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New insights into the provenance of Saudi Arabian Palaeozoic sandstones from heavy mineral analysis and single-grain geochemistry

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ABSTRACT

Saudi Arabian Palaeozoic siliciclastics cover a stratigraphic range from the Cambrian to the Permian. They crop out along the eastern margin of the Arabian Shield and are comprised of highly mature sandstones. Their heavy mineral assemblage reflects their mineralogical maturity and is dominated by the ultra-stable phases zircon, tourmaline and rutile. Less stable accessories are apatite, staurolite and garnet. Standard heavy mineral analysis of samples from two study areas in central/northern (Tabuk area) and southern (Wajid area) Saudi Arabia reveals distinct changes in provenance. Cambrian–Ordovician sandstones are first-cycle sediments, probably sourced from the 'Pan-African' basement. The overlying Hirnantian glaciogenic deposits consist of recycled Cambrian–Ordovician material. Devonian–Permian sandstones show a significant influx of fresh basement material, as attested by an increase of meta-stable heavy minerals. Single-grain geochemical analysis of rutile and garnet has proven to be a powerful supplementary technique. Rutile varietal studies reveal distinct differences in host rock lithologies between the two study areas: the Tabuk area contains predominantly felsic rutiles, whereas the Wajid area has more mafic input. Zr-in-rutile thermometry identified granulite-facies detritus in the lower Palaeozoic of the Tabuk area and has the potential to further define source areas. The distribution patterns of garnet host rock lithologies are remarkably similar in both study areas. They are dominated by amphibolite-facies metasediments and intermediate to felsic igneous rocks. Garnets derived from granulite-facies metasediments, which are scarce in the Arabian–Nubian Shield, also occur. Possible source rocks for high-grade garnets can be found in Yemen or farther south in the Mozambique Belt.

1. Introduction

The Palaeozoic succession of Saudi Arabia is dominated by highly mature siliciclastics. Sandstones crop out in a narrow band that extends over 1500 km NW–SE along the southern, eastern and northern margin of the Arabian Shield (Fig. 1a). The succession reaches a thickness of about 500 m in the outcrop and dips slightly eastwards. It continues in the subsurface, where it can reach a thickness of up to 4500 m and contains important hydrocarbon source and reservoir rocks (McGillivray and Husseini, 1992; Al-Ajmi et al., 2015). Deposition took place from the Cambrian to the Permian (Fig. 2), but age control has proven to be difficult in the mostly fossil-barren units. Depositional environments are varied, ranging from fluvial braided stream conditions to shallow marine, prodeltaic and open marine settings (Al-Ajmi et al., 2015). Several erosional hiatuses separate the sedimentary units and are used for lithostratigraphic correlations. Prominent are glaciogenic and proglacial sediments and features associated with the Hirnantian as well as Carboniferous–Permian Gondwana glaciations. According to the common and widely accepted model, the Palaeozoic succession was deposited on a stable continental shelf at a passive margin, leading to the development of a 'layer cake' stratigraphy (Sharland et al., 2001). The exact source for the Palaeozoic detritus is still under debate. The adjacent Arabian Shield most likely was a major contributor throughout the Palaeozoic, but far distant sources have to be taken into account as well (Al-Harbi and Khan, 2005, 2008, 2011; Wanas and Abdel-Maguid, 2006). Possible source areas to the south include Archean to Palaeoproterozoic terranes in Yemen (Babalola, 1999; Hussain et al., 2000, 2004; Hussain, 2001), metamorphic terranes in Eritrea and Sudan, as well as the Mozambique Belt in East Africa. A significant recycled sedimentary source is a possibility that so far could neither be proven nor refuted.

The high maturity of Palaeozoic sandstones coupled with the poor fossil record create unique problems for the interpretation of sedimentary provenance and stratigraphic correlation. Lithostratigraphic correlations in the very uniform successions are unreliable and imprecise, especially in the subsurface. Bulk-rock geochemistry can help with correlations and to infer tectonic setting and provenance, but is also dependant on modal composition. The method therefore also suffers from the poor diversity of mature siliciclastics. Another way to tackle the problem is the study of the heavy mineral fraction. Standard heavy mineral analysis (SHMA, modal analysis) has been an important tool in

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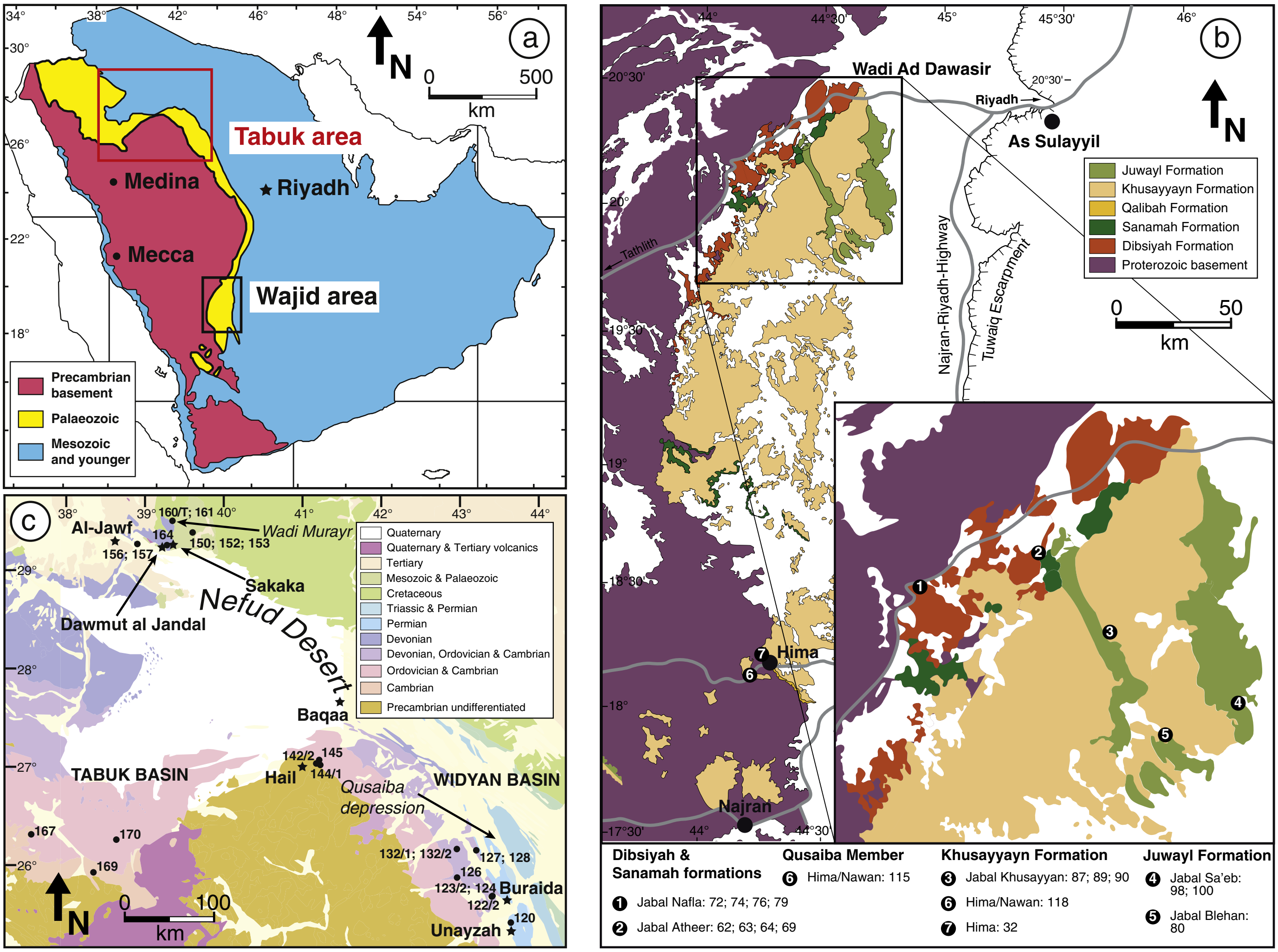

Fig. 1. Maps of the study areas. (a) Simplified geologic map of the Arabian Peninsula showing the study areas (modified after Powers, 1968). (b) Geologic map of the Wajid outcrop belt in southern Saudi Arabian, including sample points (modified after Keller et al., 2011). (c) Geologic map of the Tabuk area in northern Saudi Arabia, including sample points (modified after Pollastro et al., 1998).

provenance studies, both in ancient and recent sediments (Mange and Wright, 2007). So far, several workers have applied SHMA to the Palaeozoic succession, but have mostly concentrated their efforts on the Wajid outcrop belt of southern Saudi Arabia (Babalola, 1999; Hussain et al., 2000, 2004; Hussain, 2001; Hussain and Abdullatif, 2004; Knox et al., 2007). These studies noted the dominance of the ultra-stable fraction of zircon, tourmaline and rutile in the heavy mineral assemblage. Hussain (2001) interpreted this as the result of intensive weathering, whereas for Hussain et al. (2004) it is a clear indicator for sedimentary recycling. Babalola (1999), Hussain (2001), Hussain and Abdullatif (2004) and Hussain et al. (2004) identified acidic to intermediate igneous rocks in Yemen as the most likely source for the Wajid Group. According to these studies, other sources like metamorphic, mafic igneous and sedimentary rocks as well as the Arabian Shield to the west are only minor contributors. Knox et al. (2007) identified several distinct heavy mineral zones and significant changes in provenance signatures throughout the Wajid Group. Only a few studies have targeted the central and northern part of the country, with varying success (Powers et al., 1966; Hussain and Abdullatif, 2004; Knox et al., 2010). Powers et al. (1966) conducted a pilot study to assess the potential of heavy mineral analysis. They report a dominant ultra-stable fraction from the Saq and overlying formations (Fig. 2), which they interpreted as indicative for sedimentary recycling. Yet they also found mica (biotite and muscovite), which is surprising given its unstable nature during transport. Hussain and Abdullatif (2004) also report an abundance of the zircon, tourmaline and rutile from the Saq and Qasim formations (Fig. 2), but were unable to use their heavy mineral data for correlations. Knox et al. (2010) on the other hand were successful in studying heavy mineral assemblages of the Unayzah Formation (Fig. 2) from wells. They identified two changes in provenance within the Unayzah Formation, dividing it into three different heavy mineral units. They also tentatively recognise the potential of heavy mineral analysis for regional correlations.

In recent years, several studies were published dealing with provenance and heavy mineral studies on the northern margin of Gondwana. Most of them feature U–Pb age dating of detrital zircons, but also touch upon SHMA. Avigad et al. (2003, 2005) and Kolodner et al. (2006) used SHMA and U–Pb dating of detrital zircons from Cambrian–Ordovician sandstones from southern Israel to deduce provenance and palaeoclimate. Morag et al. (2011) utilised the corresponding Hf isotopic data to infer long-distance transport for Cambrian–Ordovician sediments. Weissbrod and Bogoch (2007) compiled heavy mineral data of Neoproterozoic to Mesozoic siliciclastic sediments from the northern margin of the Arabian–Nubian Shield (ANS) and provide a comprehensive review of heavy mineral studies in that area. Morton et al. (2011) and Meinhold et al. (2011, 2013) studied heavy mineral assemblages and detrital zircon ages of Precambrian to Mesozoic siliciclastic sediments from the Murzuq basin, Libya, in