Spectral analysis of rock samples from East Suriname using the Spectral Evolution PSR+

- Building a spectral library of rock samples -

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24 November 2017

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ABSTRACT

Spectral signatures of minerals and rocks can be used to determine mineral compositions for specific areas and can function as a useful aid for remote sensing image interpretation. In this study, the aim is to build a spectral library of common rocks and minerals for the region of East Suriname, particularly the Greenstone belt, and to test the performance of the recently purchased spectroradiometer PSR+. The samples that were used for building the spectral library were selected from multiple collections from the geological department of Naturalis, Leiden. The samples were selected based on the overlap of their location of origin with the study area and on their relation with mining sources bauxite and gold. For the evaluation of the PSR+ spectroradiometer, samples from the Peyne area, southern France, were used. Samples from the Peyne area consisted of seven different rock samples, from nine different locations. Most minerals and rocks of the Suriname collection showed impurities by iron or iron-bearing minerals due to weathering and other causes. The spectral signatures of the metasomatic rock sample showed the significant presence of the mineral muscovite and it appeared that the hornfels sample contained the same green epidote mineral as the greenstone sample.

This spectral library was created as an aid for remote sensing image interpretation for images of Suriname. However, geological image interpretation in Suriname would not be easy, due to the vast amount of vegetation and deep weathering of exposed rock and the low availability of cloud-free images.

Evaluation of the measurements of the PSR+3500 show variations (or noise) in the optical range of the spectrum measured by the first detector. The rippling effect (peaks/valleys) that was created in this range 400-1100nm, influences the spectral reflectance measurements of the rock samples. Additionally, peaks were visible in the spectral signatures at the wavelength range of the transition of the detectors. To improve the spectral reflectance curves, which is mostly needed for the optical part of the spectrum, the noise of the detectors and the transition in detectors should be as small as possible.
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ACKNOWLEDGEMENT

This research would not have been possible without the samples from Suriname, which were obtained thanks to the geological collections of Natuur Historisch Museum Naturalis, Leiden and the help of Arike Gill, who sorted out the samples that we requested. I would also like to thank Ing. Marcel van Maarseveen, for his help regarding the PSR+ Spectroradiometer and the DARWin software. I want to thank drs. Maarten Zeylmans van Emmichoven for being willing to act as my second supervisor.
1 INTRODUCTION

1.1 Spectral signatures

Spectral signatures of minerals and rocks can be used to determine mineral compositions for specific areas and can be an useful aid for remote sensing image interpretation. In this study, a spectral library of the Greenstone belt region in East Suriname is build and the performance of the recently purchased PSR+ spectroradiometer of the University of Utrecht is tested. For the evaluation of the PSR+ spectroradiometer, samples from the Peyne area, southern France, were used.

Each object contains a reflectance spectrum. When lights incidents on this object, it interacts with it, where parts of the light spectrum are reflected and other parts absorbed (van der Meer & de Jong, 2006). Reflectance is therefore defined as the ratio of intensity of light reflected from a sample, to the intensity of light incident upon it (van der Meer & de Jong, 2006). For many years, information about the earth surface has been gained from reflectance spectra, as it is a rapid and non-destructive method to study the mineralogy of rocks (van der Meer & de Jong, 2006). Apart from the wavelength bands in the optical part of the wavelength spectrum (blue;400-500nm, green;500-600 nm, red;600-700 nm), Near infrared (NIR; 700-1500 nm) and short wave infrared (1500-3000 nm) are of importance when analysing spectra of minerals (van der Meer & de Jong, 2006).

1.1.1 Absorption features

Absorption features are determined by electronic transition and charge transfer processes, associated with transition metal ions, but also by vibrational processes of H$_2$O and OH$^-$ molecules (van der Meer & de Jong, 2006). Properties of these absorption features include the position, shape, depth, width and asymmetry and are the result of the specific crystal structure in which the absorbing element resides and by the chemical structure of the mineral (van der Meer & de Jong, 2006). Absorption features are therefore directly related to the mineral composition of a rock fragment.

The most common features in the mineral spectra are caused by the electronic process called the crystal field effect (van der Meer & de Jong, 2006). This occurs due to unfilled electron shells of transition metals. It appears that in an isolated ion, these transition metals have identical energies, but that these energy levels are split when the atom is situated in a crystal field (van der Meer & de
When different energy levels are created, it becomes possible for an electron to move from a lower to higher energy level. To do this, it needs the energy of a photon that equals the energy of the difference between these energy levels. Absorption bands can also be caused by charge transfer, for example when Fe\(^{2+}\) transforms into Fe\(^{3+}\). The resulting absorption bands from charge transfers are characteristic to its mineralogy (van der Meer & de Jong, 2006).

Absorption features can also be created by vibrations of the strings that bonds atoms to form molecules (van der Meer & de Jong, 2006). Vibrations are generated when energy is absorbed by the molecule in its ground state. The frequency of the vibration is dependent on the strength of the strings. Because vibrations cost little energy, absorption features occur at high wavelengths, in the infrared region (800-2500 nm), and are deep and narrow (van der Meer & de Jong, 2006). In minerals, absorption features due to vibrational processes are mainly caused by water and hydroxyl molecules, but also by carbonate and sulphate.

Additionally, absorption band depth is influenced by the grain size of a particle. It decides the amount of light that is absorbed or scattered (van der Meer & de Jong, 2006). In general, smaller grains cause higher albedos, whereas in larger grains the absorption is larger, as the internal path for photon absorption is longer (van der Meer & de Jong, 2006).

### 1.2 Spectral evolution PSR+

The spectroradiometer PSR+3500, recently purchased by the University of Utrecht, has a spectral range of 350 to 2500 nm and a high spectral resolution, varying from 3nm to 8nm (Spectral Evolution, 2012). The spectral range is measured with three detectors, which are presented together with the spectral resolutions at Full Width Half Maximum in table 1.1.

**Table 1.1 Detectors and spectral resolutions (Full Width at Half Maximum), of the spectroradiometer PSR+.
**

<table>
<thead>
<tr>
<th>Detector</th>
<th>Type</th>
<th>Range (nm)</th>
<th>Spectral resolution (FWHM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>512 element Si photodiode array</td>
<td>350-1000</td>
<td>3 nm at 700 nm</td>
</tr>
<tr>
<td>2</td>
<td>256 element extended InGaAs photodiode array</td>
<td>970-1910</td>
<td>8 nm at 1500 nm</td>
</tr>
<tr>
<td>3</td>
<td>256 element extended InGaAs photodiode array</td>
<td>1900-2550</td>
<td>6 nm at 2100 nm</td>
</tr>
</tbody>
</table>
The PSR+3500 is provided with a contact leaf clip and a contact probe, which allows one to measure the spectral radiance of rock fragments and vegetation leaves. The contact probe contains its own light source and has a scan button. The scan can therefore be made while holding the contact probe, but it is also possible to take the target scan from the computer using the DARWin software. The instrument is further provided with lenses of varying angles (1-5°, 8° & 10°), so that a wide range of objects can be measured.

For further information about the instrument, the site of Spectral Evolution is recommended; [http://www.spectralevolution.com/spectroradiometer_PSR_plus.html](http://www.spectralevolution.com/spectroradiometer_PSR_plus.html).

### 1.3 Study areas

#### 1.3.1 Eastern Suriname

The mining sector in Suriname is the most important contribution to the country's economy, with its main focus on the metals gold, which accounted around 60% of the economic export in 2010, and bauxite, which contributed around a quarter to the total export (Briegel, 2012). Suriname belongs to one of the top ten bauxite sources in the world (Mobbs, 2016).

Some large bauxite and gold mines are found in eastern Suriname, where the primary bauxite mines are located in the North in Lelydorp and Coermotibo (Haalboom, 2012). However, as these mines are nearing depletion, new bauxite mines, such as the Kaaimanggrassie and Klaverblad mines are opened (Haalboom, 2012).

Large scale gold exploitation takes place in east Suriname, around the Brokopondo lake (figure 1.1). Some examples of gold mines are the Rosebel gold mine, owned by IAMGOLD and the Merian gold concessions of the company Surgold.
The greenstone belt

The large scale gold exploitations take place in the Suriname Greenstone belt, which is part of the Marowijne group, one of three distinguished metamorphic belts of the Suriname basement (Kroonenberg & Melitz, 1983) (figure 1.1). The geological composition of the Greenstone belt consists of three Formations. The Paramaka Formation contains low-grade metamorphic and intermediate volcanics and sediments. The Armina Formation consists of phyllites, schists and metamorphosed greywackes (metagreywackes). Figure 1.2 shows the metamorphoses of the sedimentary rock shale into intermediate-grade phyllite and schist and high-grade gneiss. Important minerals of these intermediate-grade and high-grade rocks are chlorite, muscovite and biotite (figure 1.2). The Rosebel Formation is characterized by coarse volcanioclastic metasandstones and metaconglomerates. These sedimentary rocks are characterized by clasts, for sandstone consisting of quartz and feldspar, which
are cemented by the minerals calcite, silica or iron-oxides (O'Connor, 2005). The three metamorphic belts in Suriname are separated by a large granitoid complex. Granitoids are quartz-bearing rocks and are in eastern Suriname associated with gneisses that have been partially melted and subsequently recrystallized into an igneous rock (migmatic) (De Vletter et al., 1998; Kroonenberg & Melitz, 1983).

All rocks were formed in the Precambrian, roughly 2000-1870 million years ago, during the Trans-Amazonian Orogeny (Kroonenberg & Melitz, 1983). Un-metamorphosed sandstones and conglomerates, from the Roraima Formation (± 1655 Ma) overlay the Trans-Amazonian rocks. Additionally, the basement is intersected by dolerite dikes, which could date back to either the Precambrian (± 1659 Ma) or the PermoTriassic (± 230 Ma) (De Vletter et al., 1998).

1.3.2 La Peyne, France

The Peyne river is situated in southern France and is one of the larger tributaries of the Hérault river (figure 1.3) (De Jong et al., 2003, Backwell & Bijkerk, 2010). The entire catchment covers an area of 120 km² (Backwell & Bijkerk, 2010).

The North and South of the catchment vary in geology. The North of the catchment is characterized by schist, basalt, calcareous sandstone and bauxite in the Northwest. The emergence of bauxite dates
back to the middle cretaceous, 100 ma, due to the extension of continental plates by horsts and anticlines (Backwell and Bijkerk, 2010).

The south of the catchment underwent two periods of sea transgressions, first during the Tertiary (65 Ma-40 Ma) and again during the Miocene (23 Ma) (Backwell & Bijkerk, 2010). After the sea retreated, marine deposits of sandy and silty nature remained.

Figure 1.3 Location of la Peyne catchment in France. Source: De Jong et al., 2003

1.4 Research objectives

The objective of this study can be divided into two parts, where the first aim is to build a spectral library of common rocks and minerals for the region of East Suriname, particularly the Greenstone belt, and the second aim is to test the performance of the recently purchased spectroradiometer PSR+. Two objectives are defined:

1. Creating a spectral library from a rock collection of Naturalis, for minerals that are of importance to the Greenstone Belt (Marowijne group) and analyse the spectral differences between these minerals.

2. Testing the spectrometer PSR+ of the University of Utrecht with different rock fragments from La Peyne, Hérault Province in southern France.
2 METHODS

2.1 Rock and mineral samples

Two collections were created with the PSR+ spectroradiometer. The rock sample collection of eastern Suriname was measured and compared to mineral spectra from the USGS spectral library (SPeclib V6) which was available in ENVI 5.2. For most rock sample analysis, the rock and mineral description from several sites that provides mineral rock information have been used: Rocks & minerals, by O’Connor (2005); minerals.net, by Friedman (1997-2017); Mindat (n.d.).

Samples from the Peyne area consisted of seven different rock samples, from nine different locations. This collection was not analysed in detail, but mainly used to test the performance of the PSR+3500 instrument and the DARWin application software.

2.1.1 Suriname samples

The samples that were used for building the spectral library were selected from multiple collections from the geological department of Naturalis, Leiden. The samples were selected based on the overlap of the location of origin with the study area and on their relation with mining sources bauxite and gold. Some samples were not found in Northeast Suriname, but these samples were chosen because they are very common rocks in Suriname or because of their interesting spectral signatures.

Most samples were used from the collection of J.W. Brinck (1950-1955), during his expedition about gold deposits. These samples were taken from the region around the Brokopondo lake. The presence of gold is dependent on the Formation in which it has been mineralized. Brinck (1956) found gold attached to mostly quartz, blue quartz and pyrite, and stated that ferberite is a valuable indication of gold.

Bauxite, hematite and kaolinite samples were used from a collection of the TU Hogeschool Delft (collection date unknown). These samples originated from the bauxite mines Rorac and Para, situated above the study area, Northeast Suriname. Other samples were used from collections of R.H. Verschure (n.d.), F. Voltz (± 1931), J.F. van Kersen (1955) and two gneiss samples from the Bakuys expedition (n.d.), from West Suriname. The full list of the collected samples, description and specific
location can be found as an Appendix of the Suriname collection in the form of an excel sheet. This appendix also contains pictures of the samples along with the measured spectra. Exact locations were found using Google Earth. The samples are from old expeditions (50-100 years ago), therefore, specific locations were often difficult to find. For a few samples the locations could not be traced back.

2.1.2 Peyne samples

The collection from the Peyne study area consists of the samples presented in table 2.1. The rock samples were collected in the field in April and May 2017 and their spectra was measured using the PSR+.

Table 2.1 La Peyne rock sample collection with approximate location

<table>
<thead>
<tr>
<th>Sample</th>
<th>location</th>
<th>Approximate coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bauxite</td>
<td>S Carlencas</td>
<td>43°37'32.90&quot;N 3°13'23.42&quot;E</td>
</tr>
<tr>
<td>Dolomite</td>
<td>SW Carlencas</td>
<td>43°37'32.68&quot;N 3°13'21.78&quot;E</td>
</tr>
<tr>
<td>Basalt</td>
<td>NE Pezenes les Mines</td>
<td>43°35'19.10&quot;N 3°15'6.47&quot;E</td>
</tr>
<tr>
<td>Flysch</td>
<td>N lac de Vailhan</td>
<td>43°33'20.64&quot;N 3°18'3.30&quot;E</td>
</tr>
<tr>
<td>Limestone</td>
<td>Vailhan-Neffies</td>
<td>43°33'2.34&quot;N 3°18'16.51&quot;E</td>
</tr>
<tr>
<td>Limestone II</td>
<td>S Le Mas Roland</td>
<td>43°33'37.23&quot;N 3°16'34.43&quot;E</td>
</tr>
<tr>
<td>Tuff</td>
<td>Montesquies</td>
<td>43°34'0.51&quot;N 3°16'24.43&quot;E</td>
</tr>
<tr>
<td>Red sediments</td>
<td>N lac du salagou</td>
<td>43°34'6.94&quot;N 3°16'30.61&quot;E</td>
</tr>
<tr>
<td>Limestone III</td>
<td>S Cirque de Navacalles</td>
<td>43°53'13.56&quot;N 3°30'36.02&quot;E</td>
</tr>
</tbody>
</table>
2.2 DARWin SP application software

2.2.1 Instrument control panel

The PSR+ instrument can be connected to the PC with an USB cable, via a Bluetooth adapter. When the instrument is connected, the DARWin software can be used. Each time the software is opened, the instrument has to be configured. This is done with the “Inst. Control” button on the toolbar. First, the right COM port has to be selected from the pull-down menu and then the PC should be connected to the instrument. A successful connection should display the text “COM# opened” right next to the connect button. In the upper right corner, the active instrument will be displayed (PSR+3500_serialnumber) and the instruments parameters will be loaded. After the connection is made, the type of measurement can be selected. Measurement options include: Direct Energy, which can be used when radiance and irradiance are of interest, and reflectance or absorbance, both for ratio measurements.

It should be noted that when the option Direct Energy is chosen, the reflectance values will not be saved. So when re-opening the saved file of the scan, only the reference and target scan can be displayed. In this study, the performance of the instrument is analysed, therefore the option Direct energy is chosen to keep the most spectral information; both the reference and reflectance values. But as the end purpose of the results of this study is to apply the measured reflectance curves in remote sensing software, such as ENVI or ERDAS, the reflectance curves of each scan are computed with excel and saved as a .txt file.

Finally, there is an “initialization” option of the instrument in the instrument control panel window. This can be done either once, the first time the instrument is connected, or each time the instrument is connected with the “Connect” button. The latter is advisable when multiple instruments can be selected for one PC, but is otherwise unnecessary.
2.2.2 Main menu

In the main menu a new plot can be created, where the user can choose a single measurement plot or a multiple measurement plot. The latter can be useful as different spectra can be directly compared. This option was often chosen to compare the differences in spectra for the same rock sample. The plot is shown below the main menu, where the wavelength (x-axis) is displayed in nm (figure 2.1). Next to the plot window, on the right, instrument data and measured data is displayed after the target scan is made. This data is directly stored under the name that was assigned in the instrument control panel, if the “save scan data to file” option in the main menu is on. Other important functions displayed in the main menu, are the reference and target scan, to measure the spectra. The continuous scan option allows the user to measure the target with the contact probe, which is useful for rocks with irregular surfaces. The “next scan” option, displayed in the main window, shows the name of the next scan that is made, where it automatically summarizes the scan by number. Some tools are included, such as a spectral library from the USGS (SpecLib V6) and some spectral vegetation indices, such as the Normalized Vegetation Index (NDVI).

The “Avg scan time” function can be used to alter the number of scans, over which the average is taken. A value between 1 and 100 can be chosen, where an increasing number of averages causes a smoothening of noisy signals. However, with a higher average more time is needed to complete the scan. In this study an Avg of 50 is used for measurements. The effect of this option to the results is analysed, where a granite sample is measured with the Avg. time= 100 as a reference scan. Then multiple measurements are taken with a Avg. time steps of 10, and the spectra are compared to the reference scan of 100.
2.2.3 The scan

The first step of obtaining a reflectance spectrum is the measurement of a reference spectrum. This reference spectrum is stored and only replaced when a new reference scan is taken. For the reference scan, a white tile is required, to simulate a spectrum with full reflectance. Because the instrument has to warm up in the beginning, it is wise to check the accuracy of the reference scan a couple times, until the result is satisfactory. It can best be used after 10-15 minutes. The accuracy of the reference curve can be tested by first taking a reference scan, followed by a target scan of the reference tile. For an optimal situation, the reflectance curve will show a horizontal line at 100%.

The next step is the target scan, the scan of the object to be studied. For this study, the contact probe proved to show the best results. Furthermore, the samples were not that large and contained some flat surfaces, hence the contact probe could be easily applied.

Additionally, a dark spectrum is needed to remove background noise from the measurements (Lawrence, 2015). This noise is created by energy from thermal fluctuations that generate electrons.
in the same way photons do (StellarNet, 2017). This noise is always present, even when light is not, and increases with higher temperatures (StellarNet, 2017). The Dark Mode is done internally, where a shutter automatically closes for a moment, right before the measurement is taken (Lawrence, 2015). The dark data is recorded and used to refine the detector data from the spectral instrument.

In general, Automatic Dark Mode is more sufficient, as the user does not have to take frequent Dark Mode measurements (Lawrence, 2015). A scaled Dark Mode becomes useful when timing becomes of interest (high speed, external triggering, pulsed operation).

During the scan process, 3-5 scans were taken of each sample whenever possible. For a few samples, only a single scan could be taken, due to their size or irregular surface. Every time a new sample was measured, the reference scan was renewed. Before the first sample was measured and the instrument had to warm up, a few reference scans were taken, to assure the accuracy of the instrument was satisfactory, which was mostly after 10-15 minutes. After this, the instrument remained on during the whole day of measuring. The light of the contact probe was sometimes turned off for a few minutes when it was not in use, as the contact probe would heat up to high temperatures.
3 RESULTS

3.1 Spectral analysis of the Suriname Collection

3.1.1 Minerals

The spectral curves of **hematite** (TU Delft, 1918, figure 3.1-A) and **gibbsite** (van Kersen, 1955, figure 3.1-B) from the Suriname collection are plotted in graph 3.1, together with the hematite and gibbsite curves of the USGS spectral library. Both hematite and gibbsite contain additional features compared to spectral curves of the USGS. For gibbsite this is at 810-1245 nm and for hematite, additional features occur between 743-1370 nm and 1880-2132 nm. When the measured gibbsite and hematite are plotted together with the measured ferrite from the Waniwiro hills (van Kersen 1955), it becomes clear that both samples contain impurities by iron.

The samples **pyrolusite**, **pyrite** and **ferberite**, from the collection of Brinck (1956), are plotted in the same graph. Pictures of all three samples can be seen in figure 3.2. Pyrolusite is the most common manganese mineral and ferberite is the iron-rich endmember of the mineral series wolframite, which also contains variable amounts of manganese (Friedman, 1997-2017). Pyrite is a mineral composed of iron sulfide. Graph 3.2 shows the pyrolusite sample is also rich in iron, presenting a very similar curve to that of ferrite. The USGS spectral library also contains a spectral signature of pyrolusite, which does not show any absorption features. The double absorption features of the ferberite sample between 1370-1445 nm, 1880-2060 and 2128-2231 nm, coincide with the spectral curve of ferrite, as do the absorption features between 1750-1230 nm, 1370-1445, 1880-2060 nm 2160-2236 nm from the pyrite curve, confirming the presence of iron in both ferberite and pyrite samples.
Graph 3.1 A. Spectral curves of gibbsite and hematite, displayed in ENVI 5.2 and B. spectral curves of hematite and gibbsite compared to ferrite.
Graph 3.2 Spectral signatures of pyrolusite, ferberite, pyrite and ferrite, displayed in ENVI 5.2

Figure 3.2 Samples of A. pyrite from Haute Rufin, B. pyrolusite from Haute Rufin and C. ferberite from Pakira Hill, de Jong zuid. All locations are in East Suriname.
The spectral library of Suriname contains three samples of kaolinite. One sample originates from the Nickerie river in West Suriname (figure 3.3-A), the second sample is found at the Corantijn river that borders Suriname from Guyana in the West (figure 3.3-B) and the third sample contains large amounts of iron (ferruginous kaolinite, figure 3.3-C) and is from an unknown location. Graph 3.3 shows their measured spectral signatures. The samples can be distinguished by the absorption feature of ferruginous kaolin at 760-980 nm, caused by the presence of iron. Most significant features for both samples occur between 1367-1430 nm, 1860-2030 nm and 2130-2230 nm, and are characterized by double absorption features. These features can also be seen in the spectral signature of kaolinite from the USGS spectral library. A small absorption feature for the kaolinite found near the Corantijn and Nickerie river can be seen at 980 nm, but this could also be an error created by the instrument.

A beryl-pegmatite sample from the Brinck collection (1956) that was found at the Jorkakreek, a creek of the Surinam river (figure 3.4). Features from the beryl-pegmatite sample are very similar to the beryl spectra from the USGS, only shows a lower brightness. The Beryl measurements showed a peak of almost 25% increase within a 30nm range (graph 3.4), and can be assigned to an error by the instrument. This peak has been corrected with linear interpolation. This is also done for pyrite_1 and this can also be done for other spectra in case of significant disturbances. However, for most spectra, error-peaks are very small.

Four quartz samples were used from the Suriname River, two originate from de Jong Noord (figure 3.5-A), one from de Jong Zuid (figure 3.5-B) and the fourth is from Headly Reef (3.5-C). Quartz itself is featureless, however, the spectra of the samples in graph 3.5 show absorption features at 770-1350 nm, 1370-1550 nm, 1870-2133 nm and 2140-2235. All these absorption features can be assigned to impurities by presence of iron or iron bearing minerals, such as goethite (graph 3.5).
Graph 3.3 Kaolinite samples compared to the USGS spectral curve of kaolinite, displayed in ENVI 5.2.

Figure 3.3 A. Nickerie and B. Corantijn and ferruginous kaolinite sample, C, from an unknown location.
Figure 3.4 Beryl-pegmatite sample from Jorkakreek, Marowijne River.

Graph 3.4 Beryl corrected with linear interpolation. Green spectrum is from USGS spectral library. Red and purple are measured and corrected measurement of beryl respectively.
Graph 3.5 Spectral signatures of quartz samples compared to ferrite, displayed in ENVI 5.2.

Figure 3.5-A Quartz sample from de Jong Noord, NE Suriname

Figure 3.5-B Quartz sample from de Jong Zuid, NE Suriname

Figure 3.5-C Quartz sample from Headly Reef, Suriname River.
A few quartz samples that are included contain beforehand known impurities. A quartz-diorite sample, quartz-gold sample and quartz-hematite sample are analysed. The samples can be seen in figure 3.6 and their spectral curves are shown in graph 3.6. For the quartz-gold and quartz-hematite samples the features can be attributed to the presence of iron. The mineral hematite does not contain significant features and the spectral curve of gold is not known. The quartz-diorite sample contains
some features at 1408 nm and 2199 nm that coincided with spectral features from the feldspar oligoclase, which is a mineral that can occur in diorite.

Additionally, a vulcanite sample from Berg en Dal has been measured, which is a mineral consisting of copper and telluride. This mineral is not present in the USGS library and is therefore not analysed.

### 3.1.2 Sedimentary rocks

Three bauxite samples were used from Northeast Suriname, two from the bauxite mine in Rorac and one from Para. Bauxite is a rock, formed by a group of aluminium oxides. This is generally a mixture of gibbsite, boehmite and diaspor (Friedman, 1997-2017). Graph 3.7 shows one of the bauxite signatures measured with the PSR+, and the diaspor and gibbsite reflectance curves of the USGS spectral library. Unfortunately, the spectral signature of boehmite does not exist in the spectral library from the USGS, therefore this mineral could not be used to analyse the bauxite spectra. A picture of the same bauxite sample can be seen in figure 3.7.

As can be seen in graph 3.7, the multiple absorption features between 1360-1620 nm are caused by the mineral gibbsite, where bauxite mainly follows the same pattern as gibbsite from 770 nm up to 2500 nm. The broad feature between 770-1250 nm is not visible in gibbsite and diaspor. It could indicate the presence of iron in the sample. This feature is also present in the samples from Rorac.

Three bauxite samples from the Nassau Mountain were measured, of which two contain iron (8009 & 8013) and the third one is a bauxite breccia with quartz (8015). The spectral signatures of these samples in graph 3.8 reveal the significant presence of iron for sample 8009 and to a lesser extend the presence in sample 8013. The multiple absorption features between 1880 -2050 nm, present for bauxite 8009 and 8015 are identical to the iron-bearing mineral gibbsite. The spectral curve of sample 8015 contains the most resemblance to the samples from Para and Rorac.

Laterite is a weathering product of basalt, rich in iron and aluminium (Friedman, 1997-2017). A sample of laterite from the Mindrineti creek, just Northeast of the Brokopondo river was measured (figure 3.9), along with two ferric laterite samples from Armina, near the Marowijne river (graph 3.9). The first absorption feature (750-1340 nm; 918 nm) and the feature between 1880-2050 nm confirm the presence of iron. Small double absorption features can be distinguished at 1380-1500 nm and
one with its maximum depth at 2208 for all three samples. These features could be caused by various minerals, such as: muscovite, illite, gibbsite, kaolinite or serpentine.

**Conglomerate** rocks consist of gravel-sized clasts, which are cemented together by calcite, silica or iron-oxide (O'Connor, 2005). A conglomerate sample from the Kabalebo river in West Suriname was measured (figure 3.10). Graph 3.10 shows the presence of iron and that calcite is most likely not present for this sample.

**Shale** is a clay, consisting of quartz and feldspars. Feldspar is an aluminium silicate mineral (Friedman, 1997-2017). The spectra of some feldspar minerals are shown in graph 3.11 together with the measured shale spectra. Quartz minerals are featureless and so are most feldspar minerals in the 400-2500 nm wavelength part of the spectrum. The measured shale spectrum does not contain any notable features, apart from a tiny one at 2209 nm. This feature is too small to be correlated to any feldspar mineral. Small features at 980 and 1880 are measurement errors. The measured shale sample is shown in figure 3.11.
Figure 3.7 Bauxite sample from Para, NE Suriname.

Graph 3.7 Spectral curve of bauxite compared to gibbsite and diaspore from the USGS spectral library, displayed in ENVI 5.2.
Figure 3.8 Bauxite-iron samples 8009, 8013 and 8015 from the Nassau Mountain, NE Suriname.
Figure 3.9 Laterite sample from Mindrinetti

Graph 3.9 Spectral curve of laterite and ferrite displayed in ENVI 5.2
Figure 3.10 Conglomerate sample from Kabalebo river, West Suriname.

Graph 3.10 Spectral curve of conglomerate compared to ferrite and calcite, displayed in ENVI 5.2
Graph 3.11 Spectral curve of Shale compared to feldspar minerals and quartz, displayed in ENVI 5.2

Figure 3.11 Shale sample from Marowijne river.
3.1.3 Metamorphic rocks

**Phyllite** samples were used from Brownsberg, near the Brokopondo lake (figure 3.12-A) and from Haute Rufin, near the Lawa river (figure 3.12-B). Phyllite is a metamorphic rock, intermediate between slate and schist, with shale as a parent rock (Wicander & Monroe, 2013). In general, all curves shown in graph 3.12 are relatively featureless, because of the quartz minerals. The phyllite that originated from Brownsberg shows an absorption feature between 780-1216 nm, with its deepest point around 940 nm, which could indicate the presence of iron. The feature from either chlorite or muscovite at 1410 is also present for the phyllite in Brownsberg, but not for the phyllite found near Lawa river in Haute Rufin. All phyllite spectra show a small feature at 2200 nm, which might be caused by the presence of iron. Peaks are visible at 694 for all measurements, most likely another error from the instrument.

A **schist-mica** sample was measured from Armina, near Marowijne river (graph 3.13, figure 3.13). Unlike the spectral signatures from shale and phyllite, the schist-mica contains various absorption features. When the curve is plotted along with ferrite, it can be clearly seen that these features are caused by iron.

A sample of **metasomatic rock of weathered schist** was used from the Pay mine in Rosebel (Brinck, 1956). Metasomatic is a metamorphic process where alteration of the chemical composition of the rock takes place (Zharikov et al., 2007). The spectral signatures in graph 3.14 shows a strong presence of muscovite. The sample can be seen in figure 3.14.

**Gneiss** is formed by metamorphosis of schist under high-grade conditions. Its reflectance curve is similar to that of phyllite, as they share the parent rock shale (figure 1.2). Two gneiss samples were measured from the Bakhuys expedition in Kabalebo, West Suriname (figure 3.15). The spectral curves of the samples shown in graph 3.15 are nearly featureless in the 400-2500 nm range, except for the optical range. A small feature at 2300 nm can be caused by biotite. Augite is also a common mineral in gneiss (O’Connor, 2005). However, features of these spectra cannot be traced back in the measured reflectance curves of these gneiss samples. The features at 980 and 1880 are probably caused by the error of the detectors.
Graph 3.12 Spectral signatures of phyllite (Brownsberg & Haute Rufin) compared to minerals from USGS, displayed in ENVI 5.2

Figure 3.12 Phyllite samples from A. Brownsberg and B. Haute Rufin, NE Suriname.
Graph 3.13 Spectral signatures of schist compared to ferrite, displayed in ENVI 5.2

Figure 3.13. Schist sample from Armina, East Suriname
Graph 3.14  Spectral signatures of metasomatic rock and muscovite, displayed in ENVI 5.2

Figure 3.14 Sample of metasomatic rock, from Pay Mine, NE Suriname.
Graph 3.15 Spectral signatures of gneiss compared to signatures of augite and biotite from the USGS spectral library, displayed in ENVI 5.2

Figure 3.15 Two gneiss samples, from Bakuys, W Suriname.
A greenstone sample from the van Kersen (1955) collection is used, that originates from the Nassau Mountain (figure 3.16). **Greenstone** describes metamorphic rocks formed under low pressures and temperatures, containing green minerals such as chlorite, serpentine or epidote (Friedman, 1997-2017). The spectra of these minerals are plotted together with the one of the greenstone sample, which contains a small feature at 1404 nm, 2015 and 2054 nm and 2345 nm (graph 3.16). The position of most of these features coincides with the spectral curve of epidote. The feature at 2015 nm can be caused by the mineral serpentinite. Features of chlorite are not found in the curve from the greenstone sample from Nassau Mountain, which indicates a lack of its presence.

A **hornfels** sample from Nassau Mountain was measured (van Kersen, 1955; figure 3.17). Hornfels are rocks derived from argillaceous sandstones, such as shale (Lay, 2009). The mineral composition of hornfels is dependent on the parent rock, but mostly contains minerals that are formed under high temperature conditions, such as cordierite and andalusite. Graph 3.17 shows that the hornfels sample contains iron (780-1350 nm, 1860-2050 nm, 1413 nm). The absorption features at 2255 nm and 7161 nm cannot be correlated to the features from the mineral cordierite or andalusite, but do coincide with the features of the greenstone sample at the same wavelengths. This could indicate the presence of epidote for this sample as well. The green colour of the hornfels sample reinforces this possibility.

The **Metagreywacke** sample from the Marowijne river, Armina is nearly featureless, as it contains quartz minerals (O’Connor, 2005)(graph 3.18; figure 3.18). A tiny feature at 1407 nm could be caused by the feldspar mineral orthoclase. Small features at 2250 nm and 2340 nm indicate small presences of chlorite and biotite minerals.
Graph 3.16 Spectral signatures of gneiss compared to signatures of augite and biotite from the USGS spectral library, displayed in ENVI 5.2

Figure 3.16 Greenstone sample, from Nassau Mountain, NE Suriname.
Graph 3.17 Spectral signature of hornfels compared to minerals from the USGS spectral library, displayed in ENVI 5.2

Figure 3.17 Hornfels sample from Nassau Mountain, NE Suriname.
Graph 3.18 Spectral signatures of metagraywacke compared to minerals from the USGS spectral library, displayed in ENVI 5.2

Figure 3.18 Metagraywacke sample, from Marowijne river, Suriname.
3.1.4 Igneous rocks

Granite consists mostly of orthoclase, Plagioclase and quartz. Orthoclase and Plagioclase are featureless in the 700-2500 nm range of the spectrum, causing Granite to be nearly featureless as well. Small absorption features are caused by muscovite (1415 nm, 2350-2390 nm) and maybe biotite (2300-2390 nm) (graph 3.19, figure 3.19).

Multiple dolerite samples were measured from various locations (Armina; figure 3.20-A, Brownsweg; figure 3.20-B). The reflectance curves from dolerite or diabase presented in graph 3.20 show a variety in brightness, where most reflectance spectra remained below 0.2, but some exceeded 0.5. Features occurred in the ranges of 780-1280 nm (960 nm), 1370-1585 (1415) nm and 1870-2110 nm and can be assigned to the presence of iron, or iron-bearing minerals such as goethite. The spectra that contain iron are from samples of Brownsweg. Most spectra contained barely any features. Essential minerals of dolerite are plagioclase and pyroxene, and some non-essential minerals are K-feldspar, hornblende and quartz (Mindat., n.d.). Unfortunately, plagioclase is not available in the USGS spectral library, but graph 3.21 shows two dolerite spectral curves, together with a pyroxene and hornblende spectral curve from the USGS library. However, features of the dolerite samples cannot be linked to these minerals.
Graph 3.19 Spectral signature of granite sample and spectral signatures of common minerals in granite from the USGS spectral library

Figure 3.19 Granite sample, from Kabalebo, W Suriname.
Graph 3.20 Spectral curves of dolerite samples displayed in ENVI 5.2
Graph 3.21 Spectral curves of dolerite samples along with minerals hornblende and pyroxene from the USGS spectral library, displayed in ENVI 5.2.

Figure 3.20-A Dolerite sample from Marowijne river, Armina.

Figure 3.20-B Dolerite sample from Brownsberg.
3.2 Analysis of the spectroradiometer PSR+3500

3.2.1 Accuracy instrument

Graph 3.22 shows the reference spectrum that was measured with the spectralon SRT-99-100 from Labsphere. It can be seen clearly that there is a through-effect created by the transition of the different detectors. Furthermore, the first detector shows a pattern consisting of peaks and troughs/valleys deviating from the smooth curves of detectors two and three.

![Graph 3.22 Spectral radiance curve of the spectralon reference tile (100% reflectance) in DARWin, where parts of the spectrum belonging to detectors 1, 2 and 3 are indicated.](image)

To test the accuracy of the instrument some target measurements of the spectralon have to be taken. Graph 3.23 shows the ratio of a reference and target scan from the white tile after several minutes. A line at 100% would indicate an error of 0%. The abrupt transition of the detectors is again visible, creating a difference of 0.2%. It also shows that the second detector contains the least noise, which is more present in detector three. Variations in the first detector are mainly caused by offset differences, which results in a variation between 0.2% to 0.6%. It should be noted that even when the instrument has warmed up, the accuracy varies with new measurements. After 10-15 minutes the instrument was on, the average reflectance error from the detectors was in the range of 0.4-1.0%. The noise is the most significant at the beginning and end of the wavelength spectrum.

Another pattern was observed, namely after the instrument has warmed up and the error seemed relatively low (error<0.6%), the error increased after increasing the number of scans, without renewing the reference scan (0.7%< error <1.0%). This while the contact probe was placed on the
spectralon and not touched during the measurements. It proves that to reduce the error of the measurements, it is important to regularly refresh the reference scan.

3.2.2 Effect accuracy on measurements

Graph 3.24 shows the reflectance spectra of multiple samples from the Peyne collection, measured with the contact probe. In general the curves of the same sample show the same pattern but variate in height due to differences in brightness of the sample. In the optical range 350-650 nm, the reflectance curve shows a rippling pattern, similar to the curve of the reference spectrum in graph 3.22. However, for each target measurement this pattern, or the magnitude of the peaks and troughs of the pattern, deviates from the pattern of the reference scan, allowing it to be visible in the reflectance curve as well. Furthermore, due to the transition of detectors, peaks are created at certain wavelengths. For every measurement, a peak is present at around 980 nm and a smaller peak at 1880 nm. An additional peak can sometimes be seen at 690 nm. The severity of the peaks varies for different measurements. It might help to renew the reference measurement more often, however the peaks will always be visible.
3.2.3 Number of scans

The Avg button on the main menu provides the option to choose the amount of scans taken, to average the final measurement. This option is tested by using the scan of a sample with Avg=100 as a reference, followed by target scans of Avg= 100, 90, 80,... 10. The target/reference ratio curves were analysed to see which came closest to an Avg of 100 (the maximum amount possible). Graph 3.25 shows all 10 ratios in percentage. What can be seen is that the results are almost equal for the second detector, showing the smallest error of maximum 0.3%. For the first and third detector, the error is about 2%. The results proved that an Avg of 100 did not show the best result and that the accuracies of the other Avg scans (10-90) varied for different tries. This indicates that the effect of the detectors on the accuracy is larger than the influence of the Avg option, to an extent that increasing the number of scans does not make a different for the final measurement.
3.2.4 Contact probe

The measurements of the contact probe can be influenced in multiple ways by both the sample and the user. Three of these manners were tested and it was studied in which way they affect the spectral measurements.

Surface irregularities

The rock samples of both collections show a large variety in shape. For some samples, flat surfaces are difficult to find. With a bauxite sample from the Peyne collection, two scans are taken. The first scan is taken with the contact probe placed on the rock sample, but for the second scan the contact probe is only partially placed on the sample.
The resulting spectral signatures of both measurements can be seen in graph 3.26. It shows that for the reflectance curve where the contact probe is not correctly placed on the sample, the spectral signature is lower in reflectance, but the shape and features of the curve remains the same. This indicates that there is no interference of the lightning (fluorescent) with the measurement. Because mostly the Suriname collection contains some samples with very irregular surfaces, this test is also done for gibbsite, but now the contact probe is placed on a relatively flat part of the sample during the first scan and placed on an irregular part of the surface for the second scan. The resulting curves show the same decrease in reflectance and also show no difference in the shape.

Graph 3.26 Spectral reflectance curves of bauxite from the Peyne collection, displayed in DARWin. Dark blue=rock sample completely covers the contact probe lense during scan measurement, light blue=contact probe is only partially placed on scan.

**Smooth surfaces**
There are also samples that contain a relatively flat surface, which makes it possible to place the contact probe on the sample instead of holding it. In this way, the contact probe will remain still during all the scans over which it averages. The noise of holding the sample by hand was tested with flysch from the Peyne collection. A scan of the flysch sample was used as a reference scan. The contact probe is released from the sample and placed on the sample at the approximately same position for the target scan. For the second target scan, the contact probe was picked up again and held against the sample. A third scan was made where both the probe and the sample were held. Measurements are repeated once or twice.
Graph 3.27 shows that when the contact probe is held by hand, the reflectance curve is higher, but also show that the noise is not necessarily larger. The smallest error was actually measured when both the contact probe and sample were held by hand (± by 3%).

Graph 3.27 Spectral reflectance curves of flysch. Blue= contact probe placed on sample, not touched during measurement, orange= contact probe held by hand, green= sample & contact probe held by hand.
4 DISCUSSION

A study of the Rosebel mine, held by Carlier (2012), revealed that the mineralogy of that area was dominated by three mineral groups: Kaolinites, white mica’s (muscovite, paragonite) and chlorites (Fe- chlorites). In this study, many rocks contained iron or iron-bearing minerals, which could be the same Fe- chlorites. Muscovite minerals were also present in multiple samples. For the greenstone and hornfels sample, chlorite minerals did not appear to be present, but instead it seemed that most features were caused by the mineral epidote.

This spectral library was created as an aid for remote sensing image interpretation for images of Suriname. However, geological image interpretation of Suriname is not an easy task. Apart from some interferences by clouds, the incredible amount of vegetation that covers the country could make it very difficult to identify mineralogy of Suriname. Locations of (old) mining areas are nearly the only bare spots available for geological image interpretation, but these rocks are mostly weathered due to protracted exposure. It should also be noted that the proportions of the mineral compositions vary for the same rock types at different locations, or even at the same location, which makes it difficult to assign one spectral reflectance curve to a specific rock.

Concerning the evaluation of the PSR+ spectroradiometer, it appeared that the first detector caused the most deviations in the spectral curves measurements, due to differences in offset of the curves. This detector is a different kind of detector (512 element Si photodiode array) than the second and third detectors, which are both of the same type (256 element extended InGaAs photodiode array). However, the second and third detector also showed a difference in accuracy, where the third detector caused significantly more noise. To improve the spectral reflectance curves, which is mostly needed for the optical range in the spectrum (first detector), the noise, difference in offset and the transition in detectors should be as small as possible.

Analysis of the PSR+ showed peaks at transitions of detectors on the wavelength spectrum. The severity of these peaks varied for different measurements. So far, no correlation between the instrument temperature and increase in peak errors has been found, but this is not thoroughly studied. Refreshing the reference scan more often might decrease the severity of the peak. The exact cause that increases the error should be further studied.
5 CONCLUSION

This research about the spectral reflectance curves of samples from Suriname, which were measured with the recently purchased PSR+3500 spectrometer, consisted of two research objectives.

Creating a spectral library from a rock collection of Naturalis, for minerals that are of importance to the Greenstone Belt formation and analyse the spectral differences between these minerals.

A spectral library was created with the PSR+ spectrometer and analysed. The minerals in the selection showed impurities by iron (gibbsite, hematite, quartz). For the minerals pyrolusite, pyrite and ferberite, iron is a composite element, so these features could already be expected. Samples from the metamorphic section mainly consisted of intermediate- to high-grade metamorphosed shale (phyllite, schist, gneiss) and also for these rocks, except for gneiss, the most significant absorption features were caused by iron. The spectral signatures of the metasomatic rock sample showed the significant presence of the mineral muscovite and it appeared that the hornfels sample contained the same green epidote mineral as the greenstone sample.

Testing the spectrometer PSR+ of the University of Utrecht with different rock fragments from La Peyne, France.

Overall, the PSR+3500 showed relatively good results, especially for the NIR-SWIR region. This was because the second detector contains the least amount of noise. The first detector showed the most variations, caused by offset differences and the third detector showed more noise than the second. In the optical region, the rippling pattern that was observed influences the spectral reflectance of the measurements. Peaks were visible in the spectral curves at the wavelength range of the transition of the detectors. The severity of these peaks differed for different measurements.

Results showed that the reference scan of the spectralon should be regularly refreshed, as noise increases with increased amount of target scans. Furthermore, increasing the number of scans taken to average each measurement in the Avg option, does not yield in better reflectance curves, as the noise from the detectors is too large.
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