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The White Sands of Tutong: A high-quality silica sand deposit from Borneo

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Highlights
- White Sands of Tutong investigation has confirmed the high quality of its silica sand.
- Extent of silica sand deposits was revised based on satellite imagery and spatial analysis.
- Float glass sample was successfully produced using the silica sands.

Abstract: The iconic White Sands of Tutong in Brunei Darussalam, located on the island of Borneo, have long been heralded as a potential source of glass sand. As Brunei Darussalam tries to diversify its economy, these sand deposits have come into focus as a mineral resource for sustainable development. The white glass sand deposits represent an ancient beach dune system in the Tutong district of Brunei Darussalam, where they are most extensively found. While the sand is often devoid of vegetation, it also supports a rare tropical heath forest, covering an area of around 13 km^2 with an average depth of 3 m. Grain size analysis was conducted on selected samples using laser diffraction, and grain size statistical parameters were calculated using Folk and Ward method. The results show that the Tutong White Sand can be characterised as a moderately well sorted fine sand, with symmetrical graphic skewness and mesokurtic graphic kurtosis. The X-Ray Fluorescence (RFA) analysis from the samples revealed that the sand consists of >99.5 wt% SiO_2, 0.05 wt% Fe_2O_3 and between 0.05 and 0.1 wt% TiO_2. A glass melt produced from samples showed that the glass was almost clear with only a slight discolouration. Thus, it can be concluded that the White Sands of Tutong are a high-quality quartz sand deposits and, based on its purity, compare well with other international high quality quartz sands deposit.

Keywords: Brunei, glass melt, high purity quartz, sand mining, silica sand, Southeast Asia

INTRODUCTION

Since ancient times, humans have used sand for shelter and development. Over millions of years, sand has formed through chemical weathering and erosive processes.

Quartz sand is suitable for a wide range of industrial applications (Platias, Vatalis and Charalampides, 2014). In the glass industry, quartz resources are of high importance as source or raw material for the production of container glass, flat glass, mirror glass, crystal, and optical glass. In the plastic industry, glass is used in the form of fiberglass enhanced plastic, making it one of the most important construction materials. For example, glass fibre reinforced plastic is used in rotors of wind turbines. Without glass resources, the energy transition would not be possible. Glass sand must have high and consistent chemical and mineralogical purity. Especially the contents of iron (0.025% Fe_2O_3), titanium (<0.05% TiO_2) and chromium (<1 ppm Cr_2O_3) need be minimal for white glass production, as these elements or chemical compounds can cause discolouration (Elsner, 2016). Silica sand should also have a consistent grain diameter ranging from 0.1 to 0.6 mm (Elsner, 2016). In the electronics industry, silica sand must have a very high quartz content (>99.6% SiO_2), exceptional mineralogical purity, and a well-defined grain size distribution, as it serves as the raw material for silicon wafers, computer chips, and solar panels. Impurities in the silica sand could disrupt the performance of these devices. While some countries meet their demand for silica sand from existing domestic resources, many countries rely on imports (Burkowicz, Galos and Guzik, 2020). Geostatistical evaluations are of high importance (Lindi *et al*., 2024; Wachter *et al*., 2004).

In many regions, sand overexploitation has led to ecosystem destruction, biodiversity loss, and shoreline erosion. In particular, river sand mining, which involves extracting sand from a river’s drainage network and quarry operations near a river, can be very harmful to the river and the environment (Onifade *et al*., 2023; Rentier and Cammeraat, 2022). In the 1950s, sand mining in Brunei (Yong, 2010) caused shoreline erosion at locations such as Berakas Beach and increased flooding susceptibility in Seria (Chua, Chou and Sadorra, 1987; Latif and Yong, 2021). These issues prompted the cessation of shoreline sand mining in the country. However, recently sand extraction near the coast underneath peat deposits for highway construction has caused substantial drainage to the tropical peatland (Suhip *et al*., 2020) and potentially impacted water quality (Gödeke *et al*., 2020).

Currently, sand is being extracted at a rate far greater than its renewal (UNEP, 2019). High-income countries consume, on average, ten times more materials than the poorest countries (Schandl *et al*., 2017). Recent studies estimate a 45% rise in global building sand demand between 2020 and 2060, calling for an urgent need to implement sustainable sand mining strategies (Zhong *et al*., 2022). Sand and gravel usage has increased faster than any other solid material and now represent the largest share of material use, surpassing even fossil fuels and biomass (Krausmann *et al*., 2009; Torres *et al*., 2017).

Southeast Asia has become a global sand mining hotspot (Yuen *et al*., 2024). Brunei Darussalam is trying to diversity its economy away from fossil fuels. Recent studies have identified hi-tech sectors such as semi-conductors, fibre optics, high-tech farming, and advanced manufacturing as areas for economic diversification (Radzuan, Chatwin and Hasan, 2022). Such diversification requires the implementation of robust policies. In this regard, Brunei Darussalam is actively committed to sustainable mining development and is planning to establish new guidelines for green and sustainable operations.

The guiding research question for this study was whether the silica sand in Brunei could be classified as a high purity quartz deposit, considering also that Brunei is looking into developing its mineral resources. To be classified as high-purity silica sand, trace element contamination should be less than 50 $\mu g \cdot g^{-1}$ (Harben, 2002). Due to limited data on Brunei’s silica sand deposits – most of it from 1950’s and 1980’s – this study aims to contribute to the knowledge base of Brunei’s White Sands of Tutong, analysing additional samples with state-of-the-art analytical equipment. The results of this study can serve as a basis for future research.

This project involved investigating the extent of the silica sand deposit using satellite imagery, conducting grainsize analysis, and performing chemical analysis of selected sand samples using X-ray diffractometry (XRD) and X-ray fluorescence (RFA) at Ferro GmbH, Germany. Additionally, glass melts were performed to evaluate the glass colour and sand melting properties.

MATERIALS AND METHODS

The White Sands of Tutong are located near Tutong town in Brunei Darussalam (Fig. 1) around 60 km from the capital, Bandar Seri Begawan. First described by Wilford (1961), they are believed to be remnants of an ancient beach dune system. These sands form a flat terrace deposit stretching up to 11 km in length and around 2 km in width. The deposit is dissected by the Seria–Tutong highway, with the sand forming terraces that rise to about 15 m a.s.l. These terraces lie above flat, recent to Quaternary clay deposits (Sandal (ed.), 1996). Two types of sand are present: an upper layer of fine white sand, varying in thickness between around 0.6 to 4.6 m, and an underlying humus-stained fine sand. The volume of the fine white sand deposit was previously estimated to be around 15 mln m^3 (Sandal (ed.), 1996). However, these white sands also support a rare tropical heath forest ecosystem (Din *et al*., 2015). Thus, any development must carefully consider the biodiversity and ecosystem value provided by the white sand.

Several ancient shallow wells are situated within the deposits, indicating that the groundwater table at the site is shallow (Fig. 1). This is consistent with the generally shallow groundwater levels in Brunei (Azffri *et al*., 2022; Abidin *et al*., 2024). Figure 1 shows the extent of the silica sand deposits. To create this image, the hand-drawn map from Wilford’s 1961 publication was georeferenced onto a topographical base map, since it was not originally available in digital form.

An outline of the silica sand deposit of the White Sands of Tutong was originally presented as a hand-drawn map in Wilford (1961). For this study, the map was georeferenced and overlaid onto a basemap as shown in Figure 1. Since the most recent extent of the silica sand deposit was established decades ago, an attempt was made to redefine the extent of the deposit using modern satellite imagery. For this purpose, spatial analysis was performed using ArcGIS Pro 3.1.0 together with the Spatial Analyst module.

Since vegetation at and around the White Sands of Tutong is unique (Din, Metali and Sukri, 2015), an attempt was made to define the outline of the silica sand deposit using Moderate Resolution Imagery Spectroradiometer (MODIS) satellite imagery. MODIS is an instrument onboard NASA’s Terra and Aqua satellites. For this study, MODIS Normalized Difference Vegetation Index (*NDVI*) products were used.

Vegetation indices from MODIS are generated as averages over 16-day intervals and at multiple spatial resolutions. The *NDVI* is probably the most widely used vegetation index because it is highly correlated with many other biophysical parameters related to vegetation canopy properties, processes, and functions (Curran, 1980). For this study, MODIS *NDVI* imagery at 250 m resolution was used. The selection of available satellite imagery was done through NASA’s AppEEARS package (Hufkens and Campitelli, 2023), before selected satellite imagery (Didan, 2021)

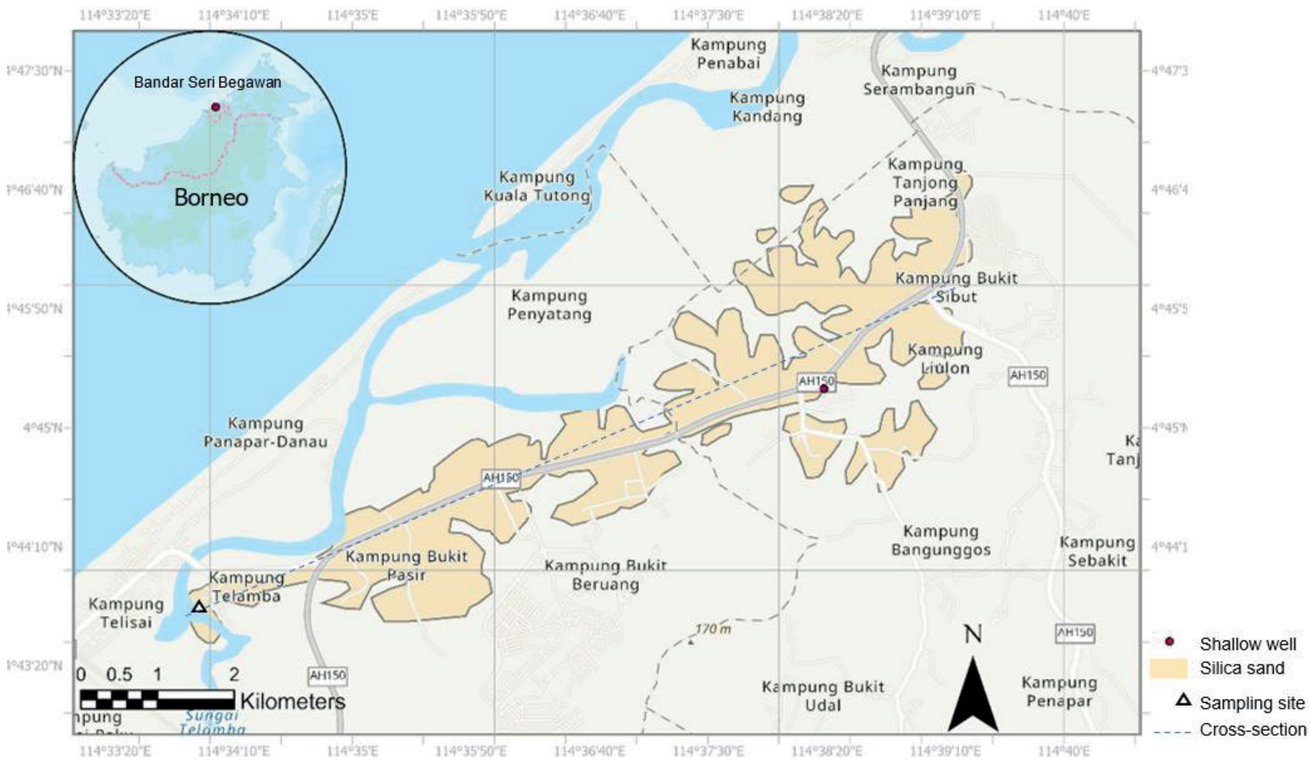

Fig. 1. Approximate extent of the White Sands of Tutong, Brunei Darussalam; source: Wilford (1961), modified

was downloaded. Furthermore, a digital terrain model with a 30-meter resolution was obtained from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data (NASA/METI/AIST/Japan Spacesystems and U.S./Japan ASTER Science Team (2019)) to analyse the elevation profile of the silica sand deposit.

Samples were taken on-site (Fig. 1) at the surface using a small shovel and were transferred into plastic ziplock bags. The sampling area was chosen based on ease of accessibility and the presence of white sands clearly visible at the surface without any vegetation cover. Three samples of around 500 g each were taken, with the total sampling material amounting to around 1.5 kg of sand. Grain size analysis was performed on selected samples using GRADISTAT version 9.1 (Blott and Pye, 2001), and grain size statistical parameters were calculated using Folk and Ward statistics (Folk and Ward, 1957). Before performing grainsize distribution analysis, the raw sample was manually sieved through a range of sieve opening sizes, including 2 mm and 0.85 mm. Organic materials, such as blades of dry grass, were removed from the sieve remains using forceps. To obtain accurate grainsize distribution data, measurements were conducted using a Malvern Panalytical Mastersizer 3000 equipped with a powder dispersion unit. The Mastersizer measures particle size distribution through laser diffraction by analysing the angular variation in the intensity of light scattered as a laser beam passes through a dispersed particulate sample. Images of the grains were taken using a digital microscope, the VHX-6000 (Keyence Corporation, Osaka, Japan).

Accurate grainsize distribution determination can help to predict the melting ability of glass. During glass melting, the dissolution of the sand grains is commonly the slowest process. In general, a narrower size range yields better results for glass melting. If the sand grains are too fine, they can cause bubbles that are difficult to remove or produce dust during the filling and weighing processes. Conversely, if the sand grains are too coarse, more energy is required for melting compared to less coarse grains. Glass manufacturers typically use grains within the range of 0.1–0.6 mm for optimal results (Schweiger *et al.*, 2010).

For the glass melting experiment, two 100 g samples of raw material were molten in an electrically heated elevator furnace (Schröder Ofen, Flörsheim, Germany). The material was heated at 1450°C for 1 h in Al_2O_3 C799 crucibles (Porzellan Fabrik Hermsdorf, Germany). The furnace, equipped with molybdenum disilicide heating elements, allowed for optimum temperature control.

The resulting glass melt was cast on brass plates and then stress-free cooled above the glass transition temperature (T_g 570°C) in an electrically heated chamber furnace (Nabertherm). The samples were subsequently cooled into room temperature. The glass chemistry selected was a model float glass composition (74-16-10 in wt%), representing SiO_2-Na_2O-CaO. For the formulation, the whole SiO_2 content was sourced from the sieved White Sand of Tutong sample, while soda (Na_2CO_3) and calcium carbonate ($CaCO_3$) where added in technical-grade quality, as used in the glass industry.

The XRD analysis was performed using a benchtop XRD (Aeris, Malvern Panalytical) with a copper tube. RFA analysis was undertaken using a Zetium XRF spectrometer (Malvern Panalytical). Thermal analysis of selected samples was performed using a STA 445 F5 Jupiter (Netzsch). For thermal analysis, samples were compared against Al_2O_3 reference material, with thermo-calibration performed using calcium oxalate monohydrate.

A subsequent iron determination of a selected sample was performed using ICP-OES/ AAS (Ferro GmbH, Frankfurt, Germany). In addition, RFA analysis was performed on an unwashed and washed samples to compare analytical results. For the washing process, the sample material was rinsed with distilled water, dried in a drying chamber, and analysed in its dry state.

RESULTS AND DISCUSSION

SPATIAL ANALYSIS

The spatial analysis using an *NDVI* map indicated that it can be a useful tool for refining the areal extent of the White Sands of Tutong (Fig. 2). Very low *NDVI* values (≤0.1) usually correspond to barren areas of rock or sand, moderate values (0.2–0.3) represent shrub and grassland, while high values (0.6–0.8) indicate temperate and tropical rainforests (Weier and Herring, 2000). For this study, an *NDVI* scene representing a 16-day average from 1st December 2023 to 31st December 2023, was selected. Using the existing satellite imagery and CNES/Airbus imagery available in Google Earth, a refined outline of the White Sands of Tutong was digitised (Fig. 3). During this process, an additional area outside the previously published extent of the deposit was identified near Kampung Penyatang (Fig. 2).

It also became obvious that infrastructure development has already occurred in some parts within the boundary of the silica sand deposits. Based on the refined outline, the silica sands now cover an area of approximately 13.4 km^2. This area is higher than the previous extent reported by Sandal (ed.) (1996) and Wilford (1961). The elevation profile of the deposit, generated from exploratory 3D analysis in ArcGIS, shows that the area, spanning from Southwest to Northeast, is mostly associated with flat low-lying terrain. Occasional steeper terrain of higher elevation, such as the feature observed at around 8,000 m (Fig. 3), may represent ancient beach dunes.

The analysis indicated that the areas with lower *NDVI* (~0.5) tend to be associated with locations where silica sand is present (Fig. 3). The area marked by green colours in the southwest of Figure 2 (Bukit Beruang) contains a settlement. Zonal statistics using Spatial Analyst in ArcGIS confirmed that the area associated with silica sands has a lower average *NDVI* value (0.59) compared to the surrounding area (0.77).

GRAIN SIZE ANALYSIS

Before XRD, RFA analysis, and the glass melt of the silica sand, grain size analysis was performed. Grain size as well as cumulative distribution are presented in Figures 4 and 5.

The grainsize statistical parameters of the Folk and Ward method are presented in Table 1.

It becomes obvious that the White Sands of Tutong can be described as a moderately well-sorted fine sand, with a symmetrical skewness and a normal kurtosis. The results from the microscopical analysis confirmed the well-sorted nature of the sand and revealed that the individual quartz grains are well-rounded (Fig. 6).

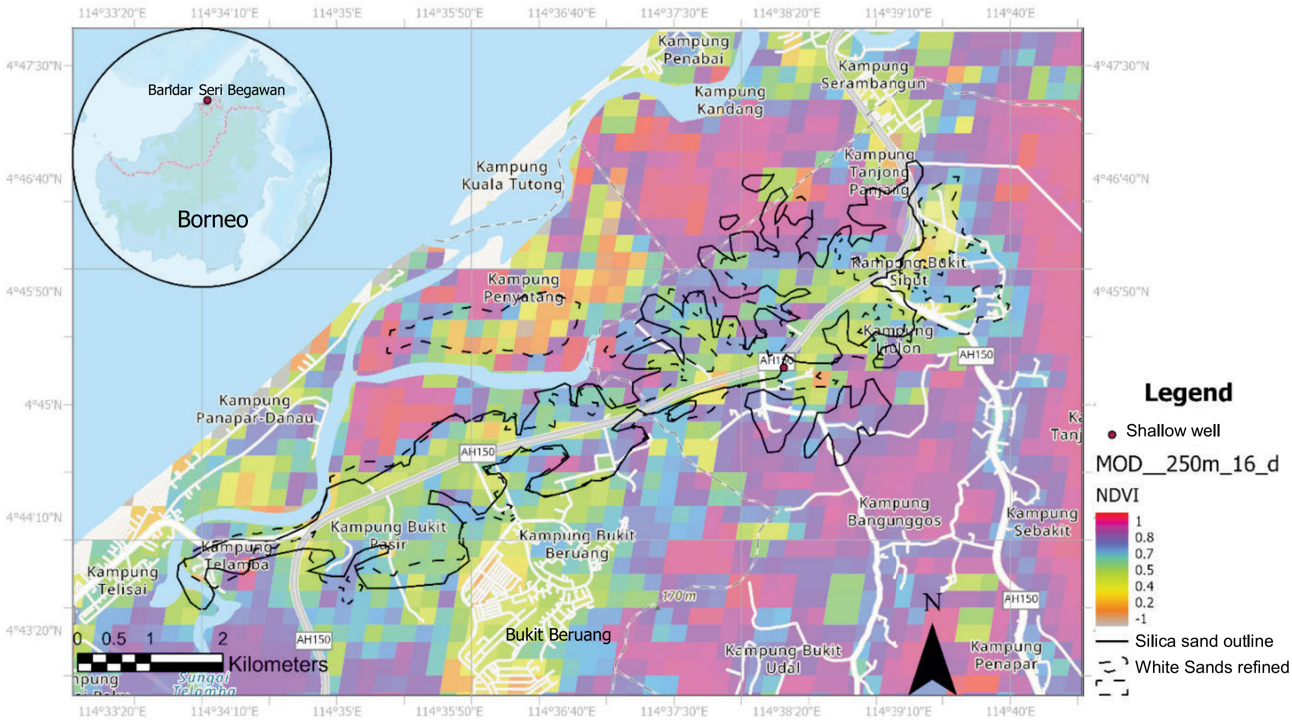

Fig. 2. Normalized Difference Vegetation Index (*NDVI*) in study area (December 2023) with silica sand outline (solid line) after Wilford (1961) and refined outline (this study)

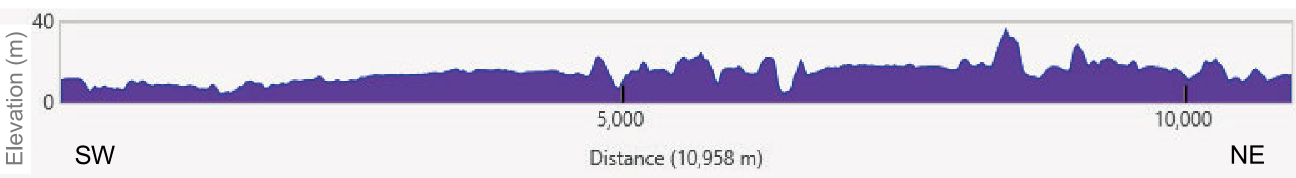

Fig. 3. Southwest–Northeast elevation profile through the silica sand deposit; source: own study

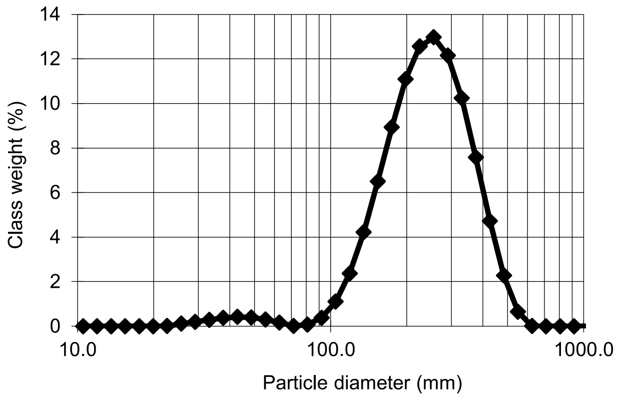

Fig. 4. Grain size distribution of the White Sands of Tutong; source: own study

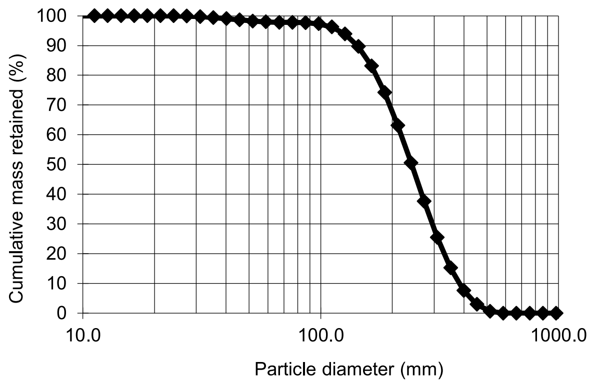

Fig. 5. Cumulative distribution of the White Sands of Tutong; source: own study

Table 1. Grainsize statistical parameters calculated using Folk and Ward method

Parameter	Geometric (mm)	Logarithmic (f)	Description
Mean ($\bar{x}$)	238.1	2.070	fine sand
Sorting (s)	1.474	0.559	moderately well sorted
Skewness (*Sk*)	–0.075	0.075	symmetrical
Kurtosis (*K*)	0.997	0.997	mesokurtic

Source: own study.

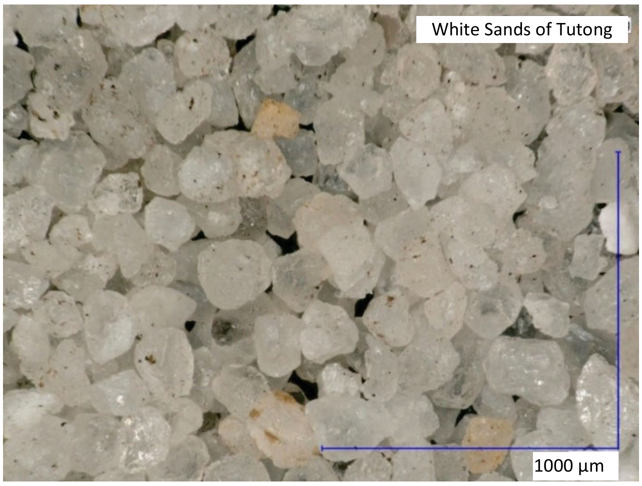

Fig. 6. White Sands of Tutong under the microscope; source: own study

X-RAY DIFFRACTOMETRY, X-RAY FLUORESCENCE AND THERMAL ANALYSIS

According to the XRD results, the samples contained 100% quartz with two small reflexes at $d = 2.52e^{-10}$ m and $1.881e^{-10}$ m which could not be clearly identified. The results from the RFA analysis of 2 samples confirmed that the sand consists of almost 100% quartz (Tab. 2).

Table 2. X-ray fluorescence analysis of the White Sands of Tutong

Component	Sample 1	Sample 2
	weight %	
SiO_2	99.83	99.5
TiO_2	0.07	0.13
Fe_2O_3	0.05	0.05
ZrO_2	0.05	–
MgO	–	0.04
K_2O	–	0.04

Source: own study.

The iron contents reported in this study represent iron content analysed on unwashed samples. Generally, the most critical impurity for optical glass is iron, whereas in the float glass industry iron oxide is used as raw material to make sure that the glass colour maintains always the same greenish tint. Thus, for this study an attempt was made to reduce iron content. After washing the samples and decanting iron content, a selected sample was measured using ICP-OES/AAS. This process significantly reduced the iron content to 0.0079 wt%. The measured iron weight % compares well with iron concentrations reported in a previous study (Wilford, 1961) which reported values between 0.004 and 0.05 wt%. An interesting observation was made while working with the samples. A strong magnet held close to the sand samples caused particles being stack to the magnet, indicating magnetism of certain mineral phases. Since no magnetite was confirmed in the RFA analysis, the experiment with the magnet could indicate that impurities that have entered the crystal lattice of ZrO_2 and TiO_2 have caused the observed magnetism. Research has shown that an induced magnetism in ZrO_2 and TiO_2 is even possible without magnetic impurities (Máca *et al.*, 2008).

Overall, the high SiO_2 content of 99.5 wt% can compare well with other silica sand deposits and is higher than, for example, the Zemmouri sands in Algeria (Boussaa Anas, 2020) and silica sands from the Lemi region in Ethiopia (Wuletaw and Mihret, 2024) with SiO_2 contents of 99.3 wt% and 96.13 wt% respectively. Götze and Lewis (1994) reported SiO_2 contents greater 99 wt% for high purity quartz sands in Germany.

A thermal analysis of the samples was also performed (Fig. 7). The thermal analysis showed the presence of quartz inversion in which quartz changes from an alpha crystal structure to a beta crystal structure. For the White Sands of Tutong, the quartz inversion was observed at a temperature of 566.2°C. It becomes obvious that only a minor mass loss can be observed during thermal analysis.

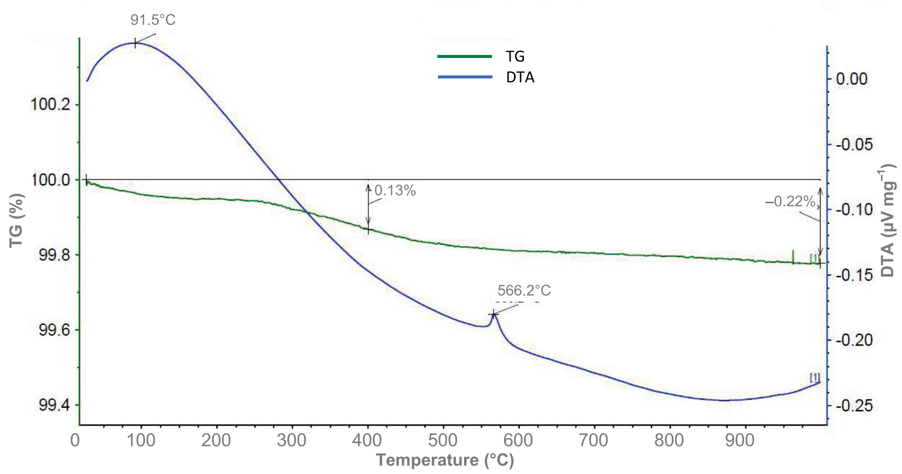

Fig. 7. Thermal analysis of the White Sands of Tutong, Thermogravity (TG) and Differential Thermal Analysis (DTA) versus Temperature; source: own study

GLASS MELT

The silica sand was successfully melted into a float glass (Fig. 8). A total of two melts were prepared which both provided identical results.

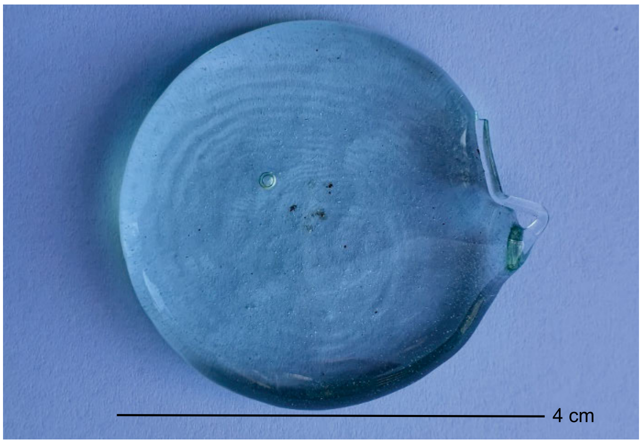

Fig. 8. Float glass produced from the White Sands of Tutong; source: own study

The glass samples still show bubbles, due to the lack of refinement in the melt. However, the main purpose of the trial was to check the glass colour and melting ability of this special sand. The glass colour was slightly greenish, indicating the presence of impurities such as iron, which had already been observed during the RFA analysis.

Since the White Sands of Tutong qualify as a high-purity quartz deposit (Pan *et al.*, 2022), the sands are well-suited to produce glass. According to the analysis, the silica sands from Brunei are suitable for producing float glass and even certain optical glasses, giving that steps are taken to reduce iron impurities in the sand (Tab. 3). This result contrasts with previous studies (Sandal (ed.), 1996), which concluded that silica sands could not be used for optical glass without providing clear evidence. The experiment showed that simple washing with distilled water, followed by decantation, significantly reduced iron concentrations.

By selecting or blending sand of possibly varying types of iron concentration, it should be possible to obtain properly graded sand suitable for manufacturing different types of glass. Future studies could investigate methods to further reduce iron impurities from the White Sands of Tutong, for which a range of options are available (Liu *et al.*, 2023). In addition, future studies are planned to produce optical glass and measure the transmission spectrum.

Table 3. Glass grades after British Standards

Grade	Product	SiO_2	Fe_2O_3	Al_2O_3	Cr_2O_3
		%			
A	optical glass	99.7	0.013	0.2	0.00015
B	table glass	99.6	0.01	0.2	0.0002
C	borosilicate glass	99.6	0.01	0.2	0.0002
D	colourless container	99.8	0.03	0.1	0.0005
E	flat glass	99.0	0.10	0.5	–
F	coloured container	97.0	0.25	0.1	–
G	insulating fibres	94.5	0.30	3.0	–

Source: BS2975:1988.

For the future development of these resources, it is important that the impact of resource extraction on human health and the ecosystem is considered (Bendixen *et al.*, 2021).

CONCLUSIONS

The study has shown that the White Sands of Tutong are a special sand deposit and indeed qualify as a high-purity silica sand deposit. Impurities were found to be less than 0.5 wt%, making the sand suitable for producing optical glass. The silica content varied between 99.5 and 99.8 wt%. After sample washing, the iron content was successfully reduced to 0.008 wt%. A glass melt was conducted successfully, resulting in the production of a sample float glass.

It is recommended to analyse additional samples, investigate the subsurface geology as well as ways to reduce the iron content of the silica sand further. Any development of silica sand resources should carefully balance the ecological value of the area with its economic potential. In any case, the silica sand in Brunei should be protected from impacts of future infrastructure development.

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CONFLICT OF INTEREST

All authors declare that they have no conflict of interest.

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