

**EVALUATING PROPERTIES OF
ARABIAN DESERT SANDS
FOR GEOLOGICAL AND ENERGY APPLICATIONS**

BY
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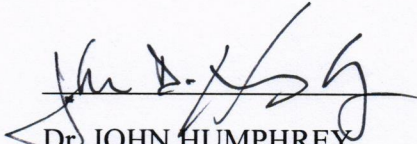
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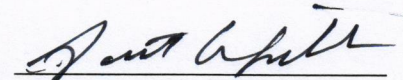
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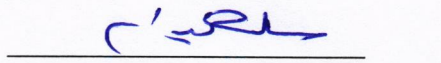
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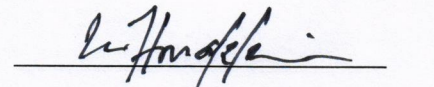
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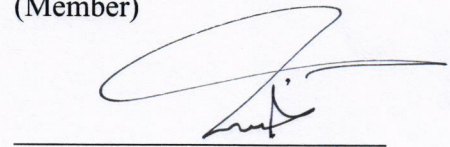

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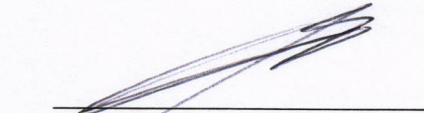

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To Mom and Dad,

I will never stop trying to make you proud, in sha' Allah. |

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LIST OF ABBREVIATIONS

CSP	:	Concentrating solar power
DSC	:	Differential scanning calorimeter
EDS	:	Energy-dispersive X-ray spectroscopy detectors
ESR	:	Electron spin resonance
PCM	:	Phase changing material
PV	:	Photovoltaic
QCI	:	Quartz crystallinity index
QEMSCAN	:	Quantitative Evaluation of Minerals by SCANNing electron microscopy
SEM	:	Scanning electron microscope
TES	:	Thermal energy storage
TGA	:	Thermogravimetric analyzer
UAE	:	United Arab Emirates
UV-VIS	:	Ultraviolet-visible
XRD	:	X-ray diffraction

|

ABSTRACT

Sands cover one third of Arabian Peninsula and represent the largest continuous body of eolian sand on Earth. This study aims to investigate quartz crystallinity of Arabian sands and sandstones to help reveal new provenance aspects. It also investigates mineralogy, thermo-physical, and thermo-optical properties of Arabian sands to help find the best candidate of Arabian sands to be employed as a thermal energy storage medium and solar absorber material for high-temperature solar thermal technologies. Systematic sampling covered Quaternary surface sediments from Nafud, Dahna corridor, and the western part of AlRub'AlKhali deserts, and Paleozoic and Mesozoic sandstones.

Quartz crystallinity index (QCI) values of sandstones were found to vary temporally and seem to be associated with geologic abundances of siliceous sponges and eolian depositional environments. QCI values of sands vary spatially and are narrower (homogenized) after unidirectional and/or long-distance transportation in AlRub'AlKhali sands. The presence of chert is suggested to be responsible for the extreme values of QCI in Arabian sands and sandstones.

The purest quartzose sands ($\geq 99\%$ quartz) possess the best thermo-physical and thermo-optical properties. These pure quartzose sands have the highest specific heat capacity, do not agglomerate up to 1200°C , and have the highest spectral absorbance after heating to 1200°C . The purest quartzose sands occupy the southwestern part of the Nafud desert. Sand of this area is proposed to be the best candidate of all Arabian sands to be used as a sensible thermal energy storage medium and solar absorber material.

ملخص الرسالة

الاسم الكامل: عمر عاطف محمد عبد الفتاح رضوان

عنوان الرسالة: تقييم خصائص رمال الصحراء العربية للتطبيقات الجيولوجية والطاقة

التخصص: الجيولوجيا

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تغطي الرمال ثلث شبه الجزيرة العربية وتمثل أكبر كتلة متواصلة من رمال على الأرض. تهدف هذه الدراسة إلى التحقق من تبلور الكوارتز المكونة للرمال والأحجار الرملية لشبه الجزيرة العربية للمساعدة في الكشف عن جوانب منشأ جديدة. كما تبحث في الخصائص المعدنية والخواص الفيزيائية الحرارية والخواص الحرارية الضوئية للرمال العربية للمساعدة في العثور على أفضل مرشح للرمال العربية لاستخدامه كوسيط لتخزين الطاقة الحرارية ومادة ماصة لضوء الشمس لتقنيات الحرارة الشمسية ذات درجات الحرارة العالية. أخذت عينات الرمال من صحراء النفود وممر الدهناء والجزء الغربي من صحراء الربع الخالي، وعينات الحجر الرملي من مكاشف صخور حقب الحياة القديمة والمتوسطة. تشير النتائج إلى أن قيم مؤشر تبلور الكوارتز تتغير زمنياً مع احتمال أن يكون التغير متأثراً بعاملين: وفرة الإسفنج السليكي وبيئات الترسيب الهوائي. كما تختلف تلك القيم مكانياً وتكون أكثر تجانساً بعد النقل أحادي الاتجاه و/أو لمسافات طويلة. وتمتلك أنقى الرمال ($\leq 99\%$ كوارتز) أفضل الخصائص الحرارية الفيزيائية والحرارية الضوئية. تتمتع رمال الكوارتز النقية هذه بأعلى سعة حرارية، ولا تتكثّل حتى 1200 درجة مئوية، ولديها أعلى امتصاص طيفي بعد التسخين إلى 1200 درجة مئوية. تحتل أنقى رمال الكوارتز الجزء الجنوبي الغربي من صحراء النفود. يُقترح أن تكون الرمال في هذه المنطقة هي الأفضل من بين جميع الرمال العربية لاستخدامها كوسيط تخزين للطاقة الحرارية المعقولة ومادة ماصة للشمس.

CHAPTER 1

INTRODUCTION

1.1 Sands and Arabian sands

Sand is a loose rock or mineral particle with an average particle size of 0.0625–2 mm. Sand is widely distributed in modern rivers, lakes, beaches, dunes, and shallow-shelf seas. The main components of most sands are quartz and feldspars. Eolian sands occupy 6% of the worldwide land surface area (Pye & Tsoar, 2009) (**Figure 1**).

The Arabian Peninsula encompasses two main geologic/geomorphic features (**Figure 2**): a western Precambrian basement (Arabian shield) and an eastern Paleozoic to Cenozoic covering of strata in a curved belt flanking the shield (Arabian platform). Paleozoic and Mesozoic sedimentary successions crop out widely in central Arabia. To the east, they are covered with continuous accumulations of active eolian sand dunes. Sands are distributed in a clockwise orientation from NNW to SSE across three main desert areas: Nafud (in the north), Dahna corridor, and Rub' Al-Khali (in the south). A series of dry river valleys, now occupied by sands, used to run eastward across the Arabian Peninsula, including the Rimah/Batin, Sahba, and ad-Dawasir wadis (Powers et al., 1966; Edgell, 2006).

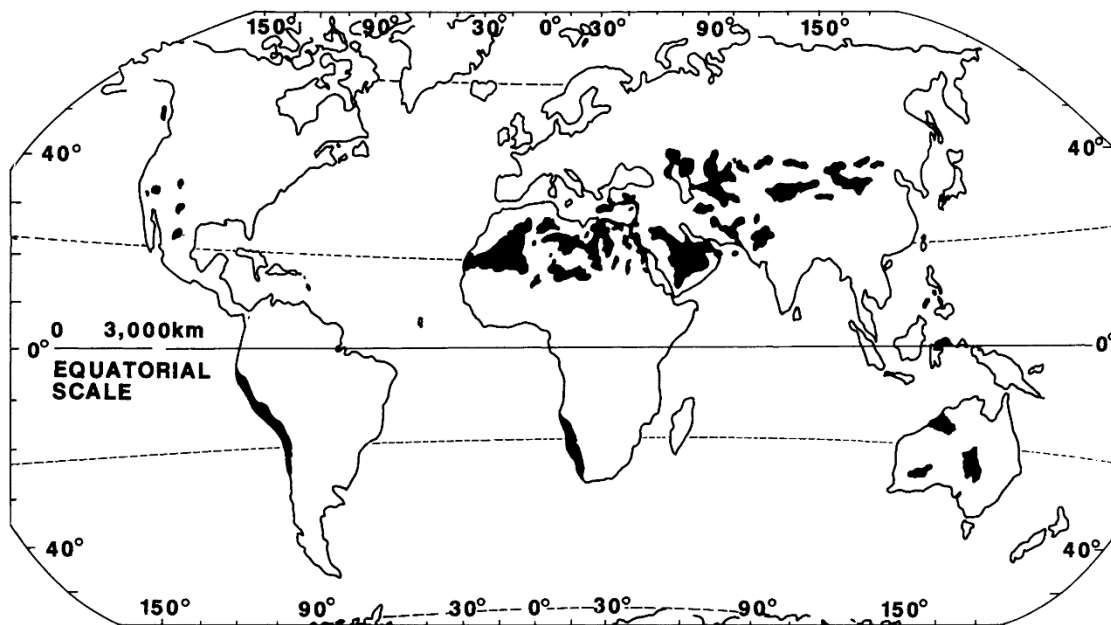


Figure 1. Global distribution of major sand seas (Pye & Tsoar, 2009).

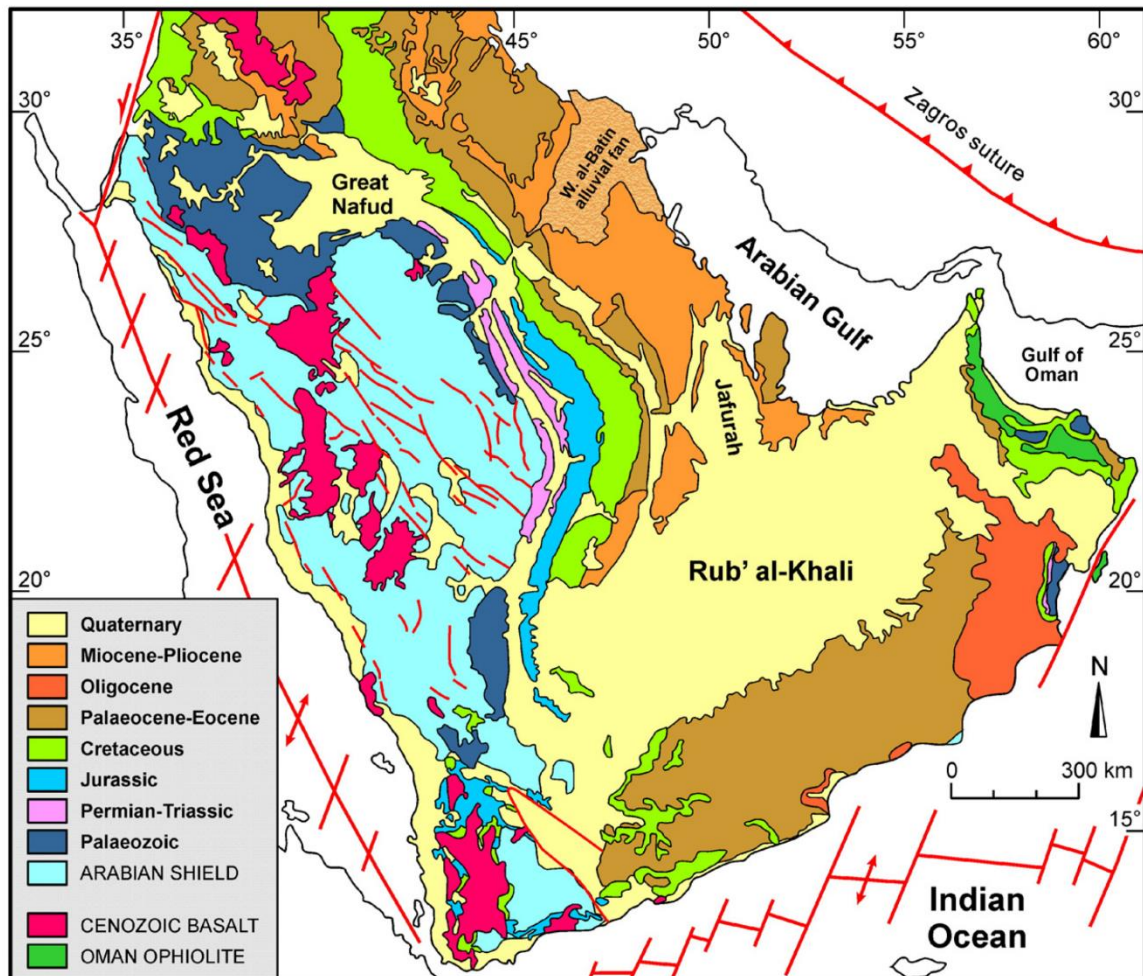


Figure 2. Geologic sketch map of Arabia (Garzanti et al., 2013).

1.2 Use of quartz crystallinity index in provenance studies

Quartz, a dominant resistant component in many rocks and sediments, crystallizes under varying thermodynamic and kinetic conditions (Götze, 2012). Quartz crystallinity index (QCI) is a semi-quantitative 0 to 10 scale that expresses the crystallinity of powdered quartz by measuring the intensity of the (212) X-ray diffraction peak (Murata & Norman, 1976). Although not thus far attributed to any particular crystal-structural property (Broekmans, 2012; Marinoni & Broekmans, 2013), QCI has successfully distinguished between quartz forming under different crystallization conditions including temperature, pressure, rate of crystallization, and age (Murata & Norman, 1976; Katayama et al., 1989). In addition to sedimentary provenance studies, QCI has been considered for use in civil engineering (to predict deleterious reactions in concrete) and in medicine (to predict the toxicity of quartz dust of respirable size) (Katayama et al., 1989; Aftree-Williams & Clapp, 2002).

Individual provenance tools can be misleading, and multiple tools should always be integrated for conclusive provenance determinations (Garzanti et al., 2013; Garzanti, 2016). Several studies have focused on using QCI in tracing east Asian dust provenance. They traced the dust from their source areas including river sediments, dry lake sediments, and mountain loess (Sun et al., 2013; Isozaki et al., 2020) to their sink areas including desert sediments (Sun et al., 2007), hemipelagic sediments (Nagashima et al., 2007), paleosols (Sun et al., 2008), and dust (Yan et al., 2015).

QCI, in combination with electron spin resonance (ESR) signal intensity, has effectively:

- discriminated among nine major deserts in east Asia and provided signatures for them as source tracers to distinguish dust provenance in marine and terrestrial environments (Sun et al., 2007, 2013),
- recognized a distinct quartz origin for different size fractions of hemipelagic sediments from the Japan Sea (Nagashima et al., 2007) and desert sediments (Sun et al., 2007),
- documented temporal provenance fluctuations in paleosol sequences of the Chinese Loess Plateau (Sun et al., 2008; Ma et al., 2015), and inner-shelf sediments of the East China Sea (Wang et al., 2020),
- recorded the change in transport dynamics between glacial and interglacial periods (Sun et al., 2008), and
- estimated the relative contribution of sources when mixing takes place between two or more end members (Sun et al., 2008).

Notwithstanding these contributions, QCI is a nascent tool and its employment in provenance studies is very limited.

1.3 Uses of sands in solar thermal technologies

Solar energy is a time-dependent energy resource, useful only during sunshine periods. To provide an uninterrupted energy supply, excess solar energy can be converted to, and stored in, other forms of energy (including mechanical, chemical, electrical, and thermal energy) that can be used later, on demand. Thermal energy storage systems stock thermal energy by heating a storage medium. Sensible heat storage stocks energy by heating liquid or solid media without changing their physical state. Solid sensible storage media are usually preferred because they are cheap, widely available, non-toxic, and non-flammable (Sterner & Stadler, 2019). Sand has been largely employed in solar thermal technologies mainly, but not exclusively, as thermal energy storage medium.

1.3.1 Solar heating

Heating accounts for 50% of global energy consumption and is responsible for 40% of global carbon dioxide emissions (IEA, 2019). Solar energy systems for space and water heating applications are usually integrated with thermal energy storage mediums including water, ground, packed-bed, and aquifers (Ann Cruickshank & Baldwin, 2016). Sand was involved and has proven beneficial in all cases:

- The heat loss from *water* tank in sandy soil is small and almost isn't influenced by its depth. Compared to granite soil, the solar fraction of water tank in sand soil is greater (Sun & Xu, 2013).
- Compared to water tanks, a higher solar fraction can be achieved using *ground* heat exchanger systems with the same area (Garg et al., 1985). Compared to

bentonite and gravel, sand provides more heat for longer duration (Pahud & Matthey, 2001; Gysen, 2003; Al-Ameen et al., 2017; Edhari & Ngo, 2017).

Regional shallow subsurface thermal variations data needs to be compiled and analyzed to find the best location for heat storage (N. Zhang et al., 2015; Møller et al., 2019).

- A sand-based *packed-bed* can transfer the solar energy from summer to winter (seasonal storage) and achieve substantial energy savings for small (Sweet & McLeskey, 2012; Hailu et al., 2017b, 2017a) and large residential buildings (Terziotti et al., 2012). Small-scale compact solar water heaters, combining solar collection and heat storage in one unit, using black-colored sands have been designed and proven efficient (Fath, 1995; Taheri et al., 2013, 2015).
- Sandstones with good reservoir properties can be used as a high-temperature *aquifer* thermal energy storage system (Pasquinelli et al., 2020).

Photovoltaic (PV) systems harness only a small fraction of the incident radiation; the rest is converted to heat, which may endanger the structure of the PV cell. Sand was proposed and considered to be a good candidate to be used as thermal energy storage medium for PV systems to store the excess heat that can be used for heating applications (Al-Hmoud et al., 2019).

1.3.2 Solar drying

Solar driers are greenhouses that uses the solar radiation to dry agricultural/food products. Although it avoids most of the disadvantages of the open-air sun drying (Mujumdar, 2020), solar drying still faces the obstacle of solar energy inconsistency.

To overcome the intermittent character of solar energy, thermal storage using sand was suggested (Aboul-Enein et al., 2000; El-Sebaai et al., 2002; Saxena et al., 2014). Sand can be added to the drying chamber, the solar collector, or both (Bennamoun, 2013). In addition to increasing the temperature, sand helped uninterrupted drying to take place and, in turn, prevented the re-absorption of moisture that used to occur during night and reduced the drying time noticeably (Ayyappan et al., 2016).

1.3.3 Solar cooking

Solar cookers are devices that utilize solar radiation to heat or cook food. They are widely used in developing countries. Although solar cookers provide a simpler, cleaner, cheaper, safer, and healthier way of cooking, they face the disadvantages of being slow and not available during the night (Panwar et al., 2012; Aramesh et al., 2019).

The thermal performance of solar cookers was successfully enhanced using sand only (Ramadan et al., 1988) or a dual thermal storage unit: sand in combination with phase changing material (PCM) (acetamide: (Yadav & Yadav, 2013; Agrawal et al., 2014; Panchal & Sadasivuni, 2020), or stearic acid or magnesium nitrate hexahydrate (Yadav et al., 2017)). Sand provides its sensible heat, allowing evening and indoor cooking and helps insulate the PCM, thereby reducing heat loss to the surrounding. Rates of evening cooking were faster than noontime cooking.

1.3.4 Solar distillation

Solar stills are distillation devices that use solar radiation to obtain fresh water from impure water (salty, brackish, or contaminated water). While it is true that solar stills are very simple to manufacture and operate (Omara & Kabeel, 2014; Sharshir et al.,

2019), their freshwater yield is extremely low during the day and equal to zero during the night (El-Sebaili et al., 2009).

The effects of built-in sandy heat reservoirs on performance of solar stills were studied and found rewarding (Omara & Kabeel, 2014; Madhu et al., 2018). Up to 75% (Tabrizi & Sharak, 2010) and 145% (Sathyamurthy et al., 2016) increase in the freshwater output has been achieved. Sand aided in increasing the temperature of the water and continuously producing freshwater during the night.

1.3.5 Solar ponds

Solar ponds are naturally (Sonnenfeld & Hudec, 1980) or artificially (Velmurugan & Srithar, 2008) made ponds that collect solar energy and store the resulting heat in the lower layer of the pond. Solar ponds encompass three layers: a lower high-salinity layer, upper low-salinity layer, and middle gradient layer. The vertical salt gradient in the middle zone impedes convection causing upper thermal insulation to the lower layer (Norton, 1992). Therefore, the lower layer maintains high temperatures, which can be extracted by a heat exchanger to be used for different applications.

Heat losses to earth below and around the pond must be minimized to improve the performance of the solar pond. Numerical (Beniwal et al., 1987) and experimental (Beniwal et al., 1988) studies were conducted to investigate the effect of encasing the bottom and the sides of the pond by sand with different thicknesses. Sand reduced considerably the heat losses and was found to have dual roles; it works as an insulating material (Beniwal et al., 1987, 1988) and as a thermal storage medium (Haruni, 1984; Velmurugan & Srithar, 2008).

1.3.6 Concentrating solar power

Concentrating solar power (CSP) plants utilize solar concentrators to convert solar radiation into heat then into power (electricity). Thermal energy storage (TES) systems stock thermal energy by heating a storage medium which can be extracted later during times of high demand and/or in the absence of the source of solar energy (Sarbu & Sebarchievici, 2018). CSP plants with TES system(s) are, therefore, more advantageous than photovoltaics.

Most common TES media are molten salts which have a temperature range from 290 °C to 565 °C. Since molten salt must be maintained above its freezing point, the minimum operating temperature imposes limitations on the system. Since degradation to salts takes place above 565 °C, the maximum operating temperature imposes limitations on the efficiency. Relative to molten salts, *sand* has mediocre thermal properties. Nonetheless, this is compensated by the exceptionally high temperature range (operation at temperatures beyond 1000 °C and with no lower temperature limit) and the extremely low cost (orders of magnitude cheaper) (Steiner et al., 2017; Diago et al., 2018).

Different systems for sand as TES were designed to optimize storage volume and storage efficiency. A comparison of passive packed-bed (single tank) and active fluidized-bed (two tanks) designs was conducted, and it indicated that the passive approach is more suitable for short storage periods (<24 hours), while the active approach is advantageous for longer storage periods (Haider et al., 2012).

Although fluidization ensures higher rates of heat transfer (Izquierdo-Barrientos et al., 2016; Almendros-Ibáñez et al., 2019), it exposes the sand particles to attrition.

Fortunately, silica sand has an extremely abrasive index number (68.3) (i.e., low attrition rates) (Knott et al., 2014a; H. Zhang et al., 2016). Different sand fluidization technologies were compared. While bubbling fluidization was found to be faster, spouted fluidization can reach higher temperatures with lower pumping costs and allow for larger range of sand sizes to be used (Díaz-Heras, Barreneche, et al., 2020; Díaz-Heras, Moya, et al., 2020).

Different heat transfer media have been used to introduce and extract heat from sand including molten salt (Pacheco et al., 2002; Bharathan & Glatzmaier, 2009; Qin et al., 2012), air (Schwaiger et al., 2014; Schlipf et al., 2015), and oil (Grirate et al., 2015; Bruch et al., 2017; Haggag et al., 2017; Xu et al., 2017; Molina et al., 2019).

In addition to being TES, sand can play other roles if subjected directly to concentrated solar radiation. In this case, sand particles will act as a particle solar receiver whose energy can be stored in insulated tanks to be used for power generation (heat collector medium) and/or utilized to heat a secondary working fluid (heat transfer medium) (Martin & Vitko, Jr, 1982; Iniesta et al., 2015; Díaz-Heras et al., 2021). Different systems for sand as a heat-collector medium (Ho, 2016; Qoaider et al., 2017) and heat-transfer medium (Golob et al., 2011; Warerkar et al., 2011; Al-Ansary et al., 2012; Nguyen et al., 2014; Al-Ansary et al., 2018) were designed.

Although sand exhibits thermal, chemical, and mechanical stability after long periods of fluidization and thermal aging, it has low capacity for absorbing direct solar radiation (≈ 0.4) (Díaz-Heras et al., 2021) and gets even lower over the aging stages (Palacios et al., 2019). To enhance the sand's solar absorption characteristics, carbon

black nanoparticles and glucose were applied to color the sands black (Gimeno-Furio et al., 2020). Although both coatings achieve more than 100% enhancement in optical properties, coating with carbon black nanoparticles was favored because it has higher working temperature and higher thermal capacity.

Choosing sand with low clay and carbonate content is imperative in high-temperature applications. Clays (Knott et al., 2014b) and carbonates (Lalitha Priya et al., 2016; Diago et al., 2018) adversely impact medium fluidization, as it causes sand agglomeration or sintering. Additionally, the presence of carbonate decreases the solar absorption of the sand.

1.3.7 Compressed air energy storage

Solar energy can be used to compress air from atmosphere into natural underground caverns. The energy stored in the compressed air can be released later to be used for generating electricity. However, compressed air energy storage (CAES) has low efficiency (Zhou et al., 2019). Sand can be used as a secondary TES system to significantly enhance CAES efficiency (Hämmerle et al., 2017).

1.3.8 Solar gasification

Gasification processes convert carbonaceous materials (cokes, coal, biomass, etc.) into fuels or chemicals. The conventional approach burns a significant part of the raw material to provide heat energy for the reaction to take place. In order to provide that needed heat, a CSP system with quartz sand as a thermal transfer/storage medium (solar gasification) has been suggested and considered to be a better alternative to the conventional approach (Gokon et al., 2014; Abe et al., 2015; Gokon et al., 2015, 2018).

Solar gasification have the advantage of increasing the amount and the quality of the fuel and reducing the CO₂ emission.

1.4 Research gap

1.4.1 Quartz crystallinity of Arabian sands and sandstones

Provenance of Arabian sandstones and sands has been studied using petrographic, heavy-mineral, U-Pb zircon dating (Garzanti et al., 2013, 2017), and geochemical methods (Benaafi & Abdullatif, 2015). Paleozoic sandstones (and Mesozoic, to lesser extent) have been suggested to be the main source of sand in the Nafud, Dahna, and the western part of AlRub'AlKhali deserts (Garzanti et al., 2013, 2017). These sources have been identified by matching detrital zircon U–Pb ages, the poor heavy-mineral assemblages, and the predominant make-up of monocrystalline quartz that commonly exhibits abraded overgrowths. Crystalline basement rocks, Mesozoic to Cenozoic carbonates, and Neogene basalts of the Arabian Peninsula have contributed little to Arabian desert sands (Garzanti et al., 2013, 2017).

There are no studies on the quartz crystallinity of Arabian sands and sandstones.

1.4.2. Using Arabian sands in solar thermal technologies

Evaluation of sands as thermal energy storage material and direct solar absorber material in the Arabian Peninsula has been initiated recently and covered United Arab

Emirates (UAE) deserts (Diago et al., 2015, 2018), and also near Riyadh (Knott et al., 2014b).

No systematic studies have evaluated sand of the Nafud, Dahna, and southwestern AlRub'AlKhali deserts for use in solar thermal technologies.

1.5. Objectives

In this study, Quaternary surface sediments (sand dunes and sand sheets) from Nafud, Dahna corridor, and the western part of AlRub'AlKhali deserts, and Paleozoic and Mesozoic sandstones were systematically sampled with the objective of:

- documenting temporal variations in QCI values of Arabian sandstones and spatial variations in QCI values of Arabian sands,
- proposing a new hypothesis on the roles of 1) marine-derived silica and silicification, and 2) eolian-derived silica in driving temporal QCI variations of ancient Arabian sandstones and spatial QCI variations of modern Arabian sands,
- documenting thermo-physical and thermo-optical properties of Arabian sands, and
- proposing the best candidate of Arabian sands to be employed as a thermal energy storage medium and solar absorber material for high-temperature solar thermal technologies.

CHAPTER 2

QUARTZ CRYSTALLINITY OF ARABIAN SANDS AND SANDSTONES

2.1. Abstract

Although quartz crystallinity index (QCI) was developed more than four decades ago, it remains a relatively new tool used in provenance studies. This study examines QCI values of Arabian sands (Quaternary sands from Nafud, Dahna, and AlRub'AlKhali deserts), and Arabian sandstones (Paleozoic and Mesozoic sandstones from northern and central Arabia). QCI values of sandstones range from 8.2 to 9.8. For Quaternary occurrences, QCI values of Nafud sands range from 7.4 to 9.5, Dahna sands range from 7.9 to 9.4, and AlRub'AlKhali sands range from 8.8 to 9.4. The data confirm that Arabian sands are derived mainly from early Paleozoic sandstones, with subordinate contributions from late Paleozoic and Mesozoic sandstones. They also highlight the role that sediment homogenization plays in narrowing QCI values of AlRub'AlKhali sands. Highest and lowest QCI values raise questions about the role of chert in controlling of QCI values of Arabian sands and sandstones. Arabian sandstones of Late Ordovician, Late Devonian, Late Permian, Late Triassic, and Cretaceous age possess the highest QCI values (>9.5). These time intervals coincide with lower abundances of siliceous sponges, and therefore fewer potential sources of chertification/silicification. Cambrian sandstones and

Quaternary sands possess the lowest QCI values (<8.5). This coincides with the fact that both are of eolian origin, environments which usually contain large quantities of quartz-rich dust that are documented to be a primary source of silica for chert formation. Therefore, we propose that the presence of chert is responsible for the extreme values of QCI in Arabian sands and sandstones.

2.2. Introduction

Quartz, a dominant resistant component in many rocks and sediments, crystallizes under varying thermodynamic and kinetic conditions (Götze, 2012). Quartz crystallinity index (QCI) is a semi-quantitative 0 to 10 scale that expresses the crystallinity of powdered quartz by measuring the intensity of the (212) X-ray diffraction peak (Murata & Norman, 1976). Although not thus far attributed to any particular crystal-structural property (Broekmans, 2012; Marinoni & Broekmans, 2013), QCI has successfully distinguished between quartz forming under different crystallization conditions including temperature, pressure, rate of crystallization, and age (Murata & Norman, 1976; Katayama et al., 1989). In addition to sedimentary provenance studies, QCI has been considered for use in civil engineering (to predict deleterious reactions in concrete) and in medicine (to predict the toxicity of quartz dust of respirable size) (Katayama et al., 1989; Atree-Williams & Clapp, 2002).

Individual provenance tools can be misleading, and multiple tools should always be integrated for conclusive provenance determinations (Garzanti et al., 2013; Garzanti,

2016). Several studies have focused on using QCI in tracing east Asian dust provenance. They traced the dust from their source areas including river sediments, dry lake sediments, and mountain loess (Sun et al., 2013; Isozaki et al., 2020) to their sink including desert sediments (Sun et al., 2007), hemipelagic sediments (Nagashima et al., 2007), paleosols (Sun et al., 2008), and dust (Yan et al., 2015).

QCI, in combination with electron spin resonance (ESR) signal intensity, has effectively:

- discriminated among nine major deserts in east Asia and provided signatures for them as source tracers to distinguish dust provenance in marine and terrestrial environments (Sun et al., 2007, 2013),
- recognized a distinct quartz origin for different size fractions of hemipelagic sediments from the Japan Sea (Nagashima et al., 2007) and desert sediments (Sun et al., 2007),
- documented temporal provenance fluctuations in paleosol sequences of the Chinese Loess Plateau (Sun et al., 2008; Ma et al., 2015), and inner-shelf sediments of the East China Sea (Wang et al., 2020),
- recorded the change in transport dynamics between glacial and interglacial periods (Sun et al., 2008), and
- estimated the relative contribution of sources when mixing takes place between two or more end members (Sun et al., 2008).

Notwithstanding these contributions, QCI is a nascent tool and its employment in provenance studies is very limited.

Provenance of Arabian sandstones and sands has been studied using petrographic, heavy-mineral, U-Pb zircon dating (Garzanti et al., 2013, 2017), and geochemical methods (Benaafi & Abdullatif, 2015). Paleozoic sandstones (and Mesozoic, to lesser extent) have been suggested to be the main source of sand in the Nafud, Dahna, and the western part of AlRub'AlKhali deserts (Garzanti et al., 2013, 2017). These sources have been identified by matching detrital zircon U–Pb ages, the poor heavy-mineral assemblages, and the predominant make-up of monocrystalline quartz that commonly exhibits abraded overgrowths. Crystalline basement rocks, Mesozoic to Cenozoic carbonates, and Neogene basalts of the Arabian Peninsula have contributed little to Arabian desert sands (Garzanti et al., 2013, 2017).

There are no studies on the quartz crystallinity of Arabian sands and sandstones. In this study, we systematically sampled Quaternary surface sediments (sand dunes and sand sheets) from Nafud, Dahna corridor, and the western part of AlRub'AlKhali deserts, and outcrop sampled Paleozoic and Mesozoic sandstones. The objective is to document the temporal variations in QCI values of Arabian sandstones and spatial variations in QCI values of Arabian sands. Moreover, we propose a new hypothesis on the roles of 1) marine-derived silica and silicification, and 2) eolian-derived silica in driving temporal QCI variations of ancient Arabian sandstones and spatial QCI variations of modern Arabian sands.

2.3. Geological background

The Arabian Peninsula encompasses two main geologic/geomorphic features (**Figure 3**): a western Precambrian basement (Arabian shield) and an eastern Paleozoic to Cenozoic covering of strata in a curved belt flanking the shield (Arabian platform). Paleozoic and Mesozoic sedimentary successions crop out widely in central Arabia. To the east, they are covered with continuous accumulations of active eolian sand dunes. Sands are distributed in a clockwise orientation from NNW to SSE across three main desert areas: Nafud (in the north), Dahna corridor, and Rub' Al-Khali (in the south). A series of dry river valleys, now occupied by sands, used to run eastward across the Arabian Peninsula, including the Rimah/Batin, Sahba, and ad-Dawasir wadis (Powers et al., 1966; Edgell, 2006).

2.4. Methodology

Forty sandstone samples were collected from Arabian platform Paleozoic and Mesozoic outcrop successions. Paleozoic samples were collected from Madinah, AlJawf, and Qasim Provinces, and Mesozoic samples were collected from Riyadh Province. No Carboniferous sandstones were sampled because they are absent in Saudi Arabian outcrops (Al-Husseini, 2004). Thirty-two Quaternary sand samples were collected from Nafud, Dahna corridor, and the western part of AlRub' AlKhali deserts. Exact coordinates

and lithostratigraphic units of the samples are given in **Table 1**; sampling locations are shown in **Figure 3**.

Sandstone samples were ground to a powder using a steel vibratory disc mill for 15 seconds. Sand samples were ground with corundum in a McCrone micronizing mill for 3 minutes. The resulting powder was screened using a 75- μm sieve, and then packed through back loading the specimen holder. X-ray diffractograms were recorded in a PANalytical Empyrean diffractometer operated at 45 kV and 40 mA using $\text{CuK}\alpha$ radiation. Samples were scanned three times in a continuous mode from 10 to $110^\circ 2\theta$ at $0.005^\circ 2\theta$ increments, with 40 s counting time per increment, and scan rate $0.036^\circ/\text{sec}$.

Quartz crystallinity indices (QCI) were determined according to the method of Murata & Norman (1976) where $\text{QCI} = 10aF/b$. The height of the quartz (212) peak (the first peak of 68° quintuplet) over low and high angle background represent the b and a values, respectively (**Figure 4**). The instrumental scaling factor (F) was calculated to adjust the QCI of the standard quartz (Malagasy clear euhedral quartz; FossilEra Co.) to 10 and was set at 1.1. Reproducibility of QCI values for repeated scans has an average value of ± 0.18 .

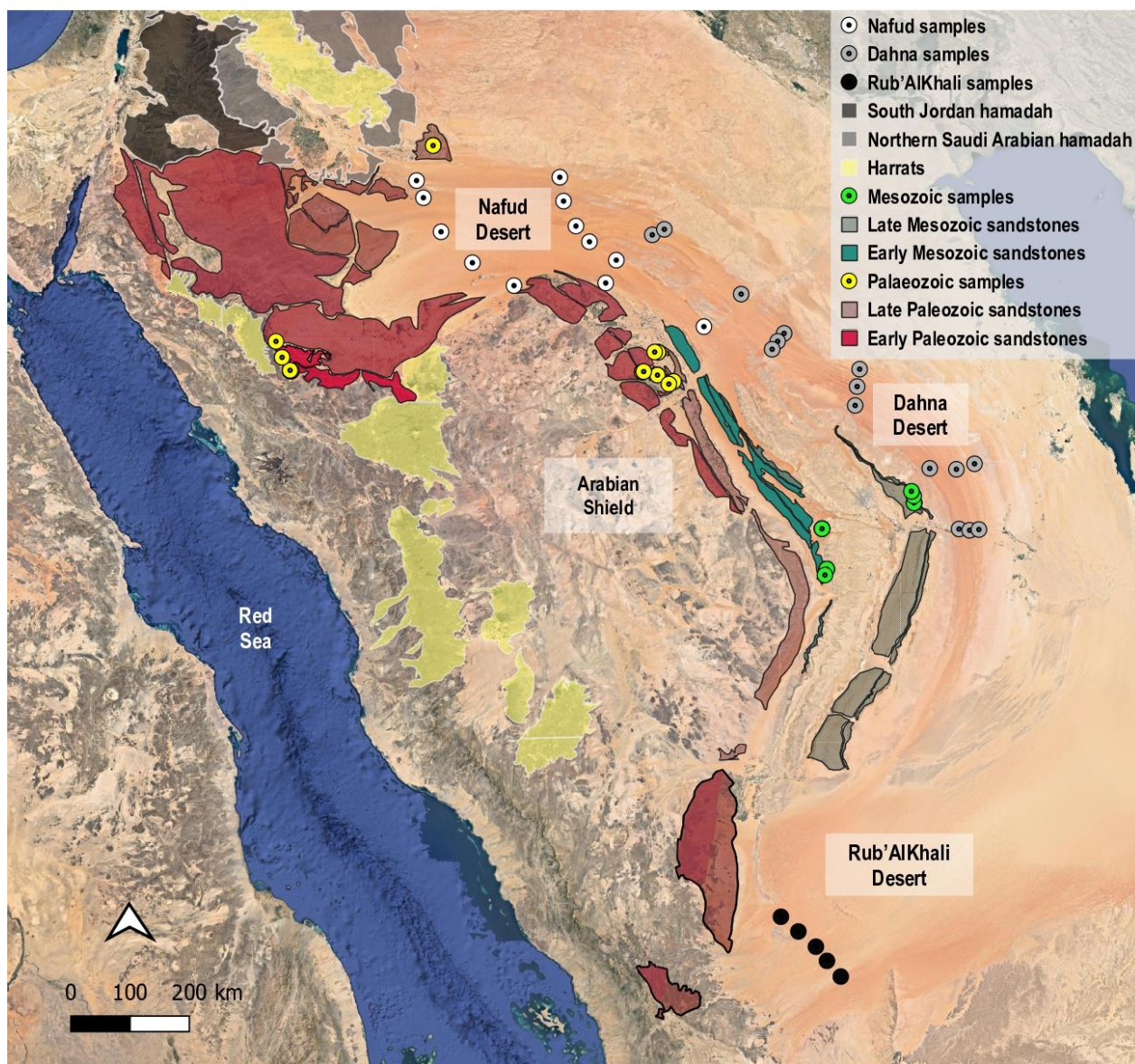


Figure 3. Google Earth™ map of the Arabian Peninsula showing sample locations. Paleozoic and Mesozoic sandstone outcrops are highlighted in shades of red and green (respectively), with darker colors for older periods (after U.S. Geological Survey, 1963).

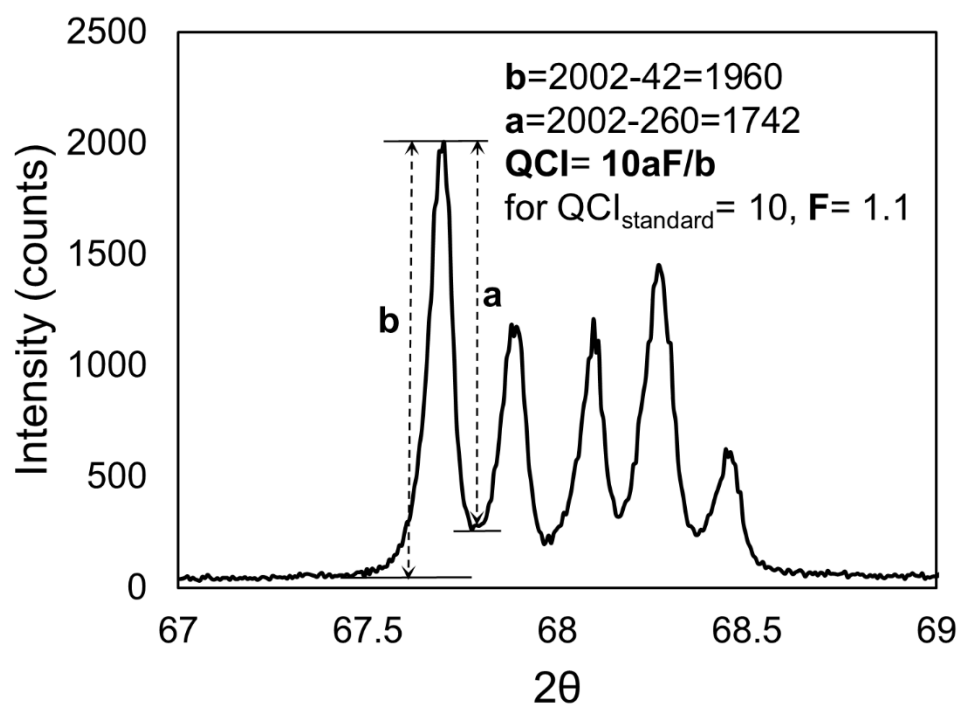


Figure 4. The 68° quintuplet in X-ray powder diffractogram of a Malagasy clear euhedral quartz crystal illustrating the calculation steps of quartz crystallinity index (QCI) and the instrumental scaling factor (F).

2.5. Results

QCI values of Arabian sandstones range between 8.2 and 9.8, with a mean value of 9.2 and a standard deviation of 0.4, whereas QCI values of Arabian sands range between 7.4 and 9.5, with a mean value of 8.7 and a standard deviation of 0.58 (**Figure 5**).

2.5.1. QCI values of Arabian sandstones

QCI values of Paleozoic and Mesozoic sandstones are virtually the same (from 8.2 to 9.8 for Paleozoic sandstones and from 8.4 to 9.8 for Mesozoic sandstones). Mesozoic sandstone values, however, are more negatively skewed (-0.6) relative to Paleozoic sandstone values (-0.36) (**Figure 5a**; **Table 1**). Highest values of QCI are recorded for the sandstone samples of Ordovician, Devonian, Permian, Triassic, and Cretaceous age (**Figure 5b**). Lowest values of QCI are recorded for the Cambrian sandstones.

2.5.2. QCI values of Arabian sands

While Nafud desert samples exhibit the widest QCI range (7.4 to 9.5) and the lowest mean (8.4), the western part of Rub'AlKhali desert displays the narrowest range (8.8 to 9.4) and the highest mean (9.1) (**Figure 5a**). Dahna corridor samples show intermediate values. QCI values of sand samples increase outward (away from the shield) in the three deserts.

Table 1. Quartz crystallinity index (QCI), location, age of Arabian sands and sandstone samples. C: Cambrian; O: Ordovician; S: Silurian; D: Devonian; P: Permian; T: Triassic; J: Jurassic; K: Cretaceous; Q: Quaternary; E: Early; M: Middle; L: Late.

Sample ID	Location	longitude	latitude	Age- Formation	QCI	Mean	Min	Max	Skewness
718-025	Nafud sands	28°32'4.00"N	42°34'35.00"E	Q	8.60 ± 0.1	8.4 ± 0.7	7.4	9.5	-0.02
718-028		28°47'3.00"N	42°20'42.00"E	Q	9.26 ± 0.1				
718-031		29°10'6.00"N	42°10'54.00"E	Q	8.97 ± 0.1				
718-035		29°35'53.00"N	42° 4'32.00"E	Q	9.53 ± 0.1				
718-040		27°52'41.00"N	41°24'55.00"E	Q	7.71 ± 0.1				
718-044		28°13'32.00"N	40°47'47.00"E	Q	8.05 ± 0.3				
718-048		28°41'7.00"N	40°19'20.00"E	Q	8.74 ± 0.1				
718-052		29°14'3.00"N	40° 1'56.00"E	Q	8.59 ± 0.4				
718-054		29°27'57.00"N	39°56'55.00"E	Q	8.94 ± 0.0				
718-004		27°16'9.00"N	44°18'24.00"E	Q	7.66 ± 0.3				
718-022		28°15'59.00"N	42°58'29.00"E	Q	7.88 ± 0.5				
718-039		27°54'21.00"N	42°48'41.00"E	Q	7.44 ± 0.4				
718-012	Dahna corridor sands	27°44'11.00"N	44°50'59.00"E	Q	8.05 ± 0.0	8.7 ± 0.5	7.9	9.4	-0.11
718-014		28°44'1.00"N	43°42'24.00"E	Q	8.19 ± 0.0				
718-016		28°38'40.00"N	43°31'7.00"E	Q	8.18 ± 0.1				
818-002		24°11'6.00"N	48°28'18.00"E	Q	8.89 ± 0.1				
818-004		24°10'34.77"N	48°20'27.65"E	Q	8.78 ± 0.4				
818-006		24°11'35.32"N	48°10'38.79"E	Q	7.94 ± 0.5				

Sample ID	Location	longitude	latitude	Age- Formation	QCI	Mean	Min	Max	Skewness
818-008		25°10'51.00"N	48°24'24.00"E	Q	8.31 ± 0.5				
818-010		25° 6'4.00"N	48° 8'5.00"E	Q	9.01 ± 0.0				
818-013		25° 6'38.00"N	47°43'28.00"E	Q	8.74 ± 0.5				
818-026		27°12'8.00"N	45°32'32.00"E	Q	9.30 ± 0.2				
818-028		27° 3'53.00"N	45°26'46.00"E	Q	9.22 ± 0.1				
818-030		26°56'6.00"N	45°21'12.00"E	Q	7.97 ± 0.3				
818-032		26° 1'56.69"N	46°35'53.50"E	Q	8.78 ± 0.1				
818-036		26°21'39.00"N	46°37'32.00"E	Q	9.21 ± 0.2				
818-039		26°35'57.00"N	46°39'22.00"E	Q	9.39 ± 0.0				
918-004	Rub'AlKhali sands	18°19'48.00"N	45°28'17.00"E	Q	8.81 ± 0.1	9.1 ± 0.2	8.8	9.4	-0.04
918-008		18° 6'8.00"N	45°43'53.00"E	Q	9.03 ± 0.1				
918-012		17°52'49.00"N	46° 0'3.00"E	Q	9.25 ± 0.2				
918-016		17°39'18.00"N	46°10'17.00"E	Q	9.37 ± 0.2				
918-020		17°25'2.00"N	46°22'60.00"E	Q	9.03 ± 0.0				
1218-06	Mesozoic sandstones (Riyadh Province)	24°41'48.81"N	47°28'59.97"E	MK-Wasia	8.86 ± 0.1	9.3 ± 0.4	8.4	9.8	-0.6
1218-07		24°45'43.69"N	47°27'8.48"E	MK-Wasia	8.39 ± 0.1				
1218-08		24°45'59.93"N	47°26'58.42"E	MK-Wasia	9.38 ± 0.2				
1218-01		24°35'38.35"N	47°29'23.09"E	EK-Biyadh	9.55 ± 0.0				
1218-02		24°35'37.56"N	47°29'21.48"E	EK-Biyadh	9.81 ± 0.1				

Sample ID	Location	longitude	latitude	Age- Formation	QCI	Mean	Min	Max	Skewness
1218-03		24°35'36.84"N	47°29'20.86"E	EK-Biyadh	9.14 ± 0.1				
1218-13		24°12'1.21"N	46° 5'37.46"E	EJ-Marrat	9.38 ± 0.1				
1218-14		24°12'0.87"N	46° 5'37.62"E	EJ-Marrat	8.89 ± 0.1				
1218-12		24°12'1.53"N	46° 5'37.40"E	LT-Minjur	9.14 ± 0.2				
1218-15		24°12'1.91"N	46° 5'37.53"E	LT-Minjur	9.19 ± 0.0				
1218-16		23°35'52.89"N	46° 8'56.22"E	LT-Minjur	9.32 ± 0.0				
1218-17		23°35'51.21"N	46° 8'56.76"E	LT-Minjur	9.22 ± 0.1				
1218-18		23°35'50.28"N	46° 8'57.20"E	LT-Minjur	9.74 ± 0.1				
1218-19		23°29'58.40"N	46° 8'24.82"E	MLT-Jilh	9.77 ± 0.1				
1118-15		26°25'28.82"N	43°50'19.38"E	LP-Khuff	9.53 ± 0.0				
1118-17		26°25'39.04"N	43°50'35.71"E	LP-Khuff	9.46 ± 0.1				
1118-09		26°52'18.17"N	43°36'21.78"E	ELP-Unayzah	9.49 ± 0.0				
1118-10		26°52'18.47"N	43°36'22.14"E	ELP-Unayzah	9.81 ± 0.1				
0319-09		29°59'48.50"N	40°11'44.27"E	LD-Jubah	9.75 ± 0.3				
0319-10		29°59'47.79"N	40°11'43.86"E	LD-Jubah	9.33 ± 0.2				
1118-08		26°52'17.72"N	43°36'21.19"E	ED-Tawil	9.17 ± 0.0				
1118-13		26°52'26.88"N	43°33'26.62"E	ES-Qusaiba	9.02 ± 0.5				
1118-14		26°52'26.87"N	43°33'26.94"E	ES-Qusaiba	8.55 ± 0.7				
1118-04		26°34'16.89"N	43°22'2.28"E	LO-Sarah	9.03 ± 0.2				

Sample ID	Location	longitude	latitude	Age- Formation	QCI	Mean	Min	Max	Skewness
1118-05	Paleozoic sandstones (Madinah, AlJawf, and Qasim Provinces)	26°34'16.77"N	43°22'2.29"E	LO-Sarah	9.48 ± 0.1	9.1 ± 0.4	8.2	9.8	-0.36
1118-07		26°34'39.80"N	43°23'31.50"E	LO-Sarah	9.33 ± 0.4				
1118-02		26°31'32.27"N	43°36'2.96"E	LO-Zarqa	8.62 ± 0.2				
1118-03		26°31'31.59"N	43°36'3.13"E	LO-Zarqa	9.13 ± 0.0				
1118-18		26°23'22.12"N	43°46'21.69"E	LO-Qasim (Quwarah)	9.67 ± 0.2				
1118-19		26°23'21.23"N	43°46'21.18"E	LO-Qasim (Quwarah)	8.97 ± 0.1				
1118-01		26°31'32.76"N	43°36'6.97"E	MO-Qasim (Kahfa)	8.95 ± 0.1				
1118-06		26°34'40.15"N	43°23'25.59"E	MO-Qasim (Kahfa)	9.19 ± 0.2				
1018-20		27° 2'7.20"N	37°48'59.64"E	LC-Saq	8.20 ± 0.3				
1018-13		26°36'58.08"N	38° 2'7.56"E	MC-Quweira	8.83 ± 0.2				
1018-17		26°47'35.52"N	37°54'36.06"E	MC-Quweira	8.91 ± 0.1				
1018-18		26°47'35.52"N	37°54'36.06"E	MC-Quweira	9.11 ± 0.3				
1018-05		26°35'2.16"N	38° 3'9.96"E	EC-Siq	9.02 ± 0.8				
1018-08		26°35'3.00"N	38° 1'46.44"E	EC-Siq	9.14 ± 0.0				
1018-11		26°36'58.08"N	38° 2'7.56"E	EC-Siq	8.85 ± 0.1				
1018-12		26°36'58.08"N	38° 2'7.56"E	EC-Siq	8.34 ± 0.1				

2.6. Discussion

2.6.1. Tempo-spatial changes in QCI values

The wide range of QCI values of Nafud sands (7.4 - 9.5) matches values of the early Paleozoic sandstones (8.2 – 9.1 for Cambrian, 8.6 – 9.7 for Ordovician, and 8.6 – 9.0 for Silurian), and suggests derivation from multiple sources and directions. The contribution of Cambrian sandstones is considered to be substantial because they are the only possible source of values below 8.5 (**Figure 5**). This excludes the late Paleozoic and Mesozoic sandstones; however, it does not explain the values below 8.2 in the Nafud sands.

QCI values of Dahna sands have a narrower range 7.9 – 9.4, which can be explained by homogenization (becoming more uniform by means of source mixing) of Nafud sands. Having a higher mean (8.7) than Nafud (8.4) may suggest partial contribution from late Paleozoic and Mesozoic sandstones to Dahna sands. QCI values of Dahna sands are less symmetric (-0.11) than Nafud (-0.02) and Rub'AlKhali (-0.04) sands, suggesting contribution from Mesozoic sandstones which has higher skewness than Paleozoic sandstone (**Table 1**).

The very narrow range in Rub'AlKhali desert sands (8.8 to 9.4) indicates intense homogenization caused by being mainly sourced from a single direction (namely, the Wajid Sandstone to the west), in addition to transportation of old Nafud and Dahna sands.

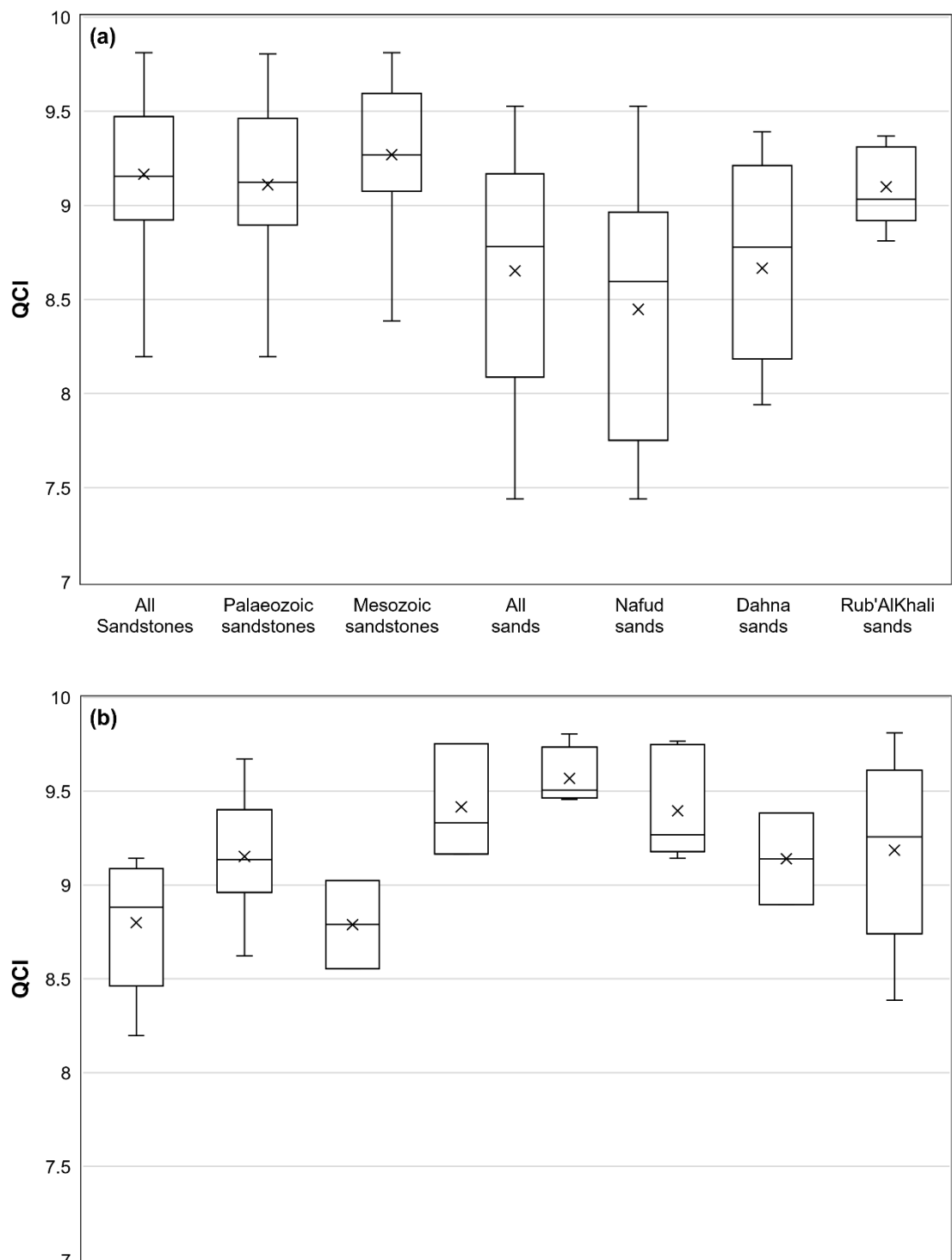


Figure 5. (a) Box plot of quartz crystallinity index values of Arabian Paleozoic and Mesozoic sandstones and Arabian sands of the Nafud, Dahna, and AlRub'AlKhali deserts. (b) Box plot of quartz crystallinity index values of Arabian sandstones arranged chronologically

2.6.2. Chert influence on QCI values ?

We have shown the utility of QCI values in aiding provenance discrimination of Arabian sands. However, there remain questions to be addressed. Prominently, why do QCI values of Arabian sandstones vary throughout geologic history (**Figure 5b**) if the provenance ultimately is the same (i.e., the Arabian shield)? Further, why do QCI values of Arabian sands have lower values than the minimum value of sandstones (**Figure 5a**) if they are principally derived from them? One possible answer for addressing both questions is the role of chert. Cherts are generally characterized by low crystallinity indices ranging from <1 to 7 (Murata & Norman, 1976; McNally & Richardson, 2005). If low crystallinity cherts contribute to the Arabian sands and sandstones, what are the potential sources of chert?

There are two possible scenarios that collectively can explain temporal changes in QCI values of Arabian sandstones over the Phanerozoic: 1) temporal variations in the abundance of siliceous organisms, particularly sponges, and the associated replacement silicification (chertification) within marine sedimentary successions, and 2) temporal and spatial variations in arid paleoclimate/paleogeography and the associated eolian quartz-rich dust availability.

The amount of silicification during the Paleozoic is estimated to be five times than that for the Mesozoic, mostly in response to the abundance of siliceous marine invertebrates (Schubert et al., 1997; Butts & Briggs, 2011; Butts, 2014). The decline in silicification during the Mesozoic correlates with the decline in the abundance of siliceous sponges following the extinction of many sponge lineages during the end-Permian biotic crisis (Kidder & Erwin, 2001). Hence, Paleozoic sandstones of Arabia

could have provided a greater intrinsic source of chert than Mesozoic sandstones. While the distribution of QCI values of Paleozoic sandstones is relatively symmetric (-0.36), QCI values of Mesozoic sandstones samples are moderately skewed (-0.60); that is, most of the values are concentrated toward high values (**Figure 5a; Table 1**). Note that QCI values below 9.0 for Mesozoic sandstones samples belong to the Jurassic and Cretaceous (**Figure 5b**), which had experienced considerable post-Triassic recovery of siliceous sponge abundance (Kidder & Erwin, 2001).

Highest values of QCI are recorded for the sandstone samples from Ordovician, Devonian, Permian, Triassic, and Cretaceous strata (**Figure 5b**). While Triassic high QCI values can be understood in the light of the aforementioned mass extinction, Cretaceous high QCI values can be linked to a shift from nearshore to offshore cherts related to the evolutionary radiation of diatoms. Ordovician, Devonian, and Permian high QCI values can be attributed to drops in abundance of siliceous sponges near the upper boundaries of these periods (Schubert et al., 1997; Kidder & Erwin, 2001). By examining the QCI values of Ordovician and Devonian sandstones (where we have both Early or Middle and Late samples; **Table 1**), we found that Late samples generally have higher values (where we expect to have low replacement silicification).

Lowest values of QCI belong to sandstone samples from the Cambrian, Ordovician, and Silurian (**Figure 5b**). This is also consistent with the temporal variations in Phanerozoic silicification trends. Silica sources (and therefore silicification) of organic origin were most prevalent during the Silurian and Ordovician (Schubert et al., 1997; Kidder & Erwin, 2001; Butts, 2014). On the other hand, Cambrian silicification was

dominated by early diagenetic silica in shallow-marine nearshore facies (inorganic origin) (Maliva et al., 1989; Kidder & Erwin, 2001).

Therefore, one can assume that cherts (of organic and inorganic origin) contributed to Phanerozoic sandstones variably, and that variation appears to be related to siliceous sponge and silicification abundance. While this assumption provides an interesting argument, it encounters an inconsistency in regard to this study. The lowest QCI values belong to Cambrian sandstones which were deposited in non-marine environments (Konert et al., 2001). In addition, Quaternary sands of the Arabian deserts have even lower QCI values.

Out of all sampled sandstones and sands, Cambrian sandstones (Janjou et al., 1998) and Quaternary sands are the only samples that represent an eolian depositional environment and were formed under warm-arid conditions (Boucot et al., 2013). Eolian dust has been proposed to be a primary source of silica for chert (Cecil, 2004). Quartz dust formed by mechanical abrasion in air is very reactive for three reasons: 1) solubility is particle-size dependent, 2) a thick amorphous layer of silica envelopes abraded quartz particles and this amorphous layer is an order of magnitude more soluble than quartz, and 3) the crystal lattice of abraded quartz particles becomes disordered to a considerable depth and this renders the abraded fine particles metastable and more soluble. The reactive quartz dust, therefore, experiences enhanced solubility and becomes susceptible to dissolution and diagenetic alteration. This hypothesis helps interpret the origin of non-marine cherts (Cecil, 2015; Cecil et al., 2018).

QCI values below 8.2 (the minimum value reported for the sampled sandstones) belong to the Nafud sand samples located in the west and south-west. Garzanti et al.

(2013) reported the existence of chert fragments along the southwest edge of Nafud sands. This indicates an increase in chert abundance is ongoing in Nafud. The wind energy is much more powerful near Nafud and declines southward (Vincent, 2008), providing an ample dust source (Gherboudj et al., 2017) for chert to be formed.

In addition to the aforementioned mechanism, there might be another source of chert. Stony deserts (hamada) of southern Jordan and northern Saudi Arabia are covered extensively with chert derived from the underlying cherty limestones of Eocene age (Edgell, 2006). These cherts extend widely, almost to the NW edge of the Great Nafud (**Figure 3**). This coincides with the southern Jordan area being a moderate dust source (Gherboudj et al., 2017) along with persistent northwesterly (shamal) winds (Ansari et al., 1986).

For the purpose of visual confirmation, selected samples of sands and sandstones with low QCI values were examined under the polarizing microscope and the presence of chert was confirmed. **Figure 6** shows detrital chert in samples of Cambrian Siq sandstones and sands of the southwestern Nafud deserts.

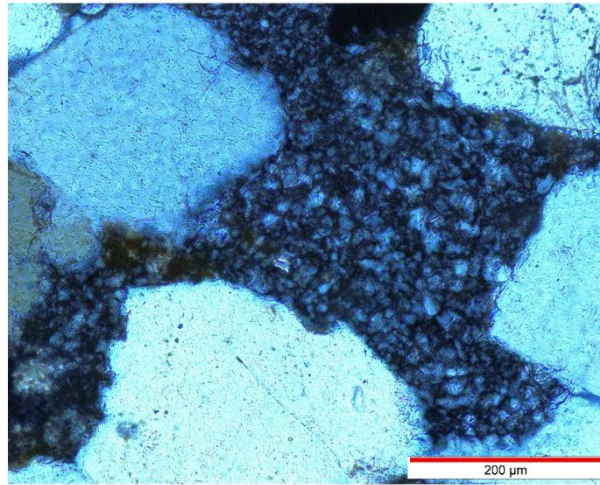
Several approaches can be considered to judge if our hypothesis, regarding the role of chert in controlling the QCI values of Arabian sands and sandstones, is robust:

- systematic petrographic examination of Arabian sands and sandstones and quantification of chert present,
- crystallinity measurements and petrographic examination of the chert covering the stony desert of southern Jordan and northern Saudi Arabia, and

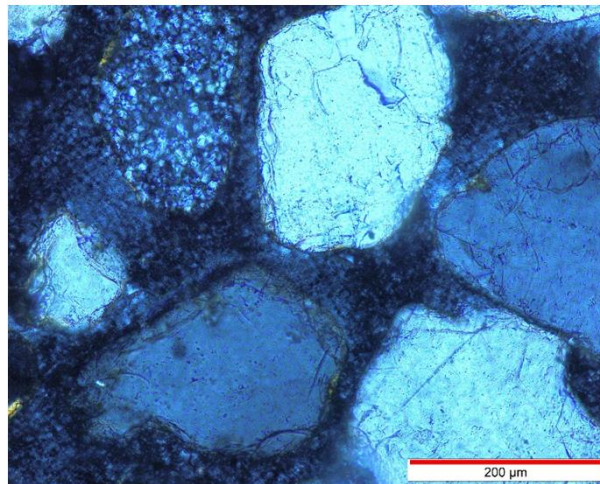
- tracking crystallinity throughout Phanerozoic sandstones from different parts of the world.

2.7. Conclusions

This study surveyed QCI values of Arabian sands of Nafud, Dahna corridor, and the western part of AlRub'AlKhali deserts, and outcrops of Paleozoic and Mesozoic Arabian sandstones. The QCI data confirmed what was petrographically and chronologically established, that early Paleozoic sandstones are the main source for Arabian sands. Moreover, the QCI data provide insight into the provenance of Arabian sandstones and sands. QCI values of sandstones vary temporally and seem to be associated with abundance of siliceous sponges and eolian depositional environments. QCI values of sands vary spatially and are narrower (homogenized) after unidirectional and/or long-distance transportation. QCI values of sands from the western and southwestern Nafud desert indicate possible ongoing chert formation or contribution of Cenozoic cherts derived from the stony desert of southern Jordan and northern Saudi Arabia to the Arabian sands.



(a)



(b)

Figure 6. Chert presence in samples with low quartz crystallinity index. (a) Photomicrograph of Cambrian Siq Fm. sandstone (cross-polarized light): Chert grain (center) surrounded by monocrystalline quartz grains. (b) Photomicrograph of southwestern Nafud sands (cross-polarized light): Chert grain (upper left) surrounded by monocrystalline quartz grains.

CHAPTER 3

THERMO-PHYSICAL AND THERMO-OPTICAL

PROPERTIES OF ARABIAN SANDS

3.1. Abstract

Sand has been utilized as a sensible thermal energy storage medium, heat transfer material, and solar absorber material for different solar thermal technologies. In this study, we examine Arabian desert sands (Nafud, Dahna, and southwestern AlRub'AlKhali deserts) to identify optimal thermal energy storage and solar radiation absorption properties. Samples were grouped into three classes: quartzose feldspar-bearing (AlRub'AlKhali desert), quartzose carbonate-bearing (eastern Dahna corridor), and pure quartzose sands (occupying most of Nafud and Dahna deserts). Feldspar in quartzose sand causes decreases in specific heat capacity, vitrifying temperature, and spectral absorbance relative to pure quartzose sand. Calcite in quartzose sand causes a significant reduction of specific heat capacity, change in grain-size distribution, and decrease in spectral absorbance relative to pure quartzose sand. The purest quartzose sands ($\geq 99\%$ quartz) have the best thermo-physical and thermo-optical properties. These pure quartzose sands have the highest specific heat capacity, do not agglomerate up to 1200°C , and have the highest spectral absorbance after heating to 1200°C . The purest quartzose sands occupy the southwestern part of the Nafud desert. Sand of this area is

proposed to be the best candidate of all Arabian sands to be used as a sensible thermal energy storage medium and solar absorber material.

3.2. Introduction

Solar energy is a time-dependent energy resource, useful only during sunshine periods. To provide an uninterrupted energy supply, excess solar energy can be converted to, and stored in, other forms of energy (including mechanical, chemical, electrical, and thermal energy) that can be used later, on demand. Thermal energy storage systems stock thermal energy by heating a storage medium. Sensible heat storage stocks energy by heating liquid or solid media without changing their physical state. Solid sensible storage media are usually preferred because they are cheap, widely available, non-toxic, and non-flammable (Sterner & Stadler, 2019).

Sand has been utilized as a natural sensible thermal energy storage (TES) medium, heat transfer material, and solar absorber material for different solar thermal technologies including: concentrating solar power (Martin & Vitko, Jr, 1982), solar ponds (Beniwal et al., 1987), solar cooking (Ramadan et al., 1988), solar water heating (Fath, 1995), solar drying (Aboul-Enein et al., 2000), solar space heating (Pahud & Matthey, 2001), solar distillation (El-Sebaei et al., 2009), and solar gasification (Gokon et al., 2014). Relative to molten salts (the most common TES media), sand has only mediocre thermal properties. Nonetheless, this is compensated by the exceptionally high temperature range (they operate at temperatures beyond 1000°C and with no lower

temperature limit) and the extremely low cost (orders of magnitude cheaper) of naturally occurring sand (Steiner et al., 2017; Diago et al., 2018). Additionally, sand exhibits thermal, chemical, and mechanical stability after long periods of fluidization and thermal aging (Díaz-Heras et al., 2021).

To find the ideal sand candidate to be employed as TES material, several criteria need to be met. El Alami et al. (2020) developed a methodology for selecting the best candidate among natural geomaterials (rocks or sediments). The methodology is based on characterization of each candidate's thermo-physical properties, thermo-mechanical properties, thermo-chemical properties, economic and environmental aspects, durability after aging, and compatibility with the used heat transfer fluid. Thermo-optical properties also need to be evaluated if the material is to be used as a direct solar absorber (Diago et al., 2018). In this study, we investigate some aspects of the thermo-physical and thermo-optical properties of Arabian sands.

The quantity of heat that sands are capable of storing depends on their specific heat capacity, maximum permitted temperature difference, and mass (Stadler et al., 2019). To design a compact storage system (less mass and lower design costs), sands with high energy density (high average specific heat capacity and maximum permitted temperature difference) are needed. Maximum allowed temperature is defined by the onset of sand agglomeration/sintering which is a function of its mineralogy. Choosing sand with low clay and carbonate content is imperative in high-temperature applications. Because they cause early sand agglomeration or sintering, clays (Knott et al., 2014b) and carbonates (Diago et al., 2018) adversely impact the fluidization, the heat transfer performance of the heat exchanger, and the ability to freely transport the particles around

the system. Specific heat capacity (the most important criteria in enhancing the performance of a thermal energy storage system) of sands is also a function of sand mineralogy.

In addition to being a TES, sand can assume other roles if subjected directly to concentrated solar radiation. In this case, sand particles will act as solar particle receivers that can be stored in insulated tanks to be used for power generation (heat collector medium) and/or utilized to heat a secondary working fluid (heat transfer medium) (Martin & Vitko, Jr, 1982; Iniesta et al., 2015; Díaz-Heras et al., 2021). Sand, however, has a low capacity for absorbing direct solar radiation (Palacios et al., 2019; Díaz-Heras et al., 2021). Spectral absorbance of carbonate-containing sands was found to decrease for all wavelengths when heat treated (Diago et al., 2018). On the other hand, the spectral absorbance of red sands with thermally stable impurities gets enhanced after heat treatment (Knott et al., 2014b).

The Arabian Peninsula encompasses four large sand seas: AlRub'AlKhali, Dahna corridor, Nafud, and Al Jafurah (**Figure 7**). Evaluation of sands as thermal energy storage material and direct solar absorber material in the Arabian Peninsula has been initiated recently and covered United Arab Emirates (UAE) deserts (Diago et al., 2015, 2018), and also near Riyadh (Knott et al., 2014b). No systematic studies have evaluated sand of the Nafud, Dahna, and southwestern AlRub'AlKhali deserts for use in solar thermal technologies. The objective of this study is to identify Arabian sands with the highest energy density and spectral absorbance properties. Thus, the goal is to identify the best candidate of Arabian sands to be employed as a thermal energy storage medium and solar absorber material for different solar thermal technologies.

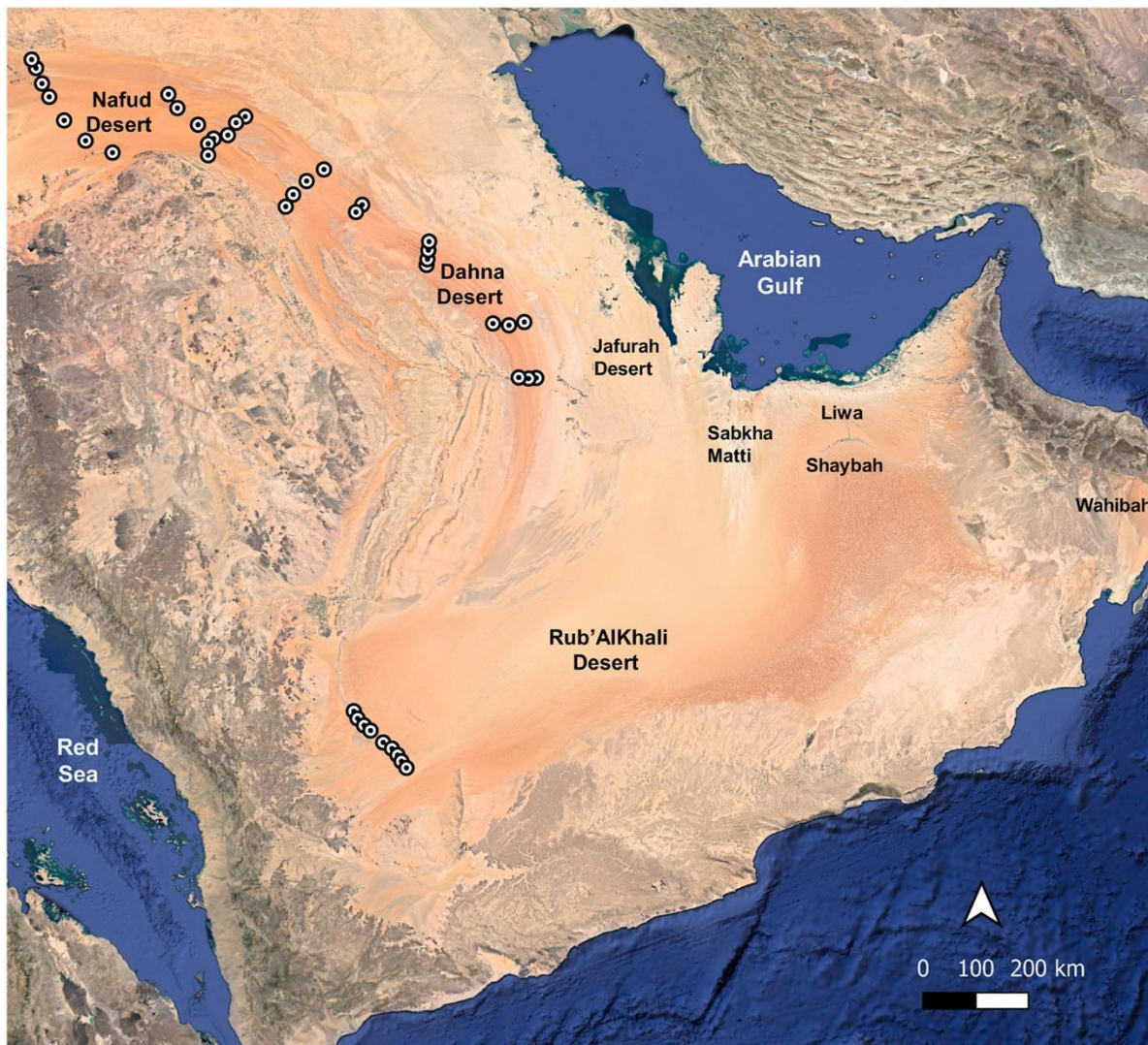


Figure 7. Google Earth TM image of the Arabian Peninsula. Sampling covered the Nafud, Dahna, and southwestern AlRub'AlKhali deserts. Circles represent sampling locations.

3.3. Materials and methods

3.3.1. Sampling

Systematic sampling of sand dunes and sand sheets along nine transects across Arabian deserts (Nafud, Dahna corridor, and southwestern AlRub'AlKhali) was carried out during 2018. Sampling locations are shown in **Figure 7**.

3.3.2. Quantitative Evaluation of Materials by SCANning electron microscopy (QEMSCAN)

Forty sand samples were embedded in one-inch epoxy disks, carbon coated, and then analyzed using Quantitative Evaluation of Minerals by SCANning electron microscopy (QEMSCAN) to identify and quantify the minerals present in the sand samples. The QEMSCAN instrument at KFUPM is based on a platform of a scanning electron microscope (SEM: Quanta 650 F – Thermo Fisher Scientific), with two energy-dispersive X-ray spectroscopy detectors (EDS: Bruker XFlash 6130), iDiscover software, and a species identification protocol database. Point spacing was established at 5 μm across a region of 1 cm^2 . SEM and EDS were used for their individual capabilities as well. While SEM was used to observe the degradation and agglomeration of sand constituents after heat treatment, EDS was used to recognize different types of sand grains and detect different types of grain coatings.

3.3.3. Differential scanning calorimetry

Ten sand samples were analyzed utilizing a simultaneous differential scanning calorimeter/thermogravimetric analyzer (DSC/TGA: NETZSCH STA 449F3) to measure

the specific heat capacity. Sand samples without pretreatment were put in alumina crucibles, run using an identical empty crucible on the reference pan, and scanned at a rate of 10 K/min from 25°C to 1000°C in an argon atmosphere. If peaks other than the one representing α - β quartz transition were noticed, the samples were allowed to cool, and a second heating cycle was carried out. Some minerals (e.g., calcite) experience decomposition in the first cycle, so the second heating better represents the state of the mineral during its operation as a TES material. The selection of samples was carried out so that all different mineralogical compositions were represented.

3.3.4. Heat treatment

Nine samples were heat treated in an electrical furnace to study the effect of elevating temperature on color, spectral absorbance, and to determine the onset temperature of agglomeration/sintering of the Arabian sands. As above, the selection was representative of all different mineralogical compositions. Samples were kept in ceramic crucibles at 400°C, 600°C, 800°C, and 1000°C for 10 hours, and at 1200°C for 6 hours. Samples were kept inside the furnace until they cooled on their own. Different specimens from the same sample were tested for each heat treatment.

3.3.5. Coating removal

Iron-oxide coating is believed to be the main cause of coloration in sands with a reddish hue (Walker, 1979; Gardner & Pye, 1981). To detect the effect of iron-oxide coatings on the color and spectral absorbance of Arabian sands, the coatings were chemically removed. Coated samples were boiled for 10 min in 15% hydrochloric acid solution (Vos et al., 2014), rinsed, and dried.

3.3.6. Color change

To observe the change in color due to heat treatment or coating removal, all samples were photographed using a Sony SELP1650 camera with a single shot to avoid changes in lighting conditions or change in camera settings. Additionally, each sample was photographed individually with the same settings using a LEICA S9i stereomicroscope.

3.3.7. Ultraviolet–visible spectroscopy

Spectral absorbance of the sand samples in the ultraviolet-visible (UV-VIS) range (200–800 nm) was calculated using a Cary 5000 UV-VIS diffuse reflectance spectrophotometer equipped with 150 mm integrating sphere and deuterium (for UV range) and halogen (for VIS range) lamps. Measurements were carried out at 1 nm intervals for nine samples, before and after heat-treatment and coating removal. Transmittance was assumed to be zero. Trapezoidal integration was performed under the curve to calculate absolute spectral absorbance. Calculation of solar-weighted absorbance was not possible, since near-infrared data weren't attainable.

3.3.8. X-ray diffraction

To observe changes in mineralogy caused by heat treatment, X-ray diffraction (XRD) was utilized. Three sand samples (before and after heat treatment at 1000°C and 1200°C) were ground with agate pestle and mortar for 10 minutes. Sample selection was carried out so that all different mineralogical compositions were represented. X-ray diffractograms were recorded in a PANalytical Empyrean diffractometer, operated at 45 kV and 40 mA, using CuK α radiation. Samples were scanned two times in a continuous mode from 4° to 70° 2 θ at 0.01° 2 θ increments, with 40 s counting time per

increment. Powder diffraction patterns were analysed using Match software to identify phases using the Crystallography Open Database.

3.4. Results

3.4.1. Mineralogy

The main component of all Arabian sand samples is quartz grains (**Figure 8**). Sand with the highest quartz content occupies the northernmost transect (transect 1 of the Nafud desert), and sand with the lowest quartz content occupies the southernmost transect (transect 9 of the AlRub'AlKhali). In AlRub'AlKhali sands, quartz ranges from 84% to 93%. In contrast, Nafud and Dahna sands have quartz content consistently above 90% and predominantly above 95% (**Figure 8a**).

Plagioclase and K-feldspar are generally below 1% in Nafud and Dahna sands, with few exceptions. In contrast, AlRub'AlKhali sands have plagioclase and K-feldspar contents that are always above 1% and with a maximum value of 6.5% (**Figure 8c**). Clays are consistently below 1.5% in all Arabian sands and below 1% along the northernmost transect (transect 1 of the Nafud desert) (**Figure 8d**). Carbonates are generally below 1% in all sampled Arabian sands, with few exceptions. They may reach up to 5% in eastern Dahna corridor sands (**Figure 8e**).

Figure 9 shows X-ray diffractograms of three samples before and after heating at 1000°C and 1200°C. Only quartz appears in sample #718-44 (**Figure 9a**). In addition to

quartz, sample #818-09 contains a small amount of calcite and trace amounts of feldspar (**Figure 9b**). On the other hand, sample #918-16 contains both alkali and plagioclase feldspar, in addition to quartz (**Figure 9c**). In all samples, a small amount of cristobalite (tetragonal SiO₂) develops upon heating to 1200°C. Feldspar peaks diminish significantly after heating to 1200°C. In calcite-containing samples, calcite peaks disappear upon heating and new peaks appear with each heat treatment. While portlandite [Ca(OH)₂] peaks appear after 1000°C heating, lime (CaO) peaks appears after heating to 1200°C.

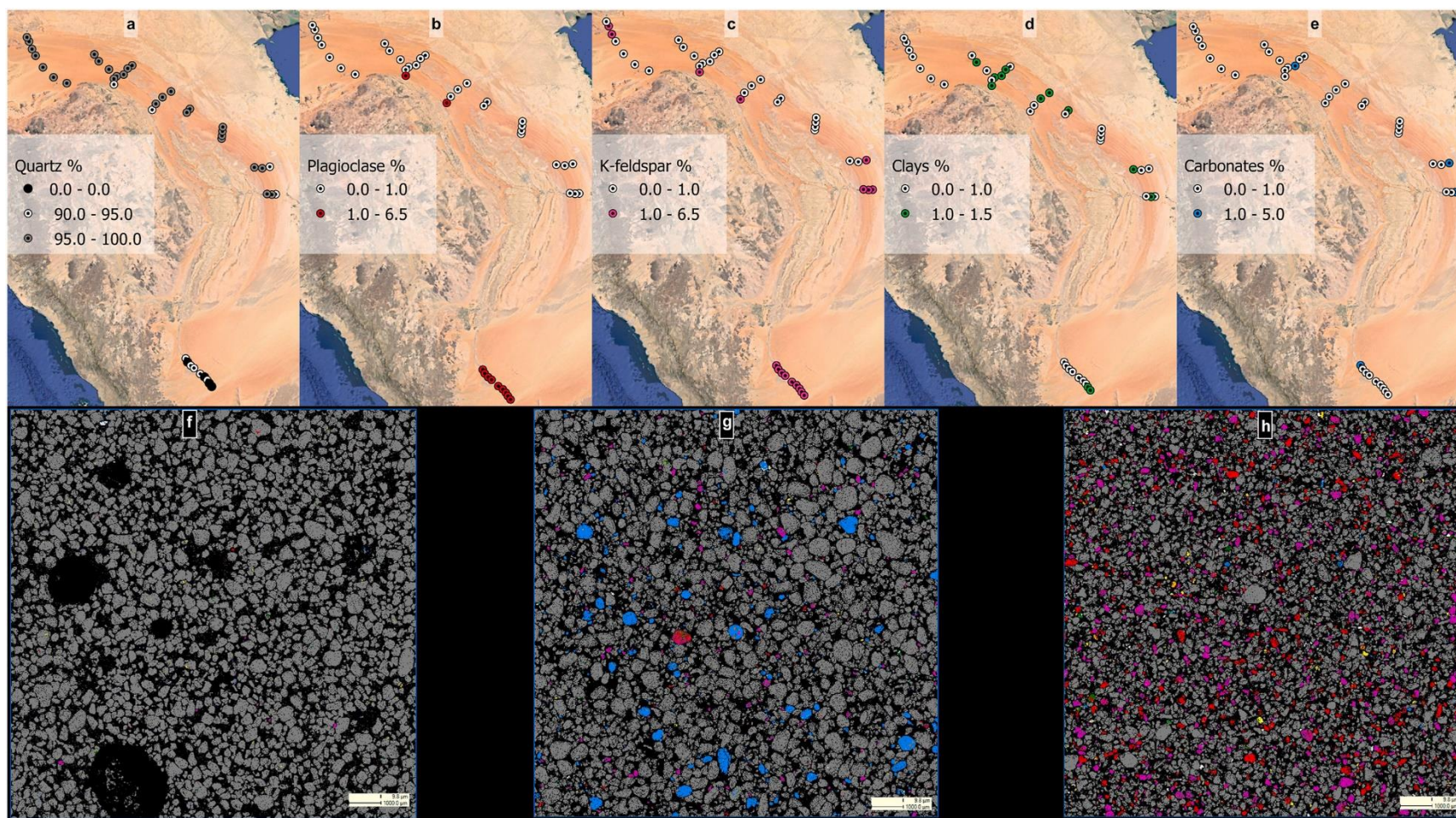


Figure 8. (a-e) Google Earth TM image of the Arabian Peninsula showing the mineral content of selected Arabian sand samples. Quantification is based on QEMSCAN data. (f-h) QEMSCAN images of selected samples. Grey color represents quartz, blue color represents carbonate minerals, red color represents plagioclase minerals, and pink color represents k-feldspar minerals. (f) QEMSCAN image of a Nafud sample. (g) QEMSCAN image of an eastern Dahna corridor sample. (h) QEMSCAN image of an AlRub'AlKhali sample..

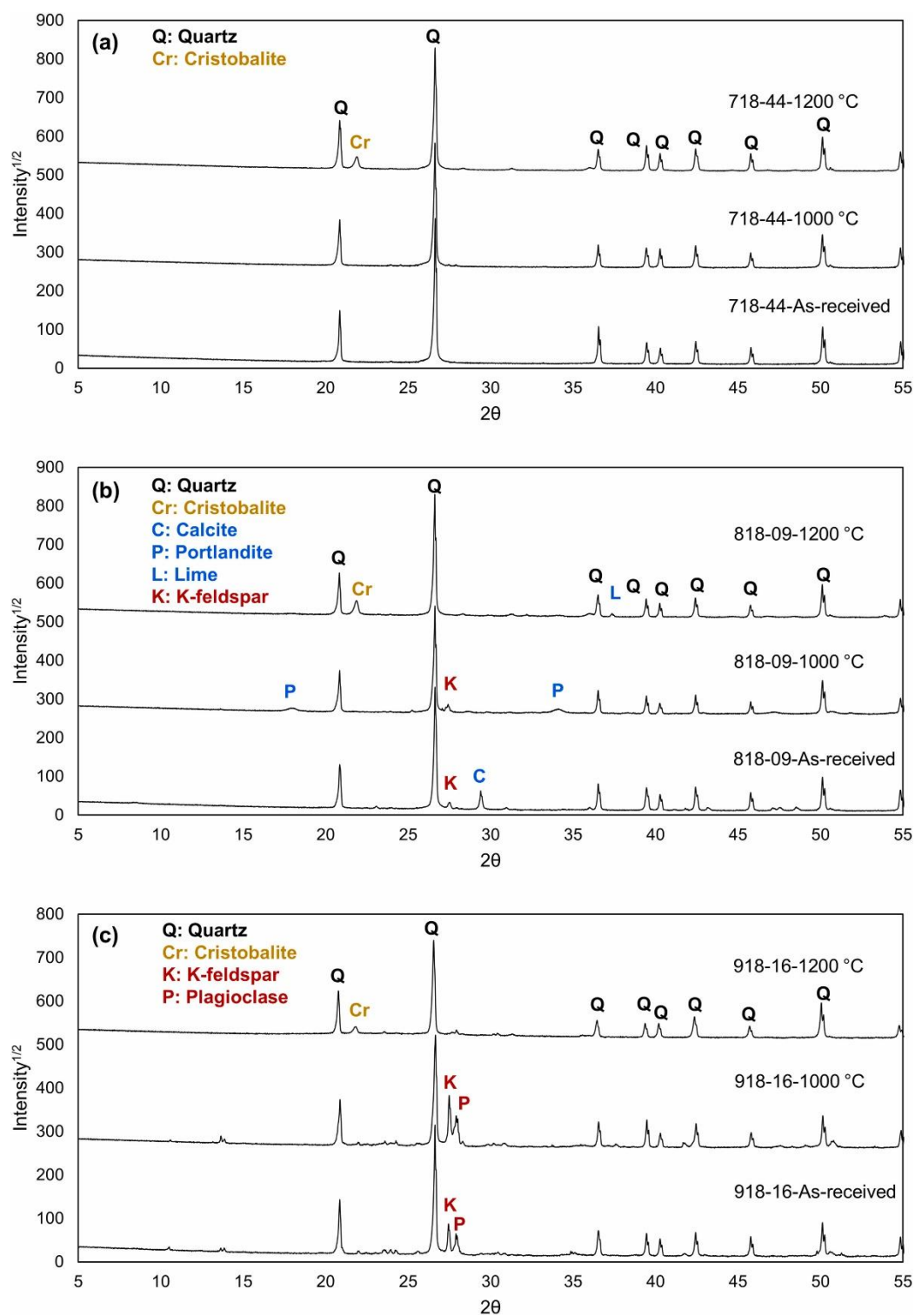


Figure 9. X-ray diffractograms of three Arabian sand samples before and after heating at 1000°C and 1200°C. (a) X-ray diffractograms of a Nafud sample. (b) X-ray diffractograms of an eastern Dahna corridor sample. (c) X-ray diffractograms of an AlRub'AlKhali sample.

3.4.2. Thermo-physical properties

In all samples, a peak representing the α - β quartz transition is present at 573°C (**Figure 10**). Another peak (between 700 and 800°C) appears in the first heating cycle of carbonate-containing sand samples. This peak represents decarbonation of calcite and it disappears in the second cycle (**Figure 10c**). The purest sand sample (#718-44: 99% quartz) possesses the highest specific heat capacity (**Figure 10**). Its average over the range between 200°C and 1000°C is 1.07 J/g°C. Less pure sand samples (#718-24, 718-54, and 718-20: 96-98% quartz) have lower specific heat capacities ranging from 0.7 to 0.9 J/g°C (**Figure 10a**). While feldspar-rich (9-13%) sand samples (#918-12 and 918-16) of AlRub' AlKhali desert have specific heat capacity values around 0.85 J/g°C, carbonate-rich (5%) sands (#818-09) of eastern Dahna desert possess the lowest specific heat capacity (0.7 J/g°C), and these go lower in the second heating cycle (0.51 J/g°C) (**Figure 10b-c**).

Carbonate-containing (2.5%-5%) sand samples were found to easily disaggregate with handling (soft agglomeration) at 1000°C. At 1200°C, carbonate-containing (2.5%-5%) and feldspar-containing (9-13%) sand samples exhibited hard agglomeration; samples had to be broken to extract them from the crucible (**Figure 11**). In contrast, the purest sand sample (#718-44: 99% quartz) did not agglomerate at all. Less pure (96-98% quartz) sand samples sometimes agglomerated.

Figure 12 shows SEM-EDS photomicrographs of three different samples before and after heat treatment. No significant changes appeared at 1000°C for pure sample (#718-44) and feldspar-containing sample (#918-16) (**Figure 12b, k, n**). Only minor exfoliation of clay coatings of quartz grains began. On the other hand, thermal

degradation of calcite occurred, producing finer grains in the carbonate-containing sample (#818-09) (**Figure 12e, h**). At 1200°C, a small number of silica grains started to crack in all samples. Thermal degradation of calcium-containing phases continued to progress, and more fine grains developed in carbonate-containing samples (**Figure 12i**). In feldspar-containing samples, fusing particles with K- and Al-containing phases developed (**Figure 12l, o**). This fusion occurred in samples with feldspar content as low as 1% (**Figure 12f**).

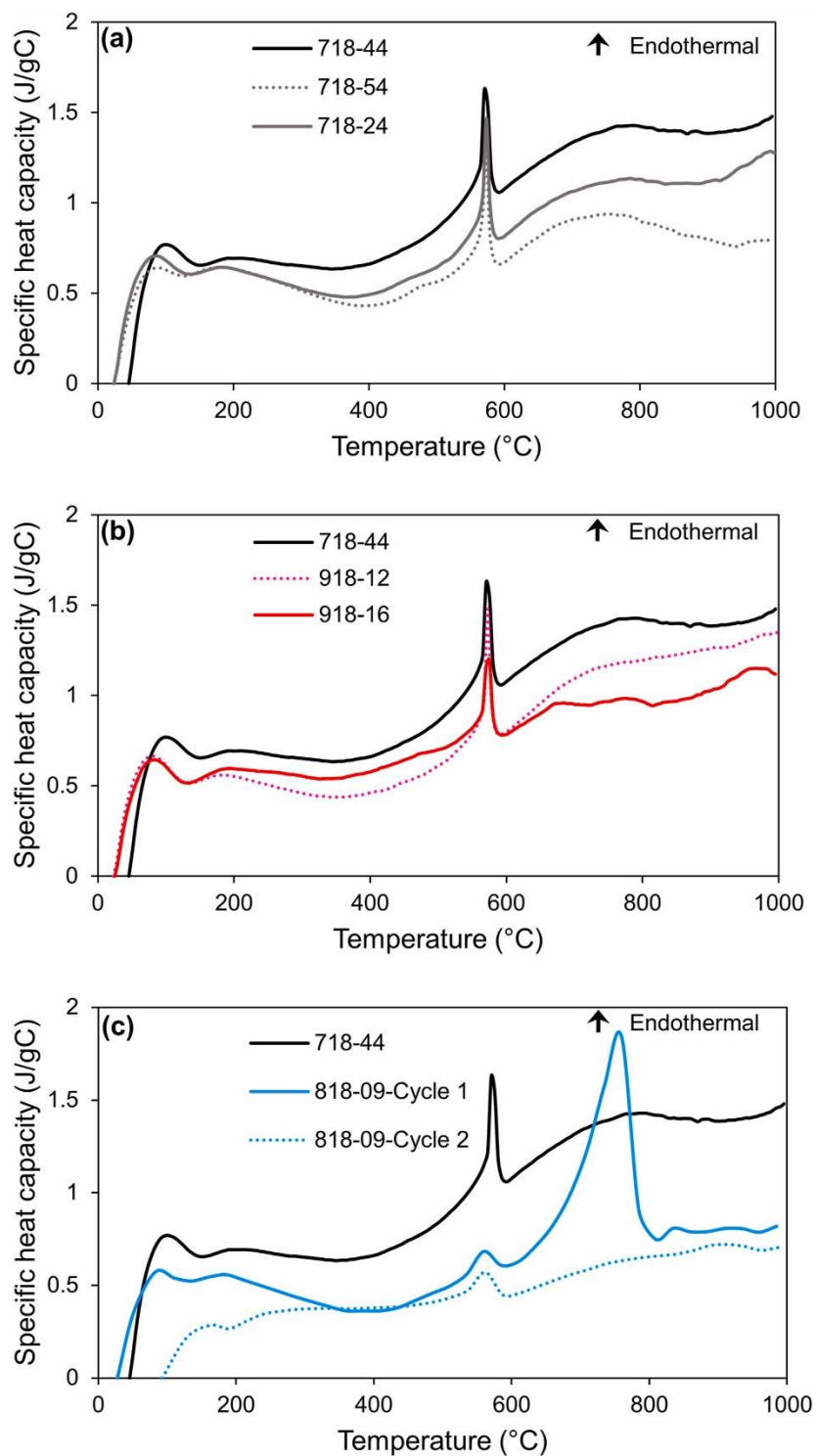


Figure 10. Specific heat capacity of Arabian sand samples. The purest sand sample (718-44) is repeated in the three figures as a reference. (a) Specific heat capacity of some Nafud samples (b) Specific heat capacity of some Rub'AlKhali samples. (c) Specific heat capacity of an eastern Dahna corridor sample.

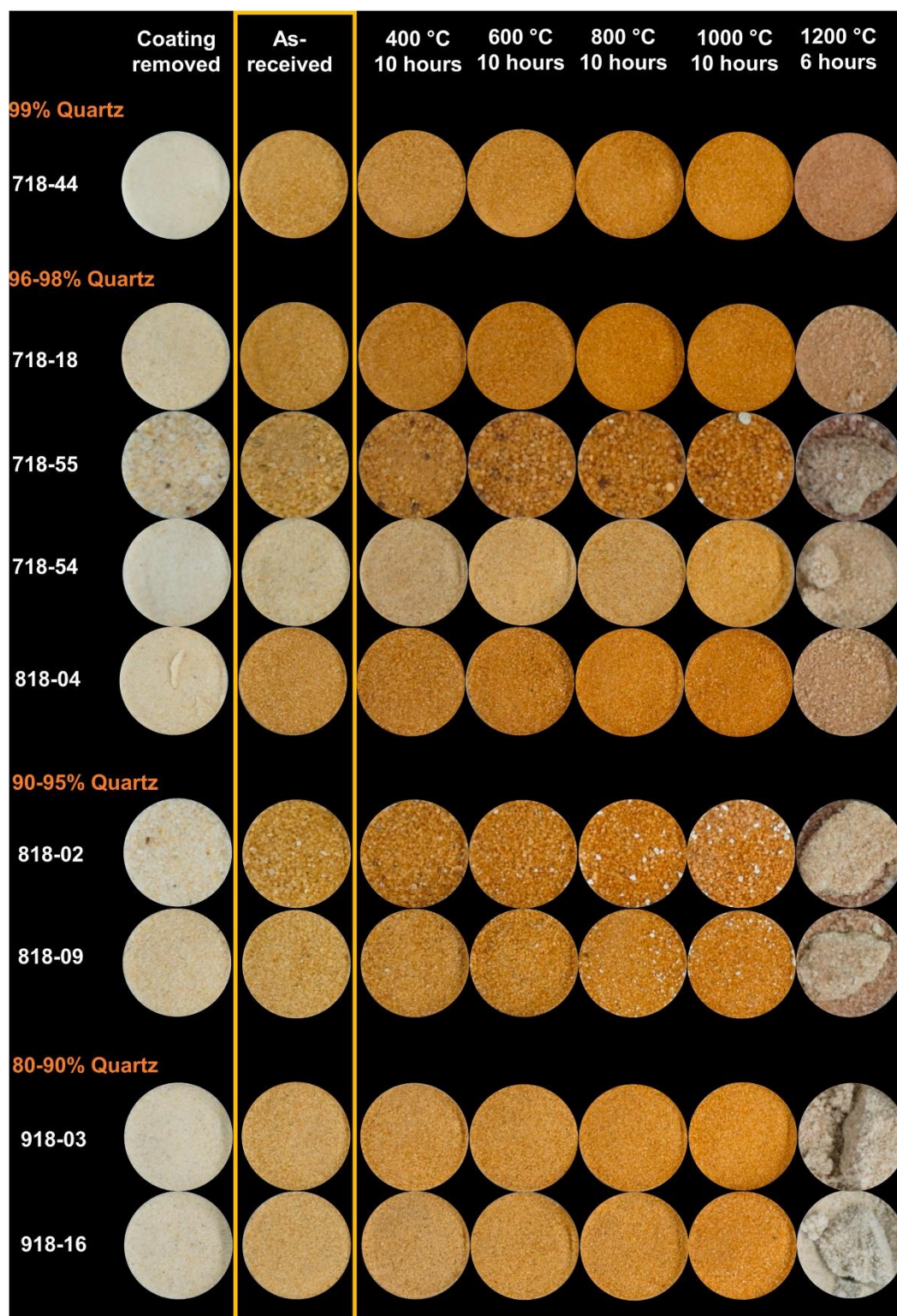


Figure 11. Photograph showing the effect of coating removal and heat treatment on the color of Arabian sands.

1200 °C
6 hours

(i)

[illegible]

(o)

11 1107
 10 kV X500.0k 5.0um X50.0k WD=11.5mm

400 μm

52

3.4.3. Thermo-optical properties

Most Arabian sand samples have different shades of light brown color (**Figure 11**). An exception is sample #718-54, which showed a beige color. After iron-oxide coating removal, all samples turned light beige (**Figure 11** and **Figure 13a,b**), with samples #718-54 least affected. With the exception of carbonate-containing sand samples (#818-02 and 818-09: 2.5-5%), all samples became darker after being subjected to 400°C, 600°C, 800°C, and 1000°C heating. At 800°C onward, some grains of the carbonate-containing samples turned white and coated the neighboring brown grains (**Figure 13c**). At 1200°C, all samples became lighter in color; sample #718-44 was least affected (**Figure 11** and **Figure 13d**).

Changes in sand color after different treatments resulted in changes in absorption in the 350-600 nm band. **Figure 14** shows the integrated absorbance over this band before and after treatment. Although the purest sand sample (#718-44) had moderate original absorbance and was the least affected by heating, ultimately it had the highest absorption at the highest temperature. After 1000°C treatment, carbonate-containing samples had the lowest absorbance. However, after the 1200°C treatment, feldspar-containing samples had the lowest absorbance.

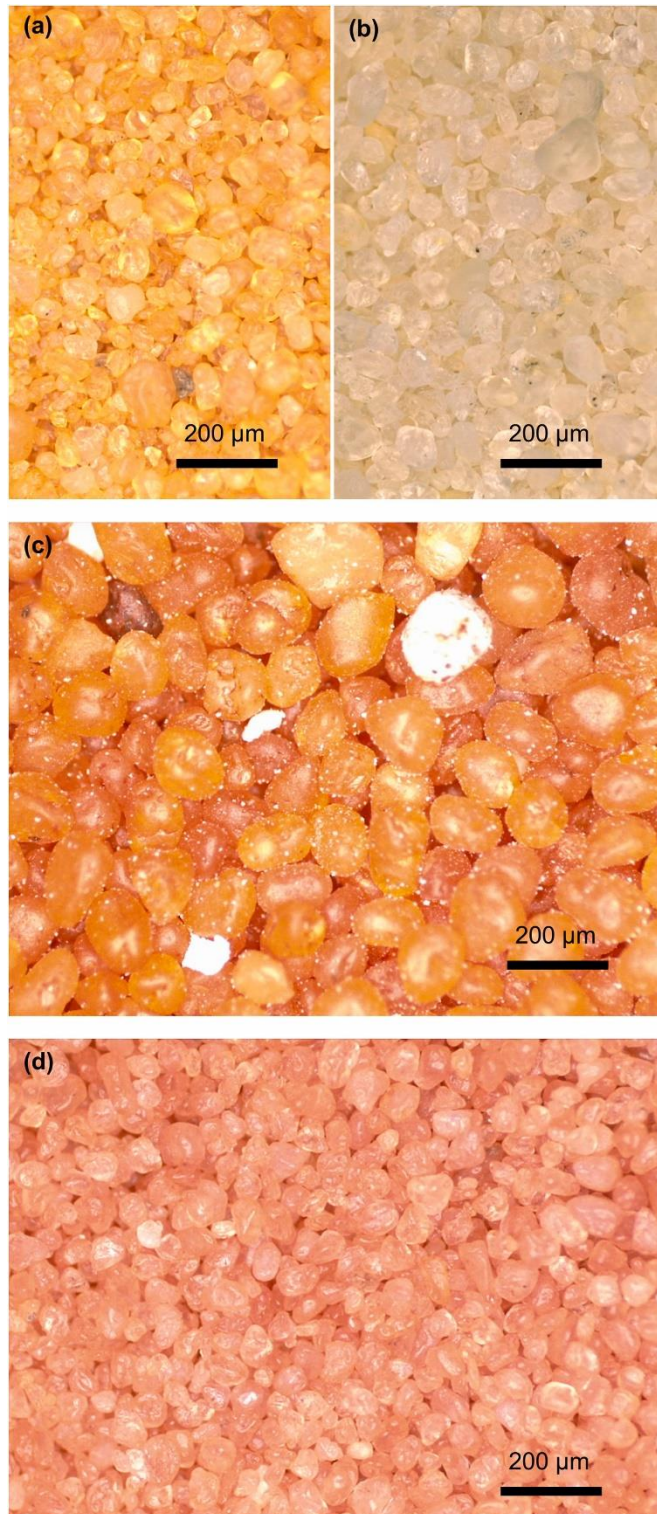


Figure 13. Photomicrograph taken under stereomicroscopic viewing of sand samples (a) before, and (b) after iron oxide coating removal. (c) Photomicrograph of an eastern Dahna corridor sample after 1000°C heating (sample #818-02). (d) Photomicrograph of the purest sand sample after 1200°C heating (sample #718-44).

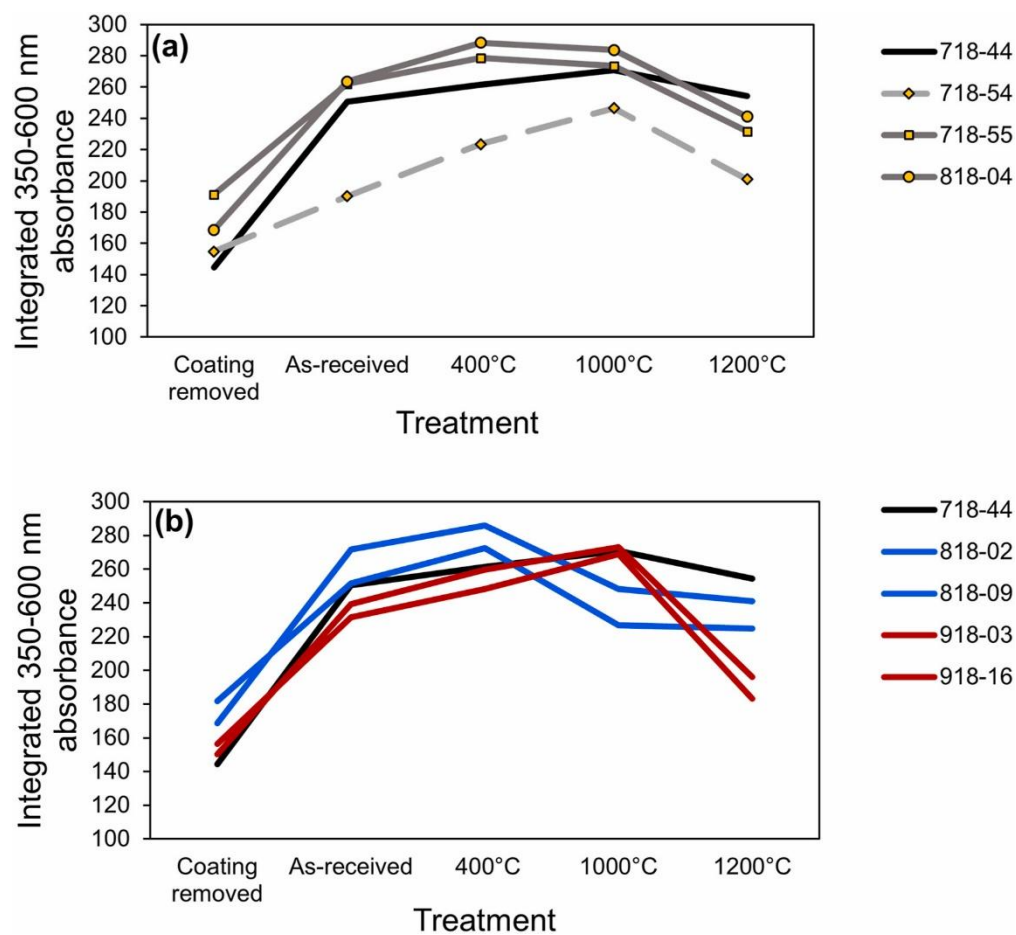


Figure 14. Integrated absorbance of 350-600 nm band of Arabian sand samples before and after coating removal and heat treatments. The purest sand sample (718-44) is repeated in the two figures as a reference (black line). (a) Grey lines represent less pure sand samples. (b) Blue and red lines represent samples of eastern Dahna corridor and AlRub'AlKhali, respectively.

3.5. Discussion

The Arabian sand samples can be categorized into three classes (Garzanti, 2019): quartzose feldspar-bearing, quartzose carbonate-bearing, and pure quartzose (**Figure 15**).

3.5.1. Quartzose feldspar-bearing sands

Quartzose feldspar-bearing sand samples are characteristic of the AlRub'AlKhali desert (**Figure 15**). In general, these sands:

- consist of less than 95% quartz, with 5-15% feldspars and a minor contribution of clays, carbonates, micas, and heavy minerals (**Figure 8**).
- have lower specific heat capacity relative to pure quartz sand samples (**Figure 10b**). This can be attributed to the presence of feldspars. Plagioclase and potassium feldspar have similar or slightly lower specific heat capacity than quartz (Birch et al., 1942).
- exhibit hard agglomeration at 1200°C. A K- and Al-containing phase is responsible for fusing grains together (**Figure 12f,l**). This is consistent with the disappearance of K-feldspar in the X-ray diffractograms (**Figure 9c**). The alkalis in feldspars (potassium and sodium ions, in particular) lower the vitrifying temperature of sands by forming glassy material at low temperature. Actually, that is why feldspar is used as a fluxing agent in ceramic and glass manufacturing (Burat et al., 2007).

- have low absorbance relative to quartzose carbonate-bearing sands and pure quartzose sands at room temperature (**Figure 14b**). Absorbance of all sand samples increases after heating to 400°C (**Figure 14**). This can be attributed to dehydroxylation of clay minerals and goethite coatings (Lugassi et al., 2014). A significant decrease in absorbance after 1200°C heating takes place in quartzose feldspar-bearing sands due to the formation of the new glassy phase derived from feldspars. That is another reason why feldspar is used in whiteware (porcelain) manufacturing (Olupot et al., 2006).

3.5.2. Quartzose carbonate-bearing sands

Quartzose carbonate-bearing sands are found occupying the eastern Dahna corridor (**Figure 15**). As a summary of their characteristics, these sands:

- consist of quartz (less than 95%) with 2-5% carbonates and minor contribution of feldspars (**Figure 8**).
- have significantly lower specific heat capacity relative to pure quartz sand samples (**Figure 10c**). The significant decrease in the second cycle of heating is due to decarbonation of calcite and lime formation. Lime (CaO) has a significantly lower specific heat capacity relative to quartz (Chase, 1998).
- exhibit hard agglomeration at 1200°C. Again, the binding phase is a K- and Al-containing material (**Figure 12f**). Although the K-feldspar content is very small (approximately 1%: **Figure 8**), the presence of small amounts of impurities of K₂O and Al₂O₃ favors the formation of glassy phases and, in turn, sintering (Shahraki et al., 2011).

- experience partial thermal degradation due to the presence of calcite. At approximately 750°C, calcite decomposes (**Figure 10**) to form lime (CaO) and releases carbon dioxide (CO₂). This reaction causes mass loss during the first heating cycle (Diago et al., 2018). Lime, in the presence of atmospheric moisture, hydrates and forms portlandite [Ca(OH)₂] (**Figure 9b**). A volume increase accompanies the hydration reaction. In fact, that is why lime is used as an expansive agent in non-explosive demolition applications (Shahraki et al., 2011). Thermal degradation of calcite, consequently, causes the formation of microcracks and segmenting of the original grain into finer grains (**Figure 12e,h,f,i**). The formation of fine grains is not desirable in applications that involve fluidization (Zhang et al., 2016). On the one hand, if the fines were to be recycled, the grain size distribution would get finer. On the other hand, if the fines were to be gathered by the dust collection system, the grain size distribution would get coarser.
- experience a significant decrease in absorbance after 1000°C heating. This can be attributed to decarbonation of calcite and the formation of lime (**Figure 11**). The resultant powder has a white color and was found to be scattered over the surrounding quartz grains (**Figure 13c**).

3.5.3. Pure quartzose sands

Pure quartzose sands occupy most of Nafud and Dahna deserts (**Figure 15**).

Experiments with the samples of these sands indicated that they:

- consist of over 95% quartz with a minor contribution of plagioclase, K-feldspar, micas, clays, carbonates, and heavy minerals (**Figure 8**). The purest sand samples occupy the southwestern part of Nafud desert.
- have variable specific heat capacity. The highest value belongs to the purest sample (#718-44) (**Figure 10a**).
- show intermediate (some samples agglomerate and some samples do not) agglomeration at 1200°C. The purest sample does not agglomerate at all (**Figure 12d**).
- experience cracking of some silica grains after 1200°C heating (**Figure 12c**). This takes place in the other two types of sand samples as well. This can be attributed to phase transformations from quartz to cristobalite (**Figure 9**). Grain volume increases because cristobalite has a lower density than quartz. This volume expansion creates tension and cracking of the quartz grains (Jusnes et al., 2018; Jusnes, 2020). Again, cracking would alter the grain size distribution, which is not desirable in applications that involve fluidization. Even if the grains appear intact after heating, they become mechanically weaker than before heating (Jusnes, 2020).
- show variable absorbance at room temperature. Pure quartzose sand samples, however, do not experience a significant decrease after 1000°C or 1200°C heating. The purest quartzose sand sample has the highest absorbance after 1200°C heating. Less pure quartzose sands have about 1.5-2.5% feldspars and clays. Less pure quartz sands originally have higher absorbance because they have more iron oxide coatings. The impurities, however, form a new glassy phase after

heating at 1200°C, leading to lower absorbance. The lowest absorbance value belongs to the sand sample (#718-54) from the northwestern part of the Nafud desert. This sample has a very small amount of iron coating, as indicated from the coating removal experiments (**Figure 14a**). Its absorbance is the least affected by the reaction with acid. Generally, sands become redder with increasing age and distance of transport (El-Baz, 1986). The color of this sand, therefore, can be interpreted to be derived recently from the nearby Miocene and Pliocene sandstones (U.S. Geological Survey, 1963).

3.5.4. Locating Arabian sand with highest energy density and spectral absorbance

To find the best sand candidates of all Arabian deserts to be used as thermal energy storage media and particle solar absorber materials, sand with the highest specific heat capacity, highest agglomeration temperature, and maximum spectral absorbance should be considered. The best thermo-physical and thermo-optical properties belong to the purest (99% quartz) sand sample (#718-44). It has the highest specific heat capacity and does not agglomerate after 1200°C heating. Moreover, it has the highest spectral absorbance after 1200°C heating. The purest sand samples occupy the southwestern part of the Nafud desert (northwestern region of Saudi Arabia) (**Figure 16**). Fortunately, the highest average direct normal irradiance values and clearest skies are characteristic of northwestern Saudi Arabia (Zell et al., 2015). The proximity of the highest average solar irradiation in the Arabian Peninsula to sand with the highest energy density and solar absorbance will provide increased efficiencies and, subsequently, low levelized costs of energy.

Two main points, however, need to be addressed in future studies. First, a small portion of quartz transforms to cristobalite after 1200°C heating, which affects the grain size distribution and weakens its mechanical properties. Second, although the purest sand sample has the highest spectral absorbance after 1200°C heating, it still has overall low absorbance. Future studies should focus on enhancing the performance of sands of the southwestern part of the Nafud desert via delaying quartz-cristobalite transformation and enhancing their solar absorbance.

3.5.5. Regional context

Compared to the desert dune sands of UAE (Diago et al., 2018), Nafud and Dahna sands of Saudi Arabia have higher energy density and spectral absorbance. Carbonate content in UAE desert sands increases steadily toward the coast, where it reaches up to more than 90% carbonate minerals (Garzanti et al., 2003). This leads to early sand agglomeration, decreases the specific heat capacity of the sands, and negatively impacts solar absorption (Diago et al., 2018).

In addition to Saudi Arabia, Garzanti et al. (2013, 2017) also provided detailed mineralogical data for UAE, Qatar, Oman, and Yemen desert sands (Garzanti et al., 2013, 2017). Based on these data, conclusions on their suitability for use in high-temperature solar thermal technologies can be drawn. While the sands of these deserts are quartzose, they contain variable amounts of feldspar, carbonate, or both. None of them are pure quartzose sand including Liwa, Jafurah, Wahibah, Shaybah, Sabkha Matti, and all fluvial and beach sands (**Figure 7**). This will render them of no interest for use in high-temperature solar thermal technologies because they will necessitate processing that will increase the levelized costs of energy.

Saudi Arabia has a growing interest in generating electricity from solar technologies including 25 GW of CSP systems by 2030 (Kassem et al., 2017). Several studies have considered using CSP for power generation in Saudi Arabia (Alraddadi & Conejo, 2021), taking into account the particularities of different locations, including Jeddah (Abu-Hamdeh & Alnefaie, 2016), Riyadh (Al Zahrani et al., 2016; Al-Ansary et al., 2018; Alsagri et al., 2019), Dhahran (Atif & Al-Sulaiman, 2018), Neom (Albarbar & Arar, 2019), and AlKhobar (Al-Kouz et al., 2020; Boretti et al., 2020). However, few studies have investigated the use of sand as TES material and direct solar absorber and have mainly focused on Riyadh or fracking sands (Al-Ansary et al., 2012; Knott et al., 2014b; Al-Ansary et al., 2018). In this study, we surveyed the Arabian deserts and located the best sand that ensures higher efficiency and lower cost. Future CSP studies should experiment on the sand of southwestern part of the Nafud desert and integrate it as TES material and solar absorber in their configuration. Although using this technology is environmentally advantageous, mining sand in large quantities might affect the neighboring ecosystems and human settlements in Hail Province. Future studies should also consider the environmental impact of such mining activities.

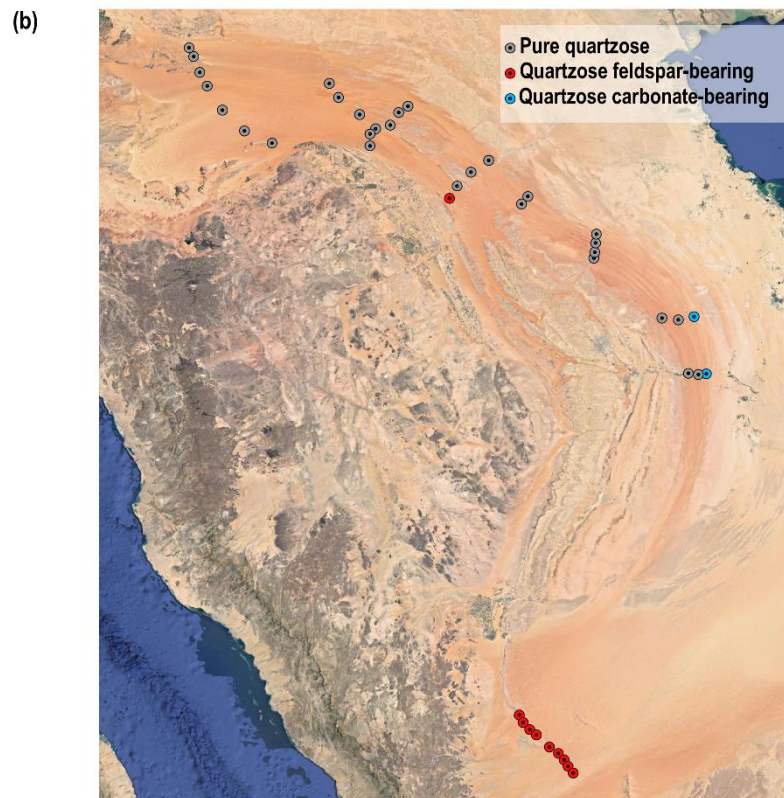
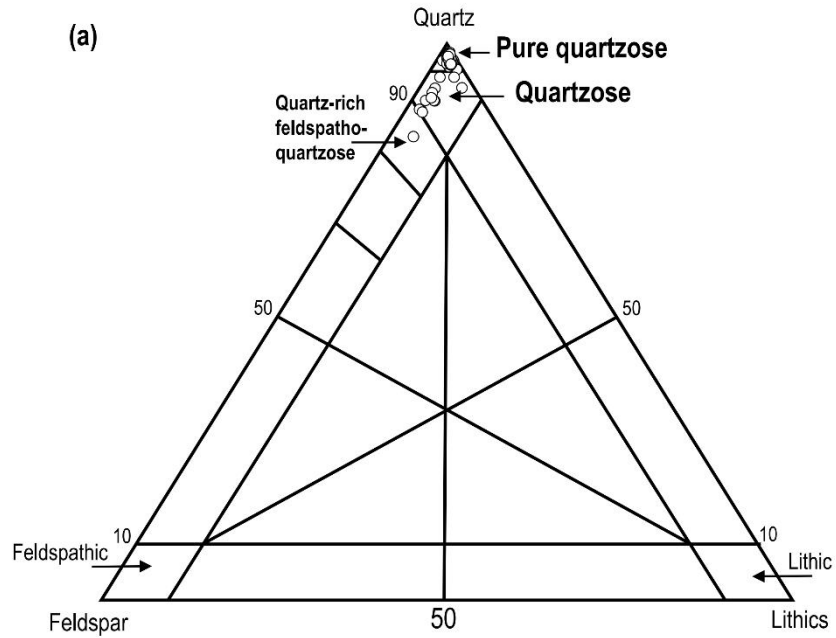


Figure 15. (a) Ternary diagram showing the classification of Arabian sands according to Garzanti (2019) classification. (b) Google Earth TM image of the Arabian Peninsula showing classification of Arabian sands according to Garzanti (2019) classification.

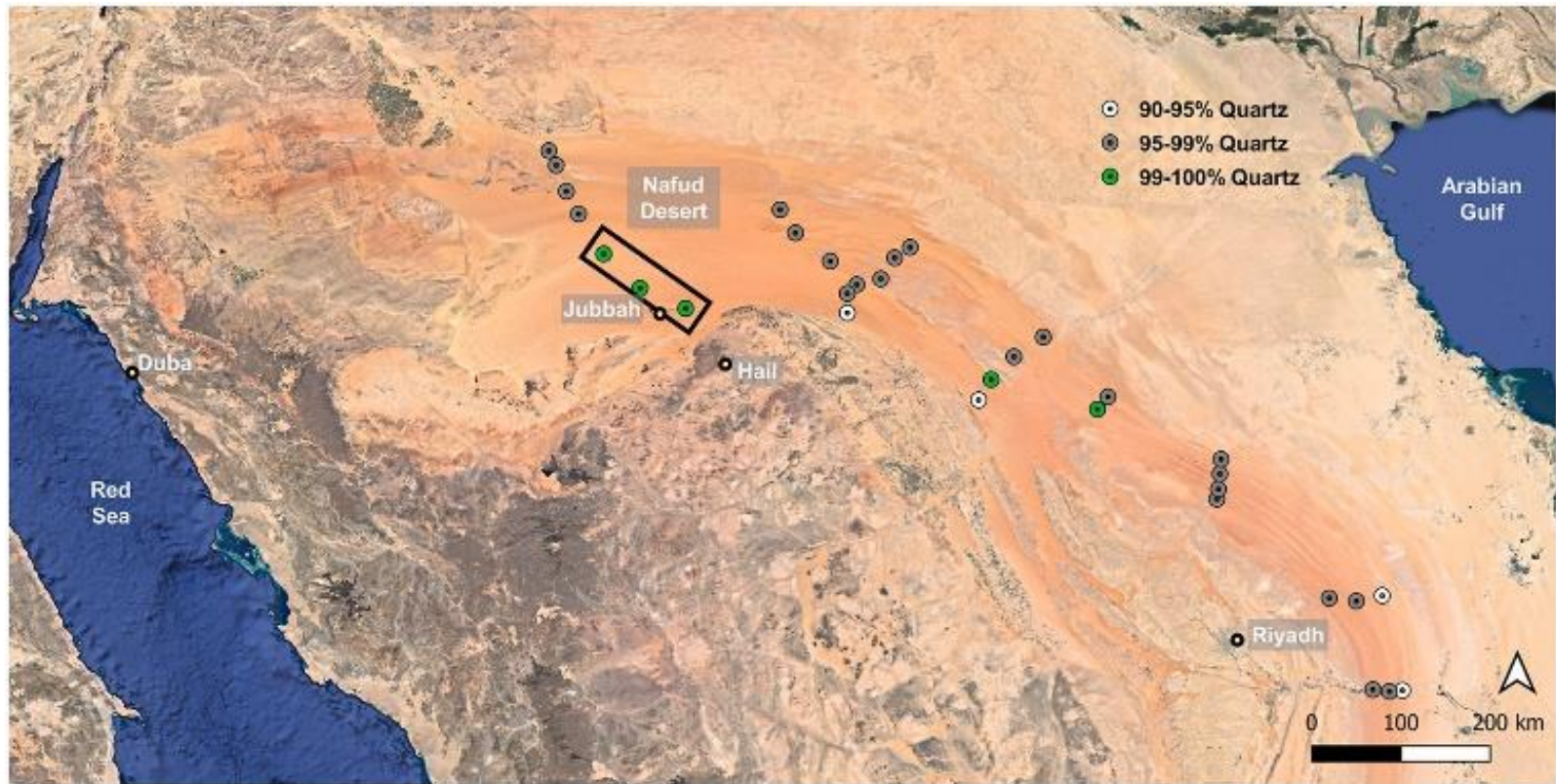


Figure 16. Location of Arabian sand with highest energy density and spectral absorbance (area outlined by black rectangle).

3.6. Conclusions

Forty sand samples covering the Nafud, Dahna, and southwestern AlRub'AlKhali deserts of Arabian Peninsula were analyzed to find the optimum sand for storing thermal energy and absorbing more solar radiation.

The presence of impurities as low as 2% (e.g., feldspar and/ or calcite) in Arabian quartzose sands is sufficient to adversely impact the performance of sands as sensible thermal energy storage media and particle solar absorber materials. Impurities can cause a decrease in specific heat capacity, decrease in vitrifying temperature, change in grain size distribution, and decrease in spectral absorbance.

The purest quartzose sands (99% quartz) were found to have the highest specific heat capacity and spectral absorbance. Additionally, they do not agglomerate after 1200°C heating. However, they may crack due to quartz-cristobalite phase transformation. Future studies should develop a methodology to delay such transformation. The purest sands occupy the southwestern part of the Nafud desert. This very same area also lies within the highest average solar irradiation zone of the Arabian Peninsula, which will lead to low levelized costs of energy.

CHAPTER 4

CONCLUSIONS

4.1. Quartz crystallinity and provenance of Arabian sands and sandstones

This study surveyed QCI values of Arabian sands of Nafud, Dahna corridor, and the western part of AlRub'AlKhali deserts, and outcrops of Paleozoic and Mesozoic Arabian sandstones. The QCI data confirmed what was petrographically and chronologically established, that early Paleozoic sandstones are the main source for Arabian sands. Moreover, the QCI data provide insight into the provenance of Arabian sandstones and sands. QCI values of sandstones vary temporally and seem to be associated with abundance of siliceous sponges and eolian depositional environments. QCI values of sands vary spatially and are narrower (homogenized) after unidirectional and/or long-distance transportation. QCI values of sands from the western and southwestern Nafud desert indicate possible ongoing chert formation or contribution of Cenozoic cherts derived from the stony desert of southern Jordan and northern Saudi Arabia to the Arabian sands.

Several approaches can be considered to judge if our hypothesis, regarding the role of chert in controlling the QCI values of Arabian sands and sandstones, is robust:

- systematic petrographic examination of Arabian sands and sandstones and quantification of chert present,
- crystallinity measurements and petrographic examination of the chert covering the stony desert of southern Jordan and northern Saudi Arabia, and
- tracking crystallinity throughout Phanerozoic sandstones from different parts of the world.

4.2. Evaluating thermo-physical and thermo-optical properties of Arabian sands for use in high-temperature solar thermal technologies

Forty sand samples covering the Nafud, Dahna, and southwestern AlRub'AlKhali deserts of Arabian Peninsula were analyzed to find the optimum sand for storing thermal energy and absorbing more solar radiation.

The presence of impurities as low as 2% (e.g., feldspar and/ or calcite) in Arabian quartzose sands is sufficient to adversely impact the performance of sands as sensible thermal energy storage media and particle solar absorber materials. Impurities can cause a decrease in specific heat capacity, decrease in vitrifying temperature, change in grain size distribution, and decrease in spectral absorbance.

The purest quartzose sands (99% quartz) were found to have the highest specific heat capacity and spectral absorbance. Additionally, they do not agglomerate after 1200°C heating. The purest sands occupy the southwestern part of the Nafud desert. This

very same area also lies within the highest average solar irradiation zone of the Arabian Peninsula, which will lead to low levelized costs of energy.

Two main points, however, need to be addressed in future studies:

- First, a small portion of quartz transforms to cristobalite after 1200°C heating, which affects the grain size distribution and weakens its mechanical properties.
- Second, although the purest sand sample has the highest spectral absorbance after 1200°C heating, it still has overall low absorbance.

Future studies should focus on enhancing the performance of sands of the southwestern part of the Nafud desert via delaying quartz-cristobalite transformation and enhancing their solar absorbance.

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Publications:

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