Tectonophysics 481 (2010) 29–37

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Lithospheric composition and thermal structure of the Arabian Shield in Jordan

H.-J. Förster [a,*], A. Förster [b], R. Oberhänsli [a], D. Stromeyer [b]

[a] Institute of Earth Sciences, University of Potsdam, P.O. Box 601553, D-14415 Potsdam, Germany
[b] Deutsches GeoForschungsZentrum, Telegrafenberg, D-14473 Potsdam, Germany

ARTICLE INFO

Article history:
Received 27 May 2008
Received in revised form 7 November 2008
Accepted 18 November 2008
Available online 27 November 2008

Keywords:
Geotherms
Surface heat flow
Xenolith
Granulite
Peridotite
Late Proterozoic terrane
Arabian Shield

ABSTRACT

In this paper, a unique set of samples from the uppermost crust down to the lithospheric mantle of Jordan is analyzed for composition and petrophysical properties (density, thermal conductivity, radiogenic heat production). These data, covering a vertical section of almost 65 km, are used in conjunction with surface heat flow to generate a detailed and comprehensive lithospheric thermal model that reflects the conditions of the Arabian Shield (AS) prior to the post-Oligocene onset of lithosphere thinning and voluminous basaltic volcanism. The pre-Miocene model geotherms, based on conductive surface heat flows of 55 and 60 mW m^{-2}, (a) meet the range of lithosphere–asthenosphere boundary depths of 110–160 km known from seismology, (b) conform to results of thermomechanical models on the origin of the Dead Sea basin that started in Miocene time, and (c) are consistent with typical xenolith-derived geotherms for terranes of similar age and lithospheric thickness. Moho temperatures (at depths between 35 and 40 km) of the AS in pre-Miocene times were most likely in the order of 530–650 °C, with mantle heat flows averaging between 24 and 29 mW m^{-2}. Results contradict former views of the late Proterozoic/early Cambrian-stabilized AS being an anomalously cold terrane. A "cold" thermal structure inferred from previously measured low surface heat flows (generally $\leq$45 mW m^{-2}) is inconsistent with the thickness, composition, and petrophysical properties of the stable lithosphere of the shield.

1. Introduction

Earlier studies have characterized the late Proterozoic Arabian Shield (AS) as a terrane of generally low conductive surface heat flow of 36–45 mW m^{-2} (Gettings, 1982; Gettings and Showail, 1982; Galanis et al., 1986). The implication was that the AS constitutes a cold continental lithosphere, thermally similar to many terranes consolidated in the Archean, averaging to 41 ± 11 mW m^{-2} (e.g., Nyblade and Pollack, 1993). This widely accepted view of a cold lithosphere was recently questioned by a heat-flow study in southeastern Jordan, which yielded a substantially higher surface heat flow of 60 ± 3 mW m^{-2} (Förster et al., 2007). This higher heat flow is in satisfactorily agreement with the global heat-flow average of stable late Proterozoic terranes far removed from Archean cratons (55 ± 17 mW m^{-2}; Rudnick et al., 1998).

Starting from the new heat-flow determination in southeastern Jordan, this paper is aimed to elaborate a consistent model of the thermal structure of the Arabian Shield in Jordan. The approach is multidisciplinary by comprehensively crosschecking results from the fields of seismics, seismology, gravity, petrology, geochemistry, petrophysics, and geothermics. It examines a unique set of samples from the uppermost crust down to the lithospheric mantle, providing a full coverage of compositional, density, thermal conductivity, and radiogenic heat production data over a vertical section of almost 65 km.

Previous inferences on the thermal state of the AS (e.g., McGuire, 1988; McGuire and Bohannon, 1989; Stein et al., 1993; Medaris and Syada, 1998) are based on the low surface heat-flow concept and considered extrapolated or supposed rather than real values for petrophysical properties and radiogenic heat production, disregarding the temperature and pressure dependence of rock thermal conductivity.

2. Evolution and regional geology of the Arabian Shield

The Arabian Peninsula (Plate) is composed of the (western) Arabian Shield (AS) and the (eastern) Arabian Platform (Fig. 1). The AS constitutes a region of Precambrian/early Cambrian basement that became exposed as result of uplift associated with rifting along the Red Sea. The shield contains the best-preserved and most widely exposed juvenile continental crust of Neoproterozoic age on Earth (e.g., Stern and Kröner, 1993; Stern and Abdelsalam, 1998), although some juvenile magmas contain older continental material of early Neoproterozoic to Archean age (Hargrove et al., 2006). Most of the AS formed during the Pan-African orogenic cycle (~1000–530 Ma) by suturing of juvenile intra-oceanic arc terrains followed by magmatic thickening, giving rise to regional metamorphism and the generation of batholiths of predominantly granitic to granodioritic composition

* Corresponding author. Tel.: +49 331 288 1242.
E-mail address: forhj@gfz-potsdam.de (H.-J. Förster).

0040-1951/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.tecto.2008.11.014

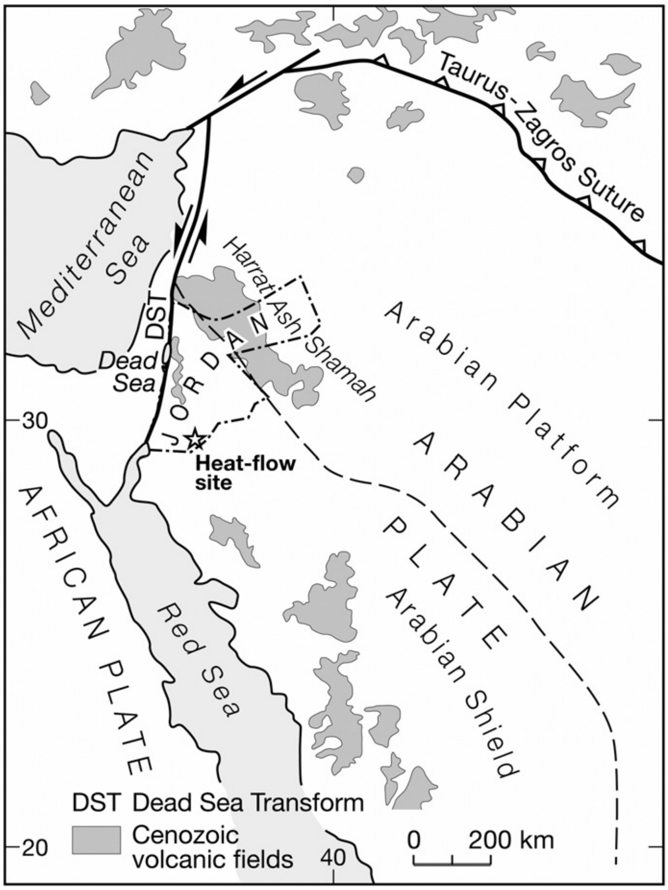

Fig. 1. Schematic geological map of the western Arabian Plate, showing the location of the heat-flow site and the distribution of Cenozoic basaltic volcanic fields.

between 630 and 610 Ma (Stoeser and Camp, 1985; Cosca et al., 1999, Katz et al., 2003; Jarrar et al., 2003). Formation of the AS was likely associated with the rise of a plume head to the upper mantle, leading to the formation of an enriched "plume mantle" and oceanic plateaus (Stein, 2003). During the last stages of its early evolution (~610 −530 Ma), the shield was subjected to strong extension. This extension was accompanied by intrusion of abundant within-plate A-type granites, alkali granites, and syenites, sometime associated with gabbros, by the emplacement of composite dykes, and by the eruption of bimodal volcanic rocks (Beyth et al., 1994; Mushkin et al., 2003; Katzir et al., 2007; Jarrar et al., 2008).

Owing to its position as a passive continental margin since early Paleozoic times, the region was the place of sediment deposition repeatedly interrupted by times of uplift and denudation. After a long period of magmatic quiescence, several minor episodes of Mesozoic intra-plate magmatic activity have been recognized in the area around the DST (Dead Sea Transform), which are thought to be associated with the evolution of the eastern Mediterranean Neo-Tethyan passive continental margin along the northern edge of Gondwana (e.g., Laws and Wilson, 1997; Wilson et al., 2000). The main events occurred during the late Triassic to early Jurassic (~200 Ma), the late Jurassic to early Cretaceous (146–115 Ma), and in the late Cretaceous (~80 Ma). During Miocene to Pliocene times, mafic volcanic activity resumed throughout the region related to the complex tectonics associated with the opening of the Red Sea at around 30 Ma and the activity of the Afar mantle plume (Wilson et al., 2000). The younger event of this two-phase continental magmatism (<14 Ma) is generally attributed to lithosphere thinning owing to asthenosphere upwelling, possibly involving a mantle-plume component (Camp and Roobol, 1992; Shaw et al., 2003; Krienitz et al., 2007; and references therein). The regional-scale heating of the upper mantle is well imaged by seismological data (Phillips et al., 2007), but is not yet recorded in the surface heat flow.

3. Sampling sites and analytical techniques

A total of 155 samples were collected from various regions of Jordan, encompassing Paleozoic sediments, Pan-African magmatic and metamorphic rocks, lower crustal granulites, and upper mantle spinel lherzolites (Fig. 2). Rock density, thermal conductivity, and radiogenic heat production were determined on unaltered specimens devoid of fractures. Density was measured at standard conditions on water-saturated samples by weighting. Thermal conductivity was measured by optical scanning (Popov et al., 1999) with the apparatus used by Norden and Förster (2006). The optical-scanning method has a high precision (1.5%) and accuracy (1.5%). Radiogenic heat production was calculated using the equation of Rybach (1976). The concentration of K was determined by X-ray fluorescence spectrometry. Thorium and U were analyzed by inductively coupled plasma-mass spectrometry (ICP-MS). Averages and standard deviations for the three parameters given in Table 1 involve between 3 and 20 single measurements. For lower crustal rocks, density, compressional wave velocity (V_p), and shear wave velocity (V_s) were calculated with the algorithm of Sobolev and Babeyko (1994), which translate bulk-rock compositions (averages of Al-Mishwat and Nasir, 2004) into modal mineralogy as function of temperature and pressure.

4. Architecture of the lithosphere

Refraction/reflection seismic soundings (El-Isa et al., 1987; Batayneh and Al Zoubi, 2001; DESERT Group et al., 2004; Mechie et al., 2005), receiver-function analyses of teleseismic records (Hofstetter and Bock, 2004; Al-Damegh et al., 2005; Mohsen et al., 2005, 2006; Hansen et al., 2007), teleseismic tomographic inversion (Koulakov and Sobolev, 2006; Laske et al., 2008), and gravity studies (Götze et al., 2007) demonstrate that four major discontinuities determine the structure of the lithosphere beneath Jordan. These features are associated with changes in lithology and correspond to discontinuities recognized elsewhere in the AS (i.e., Nasir and Safarjalani, 2000; Al-Mishwat and Nasir, 2004).

The first discontinuity at 19–20 km, which is associated with a change in V_p from 6.1–6.3 km s^{-1} to 6.7 km s^{-1} and in V_s from 3.55–3.65 km s^{-1} to 3.75 km s^{-1} (Mechie et al., 2005), corresponds to the boundary between the upper and lower crust. The second reflector, marked by a jump in V_p from 6.7 to 7.2 km s^{-1}, is located within the lower crust, at about 29 km. The third discontinuity, the Moho, is located at depths between 32 (immediately east of the DST) and 39 km. The crustal thickness in southern Jordan is about 37 km and, thus, closely approximates the average thickness of the AS crust, calculated between 36 km (Rodgers et al., 1999) and 39 km (Al-Damegh et al., 2005).

The fourth reflector, a low-velocity zone underlying a high-velocity mantle lid, marks the lithosphere–asthenosphere boundary (LAB). There is ample evidence that the lithosphere below Jordan is tectonically active and thinned, with LAB depths varying between about 55 and 80 km. Lithosphere thinning is observed throughout the AS along the Red Sea rift and the DST and beneath areas of Cenozoic basaltic volcanism (e.g., Julià et al., 2003; Hansen et al., 2007). Seismic stations define the LAB depth beneath the heat-flow area to ~65 km (Mohsen et al., 2006; Hansen et al., 2007).

5. Composition of the lithosphere

Surface geology and extensive geophysical data indicate that the upper crust is felsic to intermediate in composition. The bulk of the upper crust is composed of Pan-African metamorphic and igneous rocks, which are locally overlain by a thin, up to several kilometers