (hornblende gneiss), Sc 7-3 (amphibolite), and Sc 9-6 (hornblende gneiss) were collected from different location along the Juffa-Sadh thrust contact (Fig. 3.2). Dating of the three samples was done on hornblende minerals. In all samples, the hornblende crystals are fresh and do not show any sign of alteration. The super-imposition of thrust-related planar fabric on the earlier gneissic layering is obvious in all samples. The preferred orientation of the hornblende crystals is parallel to the thrust contact. Sample Sc 7-3 registered an age of 802.90±0.28 Ma with an MSWD=2.8 (Table 3.3; Fig. 3.9A). Samples Sc 9-6 and Sc 6-3 gave ages of 795.98±0.43 Ma with an MSWD of 1.36 and 795.26±0.48 Ma with an MSWD=2.58, respectively (Table 3.3; Fig. 3.9B and C).

Figure 3.9. Age spectra diagrams for the hornblende dated minerals obtained from samples situated along the Ayn-Said thrust contact: (A) for hornblende gneiss sample Sc 6-3, (B) for the amphibolite sample Sc 7-3, and C) for the hornblende gneiss sample Sc 9-6.
3.5.3.3 Strike-slip Shearing and low-angle gravitational collapse events. The dextral NW-trending sets of strike-slip shear zones are more pronounced than its complementary conjugate set of sinistral NE-trending set. Three samples were collected from along different NW-trending shear zones (Fig. 3.2). Sample Sc 7-2 is a biotite-mica schist that collected from along one of the NW-trending shear zones. This sample shows evidence of super-imposition of shearing fabric defined by localized shear zones and deformed and strained quartz porphyrocrysts. Biotite crystals from this sample gave an age of 779.38± 0.78 Ma and MSWD of 847 (Table 3.3; Fig. 3.10A). The biotite crystals show a preferred orientation parallel to the shear planes, while muscovite minerals show a lineation at an angle to the biotite direction. Samples Sc 4-3 and Sc 11-4 are mylonitic rocks that are intensely affected by the strike-slip shearing event.

Sample Sc 11-4 is dated using biotite mineral giving an age of 764.6±1.3 Ma and a MSWD= 12 (Table 3.3; Fig. 3.10B). The biotite is highly deformed and shattered into small crystals. It is found either as individual crystals within the rock’s matrix or as aggregates of small needle-like crystals. Sample Sc 4-3 is dated by muscovite minerals which are intensely deformed. The minerals are sometime altered to sericite. It shows a strong preferred orientation and wraps around garnets and sometimes quartz mylonitic porphyroclasts. The sample gave an age of 783.14±0.17 Ma with an MSWD=27 (Table 3.3; Fig. 3.10C).

Dating of the hornblende crystals that show over-growth within the planar fabric in sample Sc 4-4 provides an age of 787.6±2.5 Ma (Table 3.3; Fig. 3.10D). Two different hornblende setting are recognized in this sample. Smaller hornblende crystals are scattered without any preferred orientation of any kind. Larger crystals have more pronounced
orientation indicating stretching lineation developed during a low-angle detachment gravitational collapse.

Figure 3.10. Age spectra diagrams for different dated minerals obtained from samples situated strike-slip shear zones: A) for the muscovite dated mineral in the highly-sheared mica schist sample Sc 4-3, B) for the biotite dated mineral in the biotite-muscovite gneiss sample Sc 7-2, and C) for the biotite dated mineral in the mylonite sample Sc 11-4.

3.5.3.4 End of deformation. Sample Sc 6-2 is a pink pegmatite rock that was obtained from one of the unreformed dykes dissecting the core of the Ayn-Said dome (Fig. 3.2). The rock is made-up of undeformed pigmatitic k-feldspar with small amounts of muscovite and quartz. The muscovite crystals are small and undeformed with minor sericitization. A muscovite age of 752.2±2.7 Ma with an MSWD=347 was obtained from this sample (Table 3.3; Fig. 3.11). This may related to the common problem of the
Precambrian samples as it is likely not to be stable in the vacuum system at high temperature, or it could possibly implies a multiple intrusion impulse within the dyke system.

![Diagram](image)

Figure 3.11. Age spectra diagrams for the muscovite dated minerals obtained from the pink-pegmatite dike sample Sc 6-2.

3.6. DISCUSSION

3.6.1. Timing of Deformation in the SCB. The $^{40}\text{Ar}/^{39}\text{Ar}$ age dating of samples from different deformation events indicate that the present day framework of the SCB started to take shape about 828±3 Ma ago. The oldest complex in the SCB is composed of three different rock types that wedged together to form the Juffa complex with dominant gneissic layering. Previous studies suggest that the gneisses of the Juffa complex have a sedimentary protolith about 1.3 Ga old (Mercolli et al., 2006). Hence, the $^{40}\text{Ar}/^{39}\text{Ar}$ ages obtained in this study (829-814 Ma) can be taken as the cooling age of the gneissic layering in the complex. Mercolli et al. (2006) considered the period around 820 Ma as the
beginning of the climax of crustal building processes of the SCB. Hence, this event was likely accompanied by metamorphism and the formation of the gneissic layering.

The $^{40}$Ar/$^{39}$Ar ages obtained from samples collected along the Ayn-Said thrust ranges between 803 and 793 Ma which are younger than the ages obtained from samples away from the thrust contact. These ages are believed to represent the timing of the major thrusting event between the Sadh and Juffa complex. The prolong N-S shortening responsible for the accretion of the two complexes might be reflected in the ~10 Ma difference between the oldest (803 Ma) and the youngest (793 Ma) ages obtained from these samples.

The three samples collected from sheared minerals along the NW-trending strike-slip shear zones gave ages ranging between 783 Ma and 764 Ma; ages that are at least 10 Ma younger than the youngest age obtained from the samples collected from along the Ayn-Said thrust. Structural observation by AlDoukhi and Abdelsalam (in review) clearly shows that the NW-trending shear zones cut across the thrust contact. Hence, these ages are interpreted the ages from these samples to represent the timing of the NW-trending dextral strike-slip shearing event.

AlDoukhi and Abdelsalam (in review) suggested that the last event in the structural evolution of the SCB was in the form of low-angle localized gravitational collapse which locally re-activated the Ayn-Said thrust. It is expected that the sample collected from this structure to produce an age younger than those of the samples collected from the NW-trending shear zones. However, the sample that is thought to preserve planar and linear fabric formed during the localized gravitational collapse gave an age of 783. This age is comparable or slightly older than the oldest age of the NW-trending shearing event. This
age indicates a synchronous event in which the dextral movement along the NW-trending strike-slip shear zones might have triggered the reactivation of the thrust contact into low-angle detachment.

3.6.2. The Uplift History of the Salalah Crystalline Basement. An overall Temperature-time (T-t) plot of the three main complexes that made up the SCB compiled from data obtained in this study and previous studies is presented in Table 3.3 and Figure 3.12. This T-t plot indicates a massive cooling from 800°C to 300°C in a very short time span. The U/Pb zircon chronology shows an overlapped age of 820 Ma for both Juffa and Sadh complexes and not long after that (about 800 Ma) for the Mahalla complex at 825°C. Results obtained from Rb/Sr and Ar/Ar of biotite and muscovite minerals in Juffa and Sadh complexes cluster the ages of these minerals into two events. The first event was around 800 Ma and 760 Ma for the muscovite and biotite, respectively. The second event occurred around 760 Ma for the muscovite and 710 Ma for the biotite minerals. This indicates inconstant rate from high cooling rate followed by lower cooling rate. The first muscovite minerals cluster reaches 350°C around 800 Ma. This gives a 20 Ma time span of the two complexes to cool from 825°C to 350°C in case that the zircon and the first mica minerals appearance are from the same event. The second cluster indicates a slower rate from 350°C to 300°C in a 50 Ma time span. Accordingly, two cooling scenarios are suggested. The first involves a rapid cooling scenario due to vertical movements in a convergent boundary. Würsten (1994) suggested a hypothetical geothermal gradient of 45°C/km for the SCB during the retrograde path of metamorphism. This makes the exhumation rate 0.5km/Ma of the basement complexes compared to the Himalayan exhumation rate of about 10km/Ma during the fold and thrust belt due to convergent plate
boundary (Chirouze et al., 2013; Konstanze et al., 2013). The SCB could resemble the Himalayan exhumation as a result of the convergence between Western and Eastern Gondwana and the closure of the Mozambique Ocean during the East African Orogeny.

Figure 3.12. Temperature-time (T-t) plot of the Salalah Crystalline Basement geochronological analysis results. Data obtained from table 3.1.

The second scenario relates the massive cooling event to the gravitational collapse associated with the SCB exhumation as a result of the convergence between Western and Eastern Gondwana. This scenario is supported by the fact that basement went through retrograde metamorphism and temperature reduction during this period. Supported by the inconstant rate of cooling, a faster rate during the climax of the exhumation, and slower
rate at the relaxation of the collapse occurred. Comparing this second scenario with the
geochronological history of the SCB deformations: (1) It is possible that \(^{40}\text{Ar}/^{39}\text{Ar}\) ages
obtained from samples collected along the Ayn-Said thrust ranges between 803 and 793
Ma marks the exhumation time of the basement. So that the thrust contact pre-date that age
and has been overprinted by the amphibolite facies condition that associated with the
gneissic layering. (2) The overlap age between samples collected from sheared minerals
along the NW-trending strike-slip shear zones and sample that preserved planar and linear
fabric formed during the localized gravitational collapse is due to the coincide of these two
events together. This is manifested by the SE-plunging mylonitic lineation associated with
the NW-trending shear zones.

The exhumation was terminated by the deposited of sedimentary formation
overlaying the basement rocks (Marbat Formation) marking the exhumation time for the
Salalah basement rocks at 630-542 Ma (Gass et al., 1990; Mercolii et al., 2006). This
indicates that the second cooling rate that reached 300°C at 710 Ma continued at a slow
rate until the basement was totally exhumed about 540 Ma.

3.6.3. Timing of Deformation Correlated to the Arabian-Nubian shield

**History.** Despite the fact that exhumation of the SCB above sea level was accomplished
during the extensional crustal thinning of the Arabian-Nubian shield, the deformation
events in the SCB seem to be older than those in different terranes herein (Fig. 3.13). For
example, the gravitational collapse event in the SCB coincides with the initiation of the
Arabian-Nubian Shield amalgamation and pre-date the main crustal extension event of the
shield. This means that at the time that crustal extension ending in the SCB, crustal
thickening was already initiated in the west. This placed both areas in an opposite strain regimes

In addition, comparing the main strike-slip shearing event in the Arabian Shield (represented by the NW-trending sinistral Najd fault system) to the NW-trending dextral strike-slip shearing event in the SCB indicates an opposite sense of movement, although both systems have the same trend and are almost traced together if extended. However, it seems that activities along the NW-trending dextral strike-slip shear zones of

![Figure 3.13. Geochronology of tectonic events in the Arabian Shield (top part) compared with the main events in the Salalah Crystalline basement (lower part). Modified after Genna et al (2002).](image-url)
the SCB might have started earlier (~783 Ma) than the shearing activities along the Najd fault system (~640 Ma) as suggested by Stern and Johnson (2010). The authors also suggested an undated earlier dextral strike-slip component of the Najd fault system. This requires further studies to correlate the NW-trending dextral strike-slip shearing event in the SCB with those of the Najd fault system.

3.7. CONCLUSIONS

Results from $^{40}$Ar/$^{39}$Ar age dating on ten samples affected by different deformation events that sculptured the present-day structural appearance of the SCB have shown at least three different events with discrete ages. The oldest of these events falls between 828.9±2.4 Ma and 814.1±1.4 Ma. The samples exhibiting this age range are obtained from regions within the Juffa complex that are not affected by subsequent deformation. This indicates that the overall structural evolution of the SCB must have started with deformation and metamorphic events that resulted in the formation of the extensive gneissic layering of the Juffa complex. Following this event was the development of the thrust contact between the Juffa and the Sadh complexes. The samples obtained from this contact gave ages ranging between 802.90±0.28 Ma and 795.26±0.48 Ma. The third event occurred between 787.6±2.5 Ma and 764.6±1.3 Ma. This deformational event includes both deformation associated with the development of conjugate sets of dextral NW-trending and sinistral NE-trending strike-slip shear zones and low-angle SE-directed gravitational collapse. Deformation within the SCB might have seized by 752.2±2.7 Ma as
indicated by the age given by the undeformed pegmatitic sample. This age marks the end of a prolong deformation period that spanned about 50Ma.

A T-t plot of zircon, biotite, muscovite, and hornblende minerals obtained from U/Pb, Rb/Sr, K/Ar, and \(^{40}\)Ar/\(^{39}\)Ar geochronology indicates one massive cooling event. This event was tied to the fast exhumation rate of the SCB synchronizing the three deformation events. The initiation of the Salalah basement exhumation pre-dates the crustal thinning of the Arabian Nubian Shield, but was terminated at 630-542 Ma during the extensional event of it.
4. CONCLUSIONS

The final structural architecture of the SCB was shaped by four structural events. The first event resulted in the emplacement of the Sadh complex atop the Juffa complex during N-verging nappe translation deformation. Hence, this event developed the contact between the two complexes as a major thrust (the Ayn-Said thrust) that was subsequently deformed by younger deformation events. The second event re-folded the previous structure around SE- and SW-axes producing a E-W doubly-plunging antiform (Ayn-Said dome). The third event is manifested by the development of a conjugate set of NE-trending sinistral and NW-trending dextral strike-slip shear zones that dissected the Ayn-Said dome into the Ayn and the Said sub-domes. The last event in the evolution of the SCB is marked by a localized gravitational collapse. It is possible that the first three events in the evolution of the SCB originated from a single tectonic pulse characterized by N-S directed shortening. This shortening was first accommodated as N-verging nappes which were subsequently refolded about SE- and SW-plunging axes leading to the accommodation of the N-S shortening into NE-trending sinistral and NW-trending dextral strike-slip shear zones.

$^{40}\text{Ar}/^{39}\text{Ar}$ age dating showed at least three different events with discrete ages. The oldest of these events falls between 828.9±2.4 Ma and 814.1±1.4 Ma. Following this event was the development of the thrust contact between the Juffa and the Sadh complexes at about 802.90±0.28 Ma - 795.26±0.48 Ma. The third even occurred between 787.6±2.5 Ma and 764.6±1.3 Ma. This deformational event includes both deformation associated with the development of conjugate sets of dextral NW-trending and sinistral NE-trending strike-slip shear zones and low-angle SE-directed gravitational collapse. Deformation within the SCB
might have seized by 752.2±2.7 Ma. This age marks the end of a prolong deformation period that spanned about 50 Ma. The T-t plot indicates one massive cooling event. This event was tied to the fast exhumation rate of the SCB synchronizing the three deformation events. The initiation of the Salalah basement exhumation pre-dates the crustal thinning of the Arabian Nubian shield, but was terminated at 630-542 Ma during the extensional event of it.
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