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ORIGINAL PAPER

Infracambrian superimposed tectonics in the Late Proterozoic units of Mount Ablah area, southern Asir Terrane, Arabian Shield, Saudi Arabia

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Abstract Mount Ablah is a mining prospect, hosted by a dioritic igneous body that is bound to the east by greenschist grade metamorphic rocks and to the west by Ablah group volcano–sedimentary rocks. Rock units of Mount Ablah area were remapped through field investigations, petrological studies, and analysis of enhanced TM Landsat data. Ablah group rocks were divided into lower tuffaceous and upper epiclastic units. The epiclastic unit was divided into three subunits. During remapping, a sliver of serpentinite was discovered, which occurs between the dioritic igneous body and Ablah group rocks. The greenschist grade metamorphic rocks were intruded by Late Proterozoic quartz diorite prior to deposition of Ablah group rocks. The epiclastic unit is an infracambrian molassic unit that filled a graben, known as the Ablah graben. The Mount Ablah area was intruded by post-tectonic granitic rocks and affected by two superimposed F1-F2 folding events, associated with thrust and dextral faults, respectively. The first folding event involved N–S folding and thrusting. Simultaneously, stress partitioning at E–W accommodations zones produced E–W minor folds (F2) and associated E–W dextral faults. The F1–F2 folding events are contemporaneous with the Pan African deformation event, also known as the East African Orogeny (EAO). The EAO is infracambrian in age and culminated in development of the Najd sinistral fault system. The E–W dextral faults were probably reactivated during Cenozoic Red Sea rifting. The Ablah graben's infracambrian sedimentary rocks, such as siltstone, sandstone, and limestone that are mainly bound within the Ablah graben were not deformed prior to F1–F2 folding. Thus, the upper epiclastic unit of the Ablah group rocks is rheologically different from the surrounding greenschist rocks, responded to the late E–W compression in a more ductile manner than the surrounding greenschist rocks. Therefore, the Ablah graben was inverted, refolded, and crosscut by E–W dextral faults during the infracambrian EAO event, prior to development of Najd sinistral fault system, which are evident in Asir Terrane and crosscut Ablah graben.

Keywords Arabian Shield · Ablah graben · Suture zone

Introduction

This paper illustrates results of recent detailed mapping, petrological studies, and analysis of remotely sensed data in Mount Ablah area, between latitudes 20°14′ and 20°20′ north and longitudes 41°00′ and 41°30′ east. The main objectives of this paper are to present the lithostratigraphy, structural geology, and tectonic setting of the northern part of Ablah Graben area. During 650–540 Ma period, the Neoproterozoic (900–550 Ma) rocks of the Arabian Shield in Saudi Arabia underwent intra-continental molasse basins development and inversion (Genna et al. 1999; Johnson 2003), which evolved during the Pan African orogen, also known as the East African Orogen (EAO; Stern 1994; Meert and Lieberman 2008; Stern and Johnson 2010). Evolving of the molasse basins is a post-collision process of crustal thinning, magmatism, extension, erosion, subsidence, and finally, deposition of volcano–sedimentary rocks (Blasband et al. 2000; Genna et al. 2002). There are 30 or more intra-continental basins which encompass areas, ranging from over 72,000 to 200 km^2 in the Arabian Shield (Fig. 1; Johnson 2003). They unconformably overlapped

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metamorphic rocks that build up juvenile volcanic-arc terranes of the Arabian Shield, which accreted and collided during a process of transpressional subduction and ocean-basin closures, culminating in the Nabitah orogeny from 680 to 640 Ma (Stoeser and Camp 1985; Stoeser and Stacey 1988; Genna et al. 1999; Johnson et al. 2001; Nehlig et al. 2001; Genna et al. 2002; Nehlig et al. 2002; Volesky et al. 2003; Johnson 2006; Johnson and Kattan 2008; Stoeser and Frost 2006; Hargrove et al. 2006). Most of the present terrane boundaries are fault zones, decorated with ultramafic rocks, and record complex kinematic histories related to accretion and post-accretion processes (Fig. 2; Johnson and Kattan 2008).

Ablah graben is a molasse basin, located in Asir Terrane which is one of the terranes in the Arabian Shield that encompasses the southwestern part of Saudi Arabia (Fig. 2). Ablah Graben is one of Asir Terrane's north-trending belts, which are N–S sigmoidal belts of metamorphosed volcanic, plutonic, and sedimentary rocks (Fig. 2), and are cut by numerous shear zones (Fig. 3; Johnson et al. 2001). Ablah graben's rocks form a long and narrow belt, which is bound by two wider belts of the Thurat pluton and Bidah belt's mafic volcanic rocks on the west, and by the An-Nimas batholith and Shwas belt's meta-volcanics and meta-sedimentary rocks on the east (Fig. 2; Johnson 2006). The Ablah graben formed along a north-trending dextral fault and cross-cut by sinistral faults, in which the right-lateral shearing is older than the left-lateral shearing (Donzeau et al. 1989; Johnson and Kattan 2001; Volesky et al. 2003). The right-lateral shearing developed during Nabitah orogen, whereas the sinistral shearing is associated with the EAO. The EAO is infracambrian in age and culminated in development of the Najd sinistral fault system (e.g., Moore 1979). Deformation intensifies southward in the Ablah graben

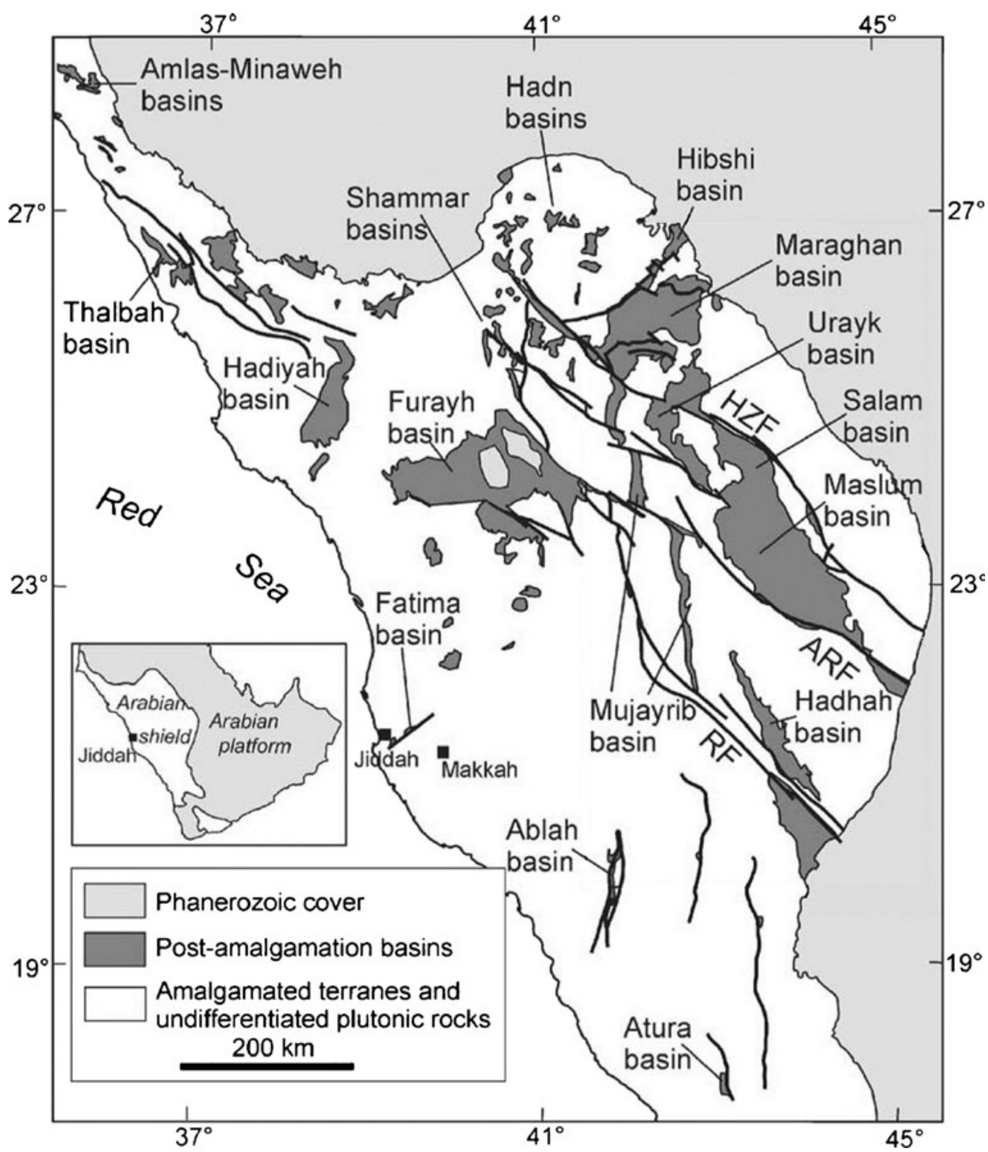

Fig. 1 Post-accretion molasse basins in the Arabian shield. *HZF* Halaban-Zarghat fault zone, *ARF* Ar Rika fault zone, *RF* Ruwah fault zone, adopted from Johnson (2003)

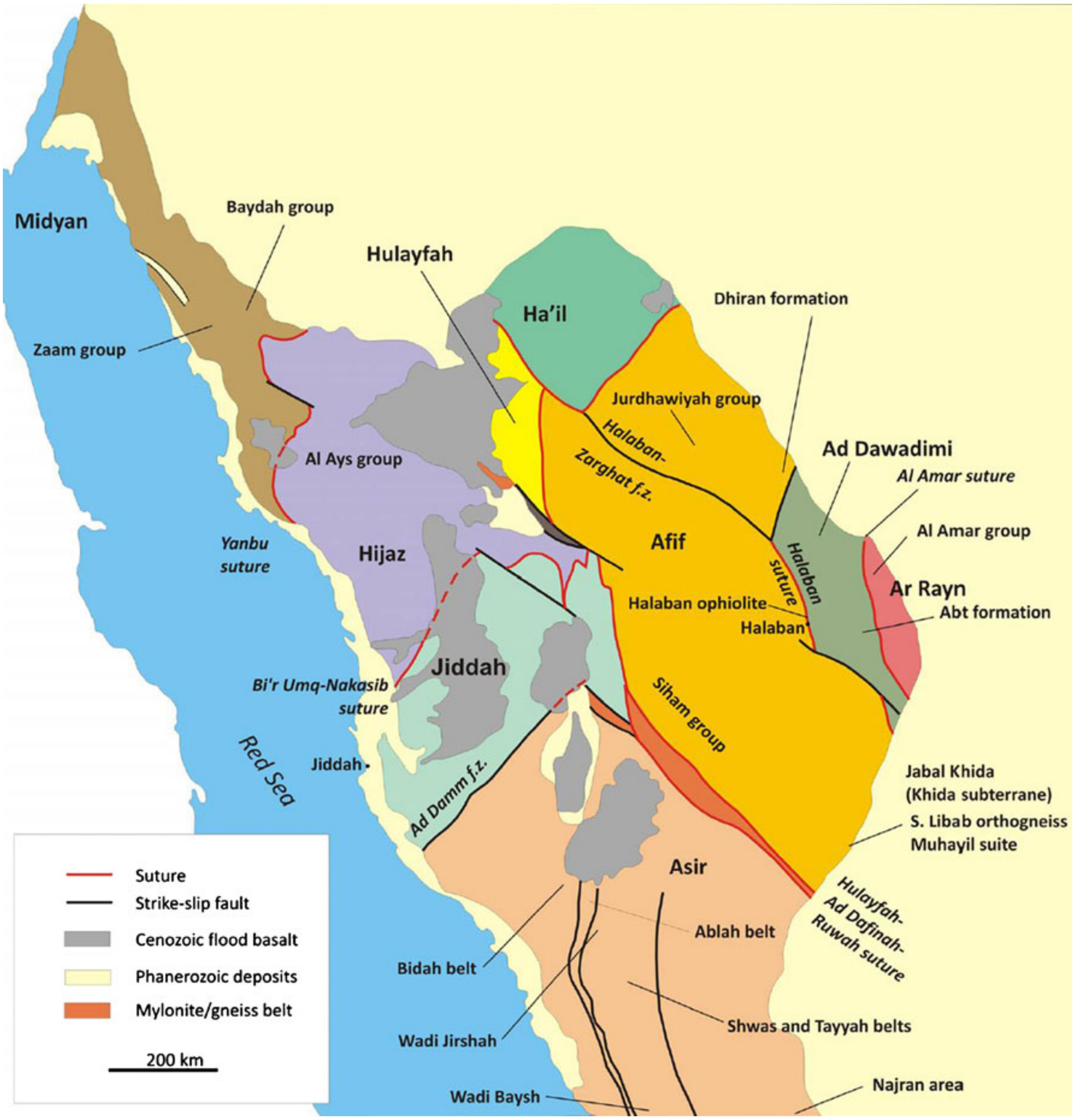

Fig. 2 Tectono-stratigraphic terranes and terrane boundaries of the Arabian shield, Saudi Arabia, and locations of lithostratigraphic units within terranes, such as Bidah, Ablah, and Shwas belts in Asir terrane, adopted from Johnson and Kattan (2008). Note that Stoeser and Frost (2006) subdivided Asir terrane into three subterranes, two of them are equivalent to Shwas and Bidah belts, separated by Ablah belt

as beds thicken, and N–S folds become tighter and their axes become sigmoidal towards the south (Greenwood 1975, 1985a, b; Genna et al. 2002; Johnson 2006). The metamorphic grade reaches amphibolite-facies conditions in the southern part of Ablah graben area (Greenwood 1985a, b).

Methodology

Landsat TM data were enhanced by different methods, such as principal correlation analysis, linear stretch, and high pass filtering techniques. These TM data were interpreted and used as base maps for this study. Field work and detailed mapping included rock units' identification and verification, and structural data synthesis, which were taking place in field camp near Mount Ablah. It also included rock samples collection and preparation for thin-section studies. Results of petrological studies and structural data synthesis and analysis were used for constructing geological and structural maps, which are used for tectonic analyses and interpretations.

Results

The results are explained in the following lithostratigraphy and structural geology subsections. The first subsection

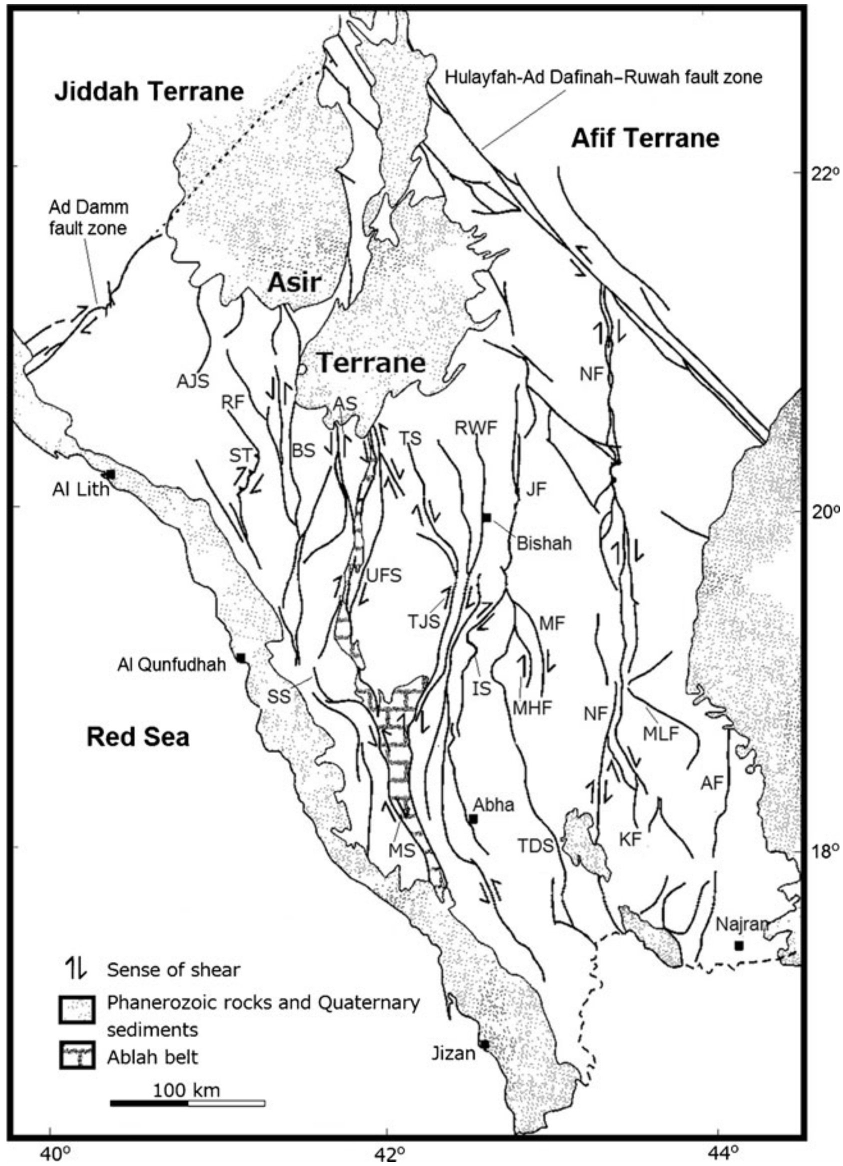

Fig. 3 Tectonic map of Asir terrane showing dextral and sinistral shear and fault zones, adopted from Johnson et al. (2001). *AF* Asharah fault zone, *AJS* A1 Ajr shear zone, *AS* Aqiq shear zone, *BS* Baydah shear zone, *IS* Ibran shear zone, *JF* Junaynah fault zone, *MF Al* Musayrij fault zone, *MHF* Muhadit fault zone, *MLF Al* Mulha fault zone, *MS* Muhayil shear zone, *NE* Nabitah fault zone, *RF* Rama fault zone, *RWF* Rawshan fault zone, *SS* Sayayil shear zone, *ST* Sharah thrust, *TDS* Tindahah shear zone, *TJS* Tarj shear zone, *TS* Tabalah shear zone, *UFS* Umm Farwah shear zone

shows results of the geological and detailed mapping and petrological studies. The second subsection shows results of structural data synthesis and analysis. The petrological studies and structural data synthesis are adopted from Bamousa (1992), analyzed and interpreted in this study.

Lithostratigraphic units

There are mainly five lithostratigraphic units in Mount Ablah area, corresponding to different phases of lithotectonic evolution of the Mount Ablah area and Ablah graben (Table 1); they are from older to younger as follows.

- Pre-Pan-African Late Proterozoic greenschist grade metamorphic rocks.
- Pre-Pan-African Late Proterozoic meta-quartz diorite or tonalite rocks including a sliver of serpentinite.
- Pan-African infracambrian Ablah group volcano–sedimentary rocks.
- Post-tectonic infracambrian granitic rocks.
- Cenozoic flood basalt (Fig. 4).

Greenschist grade metamorphic unit

The metamorphic unit is the oldest unit, composed dominantly of meta-andesite and meta-rhyolite that are bound to the west by strips of met–basalt and chlorite schist (Fig. 4). The metabasalt unit contains boulders of pillow lava (Fig. 5), indicating submarine flow and oceanic affinity. The metamorphic unit occupies the eastern part of the study area, and it is part of Jiddah group (Greenwood 1975) or Shwas Belt's volcanic and sedimentary rocks (Johnson 2006). It is part of the pre-Pan-African Proterozoic

Table 1 Summary of lithotectonic events occurred in the study area, their important geologic features and possible ages adopted from references mentioned in the text

Lithotectonic event	Geologic feature in the study area	Age
Subduction of oceanic crusts and development of a volcanic arc.	Development of Bidah and Shwas belts (Jiddah group) volcaniclastic rocks.	Pre 900 Ma
Accretion of volcanic-arc terranes formed by oceanic bearing rocks	Greenschist metamorphism of Bidah and Shwas belts.	900 Ma
Syn-tectonic magmatism	An-Nimas Batholith	837 Ma
Nabitah orogen	N–S dextral shearing.	680–640 Ma
Post-collision crustal thinning and extension	Development of Ablah graben along N–S dextral fault. Deposition of Ablah group rocks.	641–613 Ma
Post-tectonic magmatism	Granitic intrusive and associated extrusive bodies.	613 Ma
East African Orogen (EAO)	N–S F1 folds and thrust faults. E–W F2 superimposed folds and dextral faults.	600–550 Ma
Najd fault system	NW sinistral shearing.	Post EAO
Red Sea rifting	Flood basalts. Reactivation of E–W dextral faults.	Cenozoic—recent

deposits of Saudi Arabia, which are highly deformed and metamorphosed lower unit including sericite schist, gneiss, migmatite, and numerous lava flows (Genna et al. 1999, 2002). It is intruded by the lower Cryogenian An-Nimas

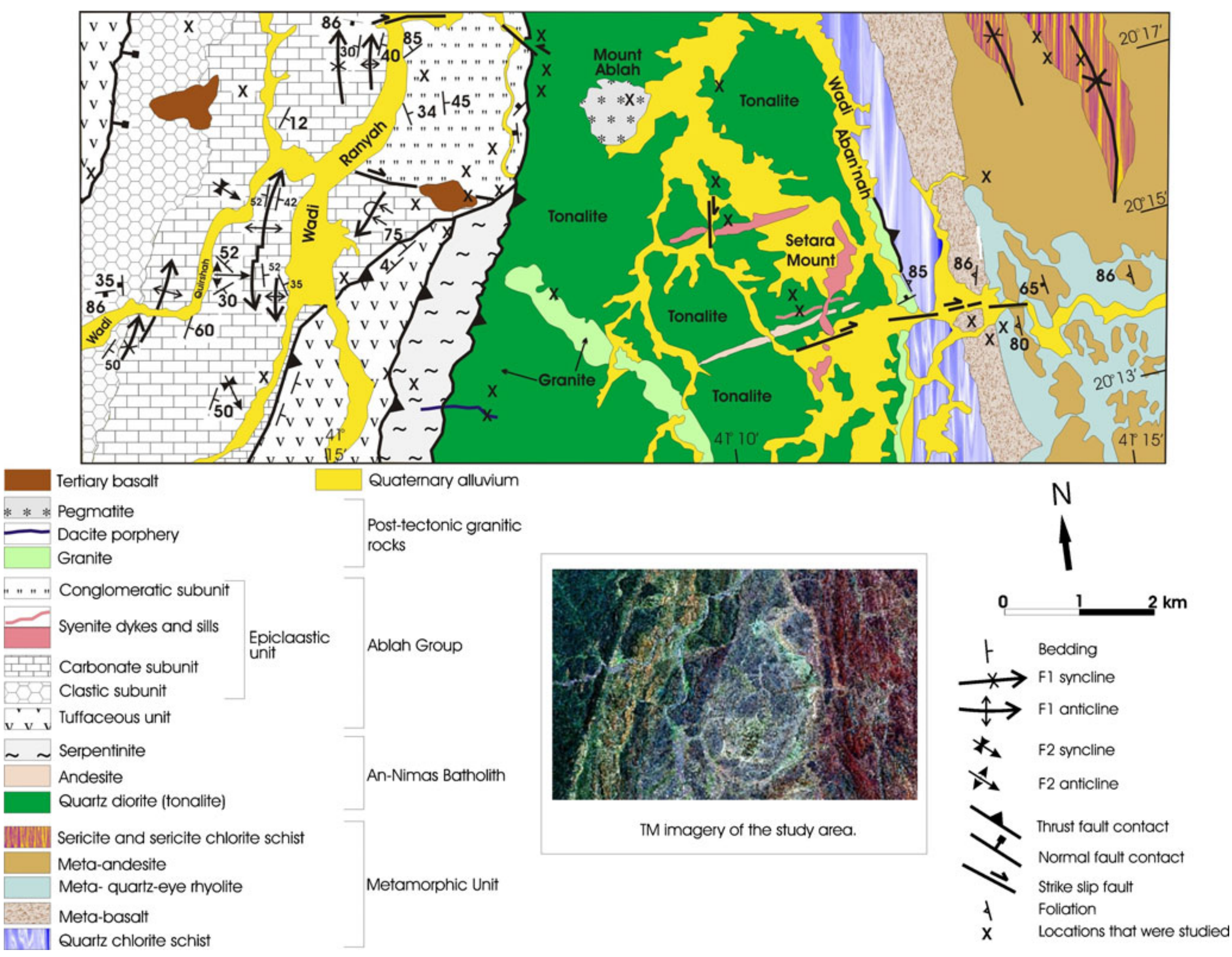

Fig. 4 Geologic map of the study area

Fig. 5 Boulders of pillow lava within the meta-basalt unit

batholith, underlies Ablah group and has oceanic and volcanic-arc affinity (Stoeser and Frost 2006; Hargrove et al. 2006; Johnson 2006).

Dioritic pluton

The unit is mainly composed of quartz dirorite or tonalite and has a lower greenschist grade metamorphism, which is evident by alteration of feldspar minerals into serecite (Greenwood 1975; Bamousa 1992). It comprises the middle part of the study area between the greenschist rocks on the east, and Ablah group rocks on the west. It was intruded by several granitic bodies, is affected by gneissosity near its western flank, and forms a ring structure. The tonalite is part of An-Nimas batholith, which consists of pre-tectonic mafic to intermediate plutonic rocks (Johnson 2006). The An-Nimas batholith is dated at 837±50 Ma by the Rb–Sr whole-rock method, and 816±4 and 797±7 Ma by the U–Pb zircon method; therefore, it is inferred to be lower Cryogenian (Johnson 2006, and references therein).

Serpentinite unit

This unit was assigned in mapping to Jiddah group (Greenwood 1975). Petrological studies suggest that it is a serpentinite, and fieldwork studies suggest that it is originally peridotite and marbleized peridotite, which can be found as small patches within the serpentinite unit (Bamousa 1992). The unit crops out as a sliver, bound by Ablah group rocks to the west and the met-tonalite to the east (Fig. 4). This suggests that it is probably part of the meta-tonalite of An-Nimas batholith because it follows the general trend of the ring structure (Fig. 4). The unit could be an exotic rock sliver that was brought with the meta-tonlite body, juxtaposed to Ablah group rocks during first deformation event.

Ablah group rocks

Ablah group referred exclusively to a sedimentary succession inside Ablah graben (Greenwood 1975). Donzeau et al. (1989) included a lower volcanic unit to the Ablah group rocks, originally mapped by Greenwood (1975) as part of the older Jiddah group rocks. Thus, Ablah group rocks are composed of two units (Genna et al. 1999; Johnson et al. 2001) which are in this paper the lower tuffaceous and upper epiclastic units. Upper Ablah group rocks are part of the deformed Pan-African molassic units of the Arabian Shield (Genna et al. 1999, and references therein). The unit fills generally a north-trending graben, known as Ablah graben, which represents a deformed sedimentary intra-continental basin between the rocks of the An-Nimas batholith and Shwas Belt to the east and those of the Thurat batholith and Bidah Belt to the west (Genna et al. 1999; Johnson 2006). The Ablah graben formed a sedimentary basin, filled with the epiclastic unit, and positively inverted during later tectonic events. Therefore, Ablah group rocks are deformed but unmetamorphosed (Cater and Johnson 1986; Johnson 2003, 2006).

Tuffaceous unit The tuffaeous unit is composed of lithic crystal tuff and crystal tuff (Bamousa 1992). The lithic crystal tuffs contain minor glass shards, and it is acidic in composition. The lithic tuffs contain no glassy shards and it is composed mainly of lithic fragments and sanidine, reflecting acidic composition. The tuffaceous unit is exposed repeatedly along the eastern and western flanks of Ablah graben, to the east and to the west of the epiclastic unit (Fig. 4). The eastern exposure of the tuffaceous rocks are over-thrusted by the tonalite to the east, and are thrusted over the epiclastic unit to the west, in which the thrust faults trend northerly and dip easterly. The western exposure of the tuffaceous unit is separated from the epiclastic unit by a normal fault that trends northerly and dips easterly (Greenwood 1975). The unit is bound by the Thurat batholith to the west and includes a marbleized unit that is overlain by a thick rhyolite sill (*Op Cite*). This rhyolite flow rock was dated by the Pb/Pb zircon evaporation method at 641±1 Ma (Genna et al. 1999) and by the SHRIMP method at 613±7 Ma (Johnson et al. 2001), indicating the group spans the Cryogenian–Ediacaran boundary (Johnson 2006).

Epiclastic unit Greenwood (1975) referred exclusively to this unit as Ablah group, and subdivided this unit into two formations. The lower formation is not exposed in the study area, and the exposed part of the epiclastic unit is the upper part, known as Thurat Formation. The upper part of the epiclastic unit is subdivided into three members younging towards the east, which are the clastic, carbonate, and conglomeratic subunits from older to younger respectively as suggested by primary structures such as graded bedding and cross-bedding (Bamousa 1992).

The clastic subunit is composed of conglomerate, sandstone, and siltstone. The sandstone rocks range in composition from arkozic wacke, quartz wacke, and feldspathic litharenite. All of three rock types show the right way up, which is evident by primary structures such as graded bedding and cross-bedding (Fig. 6). The carbonate subunit has a composition of limestone, lime mudstone, and dolomite. It also contains algal stromatolite cones and algal mats. The subunit was extruded by a quartz syenite sill that is deformed by isoclinal folds. The conglomeratic subunit is the third and youngest subunit of Thurat Formation. The subunit is composed of conglomerate, limestone rocks that are interbedded with andesite sills. Bamousa (1992) reported that some of the pebbles of the conglomerate rocks are originally limestone pebbles.

Granitic rocks

The granitic rocks appear to be the youngest Late Proterozoic rocks as they cross-cut all pre-existing rock units. Greenwood (1975) mapped the area within Al-Aqiq Quad and referred to these igneous bodies as granite and rhyolite only, which intruded and extruded the quartz-diorite. Petrological studies suggest that several dykes are quartz syenite and dacite, such as Setarah Mountain which occurs in the central part of the study area (Fig. 4). The granite rocks appear older than the quartz syenite of Setarah Mountain because they are altered and slightly metamorphosed (Bamousa 1992). The quartz syenite is also present to the southwest of the study area and forms folded sills within the epiclastic rocks. The granitic rocks intruded the tonlite and epiclastic rocks, and are faulted against the metamorphic unit by a subvertical mylonite shear zone that dips to the east (Fig. 4). Therefore, it is considered to be younger than Ablah group, and it is chiefly post-tectonic Ediacarian intrusion (Johnson 2006), which appear to be syn-tectonic to folding and associated faulting events that deformed Ablah group rocks.

Structural geology of the Ablah Mountain area

The Ablah succession was folded by an earlier event that formed N–S isoclinals folds (F1). These folds extend for several kilometers, mainly within the Ablah graben. The F1

Fig. 6 Map view of planar cross-bedding in the fine-grained rocks of the clastic subunit

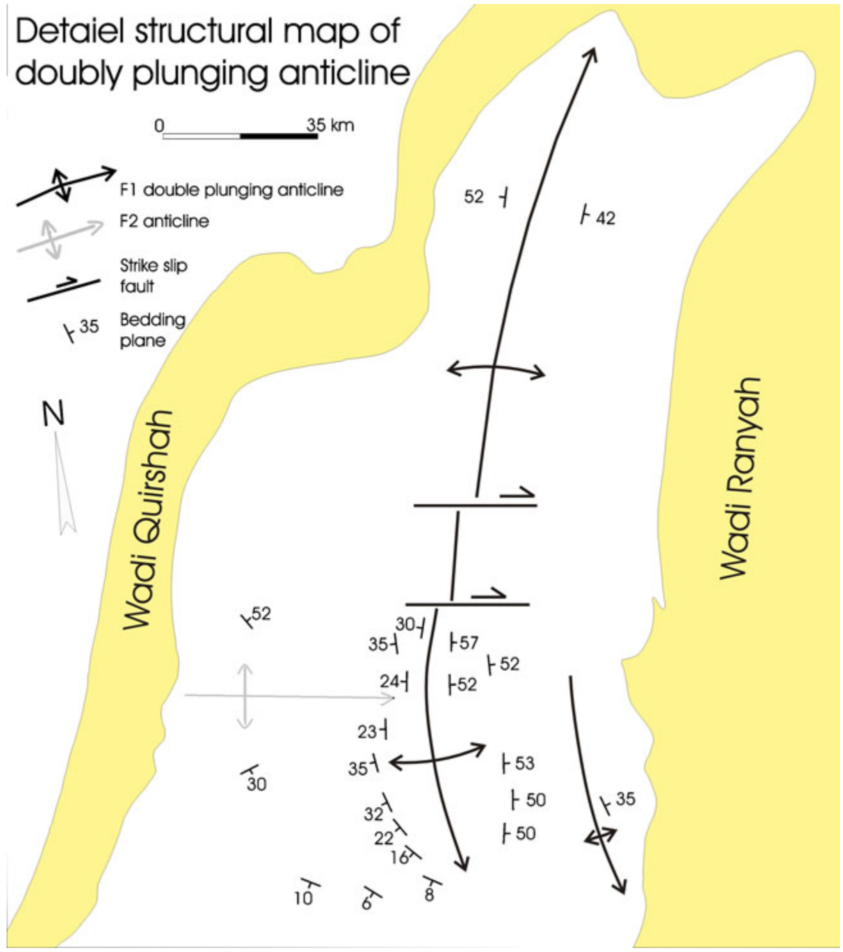

Fig. 7 Detailed structural map of the doubly plunging anticline

isoclinal folds seem to be affecting the metamorphic unit (Fig. 4). The F1 folds were superimposed by minor easterly plunging folds (F2), which are mainly limited to the Ablah graben area, and appear to be overturned folds which suggest that they are related to shearing (Fig. 7). The superimposition of the folding events developed plunging anticlines, which are present in the study area (Fig. 8). There are several doubly plunging anticlines and synclines in Ablah graben to the south and north of the study area (Greenwood 1975). F1–F2 axial plane cleavages intersection produced L2 intersection lineation. The E–W F2 folds are also associated with E–W dextral faults (Fig. 9), which seems to be reactivated recently because they crosscut tertiary basalt flow (Fig. 4). The E–W dextral faults are more abundant in the metamorphic and dioritic units than Ablah group rocks, which suggest that they responded to

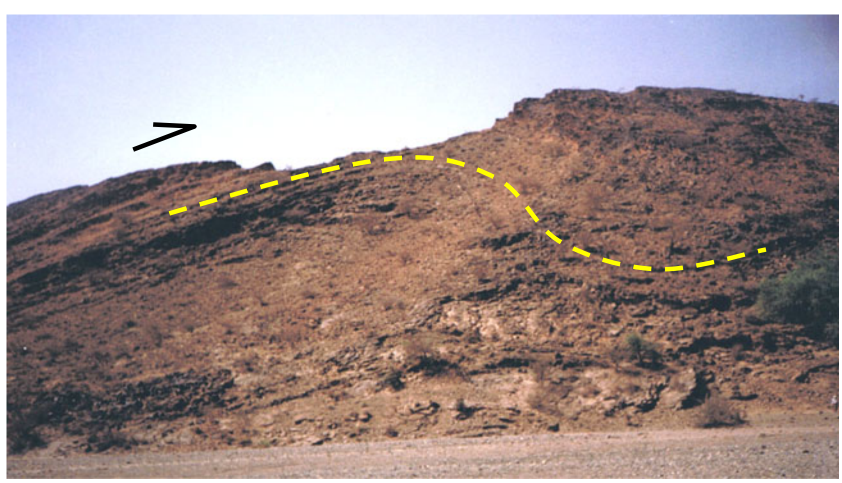

Fig. 8 View of F2 folds, looking NE

Fig. 9 Minor thrust fault. View looking NE

the late E–W compression in a more ductile manner than the surrounding greenschist rocks.

Thrust faults are also present in the study area. There are major thrust contacts and thrust faults that separate main lithological units, and minor thrust faults that cross-cut individual rock types (Fig. 10). One of the major thrust faults separates the granite rock from the metamorphic unit, in which the granite intruded the tonalite rocks after development of ring structures. Also, a major thrust fault was inferred between the epiclastic and tuffaceous unit. Moreover, the sliver of serpentinite is separated from Ablah group and the tonlite rocks by thrust faults (Fig. 3). Thrust faults and F1 folds are trending N–S and they are attributed to E–W compression. This E–W compression was transferred along local E–W accommodation zones, producing the E–W dextral faults and associated F2 folds (e.g., Cunningham and Mann 2007).

Summary and conclusion

The Ablah graben area, including Mount Ablah area, underwent nine phases of lithotectonic evolution between Late Proterozoic–Cenozoic period which is summarized in Table 1. The Ablah graben rocks vary in lithology and age from volcanic arc related and greenschist metamorphic rocks. The greenschist grade meta-volcanic and oceanic bearing unit is considered as basement rocks, and intruded by lower Crygenian An-Nimas batholith (Johnson et al. 2001; Johnson 2006). The deposition of Ablah group rocks occurred during Cryogenian–Ediacaran boundary, and they are part of the Neoproterozoic and infracambrian rocks that deposited in post-amalgamation basins (Genna et al. 1999; Johnson et al. 2001; Johnson 2003). The area was intruded by post-tectonic granitic bodies, subsequent to deposition of

Fig. 10 En echelon dextral faults, cross-cutting the right limb of the doubly plunging anticline. View looking N

Ablah group. The area was subsequently affected by folding and thrust faults then refolding and dextral faulting during the EAO event (Table 1).

Ablah graben developed after a long history of tectono-sedimentary setting began with crustal thinning through basin development, deposition of molasse sediments and post-tectonic intrusion, and finally terminated by closure, compression, and inversion. Although Ablah graben is an intra-continental basin, is not completely distorted and transformed into mélange and did not develop a thrust wedge, it is still an N–S trending litho-tectonic zone of discontinuity within one terrane, which accommodated discontinuous and localized strain. This N–S narrow and long belt of deformed but un-metamorphosed volcano–sedimentary rocks separates between two wider belts of greenschist grade metamorphic rocks. Stoeser and Frost (2006) divided Asir Terranes into subterranes, two of them are equivalent to Shwas and Bidah belts, separated by Ablah belt (Fig. 2). Thus, it could be interpreted as a suture zone that divides part of Asir Terrane, especially because it developed along N–S dextral fault, which is related to the older Nabitah orogen and inverted during the EAO.

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