Infrared Spectroscopy and Geochemical analyses of volcanic rocks from the Paraná Basin (Brazil)

María Lujan Iglesias, Carsten Laukamp
EP136935
01.06.2013
# Contents

Acknowledgments ................................................................................................................................... iv

1 Introduction .................................................................................................................................... 6
  1.1 Geological Setting .................................................................................................................. 6

2 Methods .......................................................................................................................................... 9
  2.1 Scanning Electron Microscope (SEM) with Energy Dispersive Spectroscopy (EDS) ............ 9
  2.2 Fourier Transform Infrared Spectroscopy (FTIR) ................................................................ 10

3 Results ........................................................................................................................................... 11
  3.1 Whole rock spectral signatures .......................................................................................... 11
  3.2 Mineral spectral signatures ................................................................................................ 14

4 Discussion and Conclusions........................................................................................................... 20

References ............................................................................................................................................. 21

Appendix 1: associated files in folder EP136935 .............................................................................. 22
Appendix 2a: Thin Section Image MM007 ........................................................................................ 23
Appendix 2b: Thin Section Image PD03 (fresh rock and weathering surface) ................................ 24
Appendix 2c: Thin Section Image PD03A (fresh rock) ..................................................................... 25
Figures

Figure 1  Map of the distribution of the volcanic rocks type in the Paraná Basin (SCHENATO et al., 2003). The studied samples belong to the Paranapanema Formation (red square) and to the Caxias and Gramado Formation (yellow square). ...................................................................................................................................... 7

Figure 2  TAS (Total-Alkali vs. Silica) Diagram of the Paraná Basin volcanic rocks utilizing the geochemical data from PEATE et al. (1992) and from the samples used for this study. ............................................. 8

Figure 3  Photomicrograph showing textural aspects of sample PD03 (TiO2, 3.82 wt. %): (a) plane polarized light, and (b) crossed polarized light (fsp – feldspar, px – pyroxene). .............................................. 11

Figure 4  Photomicrograph showing textural aspect of sample MM007 (TiO2, 0.93 wt. %): (a) plane polarized light, and (b) crossed polarized light (fsp – feldspar, px – pyroxene). .............................................. 11

Figure 5  Reflectance spectra for a high-TiO2 sample (red), low-TiO2 sample (pink), and for three reference silicate minerals. Black arrow indicates the location of the Christiansen Feature. ..................... 12

Figure 6  SCFM (SiO2 / (SiO2 + CaO + FeO+ MgO)) vs. Christiansen Frequency (CF) for samples belonging to the Paranapanema Formation (high TiO2) and for the Caxias and Gramado Formations (low TiO2). Samples presented as points are from SALISBURY & WALTER (1989), triangles from PEATE et al. (1992). .......................................................................................................................................... 13

Figure 7  Images from transmitted light, SEM and infrared microscopic measurements of feldspar, pyroxene and an opaque phase from the high-TiO2 sample PD03 (TiO2 of 3.82 %). Green points were measured using EDX (see Appendix 1 for respective results). ........................................................................................................ 14

Figure 8  Images from transmitted light, SEM and infrared microscopic measurements of altered pyroxene, matrix and an opaque phase from the low-TiO2 sample MM007 (TiO2 0.93 %). ............ 15

Figure 9  Reflectance spectra of minerals in the high-TiO2 sample compared with references spectra from the JPL Spectral Library PD03 (TiO2 of 3.82 %). ........................................................................................................... 16

Figure 10  Reflectance spectra of minerals in the low-TiO2 sample MM007 (TiO2 of 0.93 %). ......... 17

Figure 11  Opaque mineral belonging to one high-TiO2 sample PD03. The image in the middle corresponds to the SEM image showing ilmenite (a) and titanomagnetite (b), both with their respective compositional data. In the right corner is the FTIR Hyperion image of area b. Green points were measured using EDX (see Appendix 1 for respective results). ................................................................. 18

Figure 12  Opaque mineral belonging to low-TiO2 sample MM007. The image in the middle corresponds to the SEM image showing the titanomagnetite with the geochemical data. In the right corner is the FTIR Hyperion image. ............................................................................................................. 18

Figure 13  Map TIR reflectance spectra of opaque minerals in the high-TiO2 samples (pink – Ti-magnetite; red - ilmenite) and the low-TiO2 samples (black), compared with ilmenite and magnetite spectra from the JPL Spectral Library. The grey shaded band indicates the position of the Fe-O Bending in magnetite. ............................................................................................................. 19
Tables

Table 1 Classification criteria for basalt magma types (in wt%) ............................................................. 8
Acknowledgments

We are grateful to Bobby Pejcic for his accessibility and willingness when for using the laboratory equipment.

The project was supported by CSIRO’s Minerals Down Under National Research Flagship program by providing funding for Maria’s student internship.
1 Introduction

The current stratigraphy of volcanic rocks from the Paraná Basin is based mainly on whole rock geochemical analyses, which allow the subdivision of the basalt flows in high-TiO₂ and low-TiO₂ rocks. The project aims to find thermal infrared spectral signatures of the volcanic rocks that correlate with their geochemical signatures. For this, 11 rock samples were first analysed with the Bruker FTIR to identify the spectral signature of the basalts and dacites, which contain feldspar, pyroxene and magnetite as major mineral phases. After that, thin sections of every sample were analysed using thin section petrography, a scanning electron microscope (SEM) fitted with an EDAX energy dispersive spectrometer (EDS), as well as a Bruker Hyperion microscope connected to the FTIR. The petrographic, geochemical and spectroscopic data show comparable results. Samples with high-TiO₂ values contain ilmenite and titano-magnetite, whereas the low-TiO₂ rocks contain only titano-magnetite as main Ti-bearing phase. Titano-magnetite and ilmenite show distinct spectral signatures in the thermal infrared wavelength range. However, spectral signatures of the rock samples are complicated by overlapping spectral signatures of single mineral components. The more coarse crystalline samples allow a better separation of individual components when compared to the more fine crystalline samples. The preliminary results suggest that there may be scope to develop thermal infrared spectroscopy as a faster method for lithostratigraphic classification of rocks from the Paraná Basin and other volcanic suites worldwide.

1.1 Geological Setting

The Paraná continental flood basalt province covers an area of approximately 1.2 million km² (Figure 1) and represents a very important volcanic province related to the Paraná-Etendeka event, with 0.8x10⁶ km³ of lava flows. It was formed during the opening of the South Atlantic Ocean in the Early Cretaceous (PEATE et al., 1992). Major rock types are basalts and dacite to rhyolite, (Figure 2). The bimodality is given by the difference of SiO₂ content, which is around 52 wt% for basalts and ca. 68 wt% for dacites (PEATE et al., 1992).

Two magmatic groups have been identified (MELFI et al., 1988), according to their chemical characteristics:

(1) A low-TiO₂ (< 2 wt%) group comprising the Gramado, Caixas, Esmeralda and Ribera magmatic series and
(2) A high-TiO₂ (>2 wt%) group containing Pitanga, the Paranapanema and the Urubici magmatic series.

The main objective of this paper is to identify and differentiate these groups of rocks from their thermal infrared spectra. To achieve this, 11 samples were selected, with six belonging to the Paranapanema Formation (high-TiO₂ group) and five from the Caxias and Gramado Formation (low-TiO₂ group). They were analysed by means of spectroscopic, petrographic and geochemical techniques, followed by a comparison of the analytical results.

Figure 1  Map of the distribution of the volcanic rocks type in the Paraná Basin (SCHENATO et al., 2003). The studied samples belong to the Paranapanema Formation (red square) and to the Caxias and Gramado Formation (yellow square).
Infrared Spectroscopy and Geochemical analyses of volcanic rocks from the Parana Basin (Brazil)

Figure 2 TAS (Total-Alkali vs. Silica) Diagram of the Paraná Basin volcanic rocks utilizing the geochemical data from PEATE et al. (1992) and from the samples used for this study.

The basic, high-TiO$_2$ type lavas occur in the north of the Paraná Basin, and the low-TiO$_2$ type basalt and rhyolitic lavas occur from the centre to the southeast of the basin. The exception is the high-TiO$_2$ Urubici type, which occurs in the southern part.

For any Paraná sample to be uniquely assigned to one of these magma types, a set of diagnostic criteria that can resolve the compositional differences between these magma types needs to be established. Previous discrimination, such as by PEATE et al. (1992), has been restricted to trace element data. This approach has produced a preliminary set of proposed limits on the compositional range for specific elements within each magma type defined by PEATE et al., 1992 (Table 1).

Table 1 Classification criteria for basalt magma types (in wt%)

<table>
<thead>
<tr>
<th></th>
<th>High-TiO$_2$ (&gt; 2 wt%)</th>
<th>Low-TiO$_2$ (&lt; 2 wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Urubici</td>
<td>Pitanga</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>&gt;49</td>
<td>&gt;47</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>&gt;3.3</td>
<td>&gt;2.8</td>
</tr>
<tr>
<td>P$_2$O$_5$</td>
<td>&gt;0.45</td>
<td>&gt;0.35</td>
</tr>
<tr>
<td>Fe$_2$O$_3$(t)</td>
<td>&lt;14.5</td>
<td>12.5 - 18</td>
</tr>
</tbody>
</table>

(compiled from PEATE et al., 1992; total iron expressed as Fe$_2$O$_3$(t))
2 Methods

Eleven rock samples from the Paraná Basin were selected (from both TiO$_2$ groups) to be studied at the ARRC (Australian Resources Research Centre) of the CSIRO (Commonwealth Scientific and Industrial Research Organization), Australia.

They rock samples were analysed first with the Bruker FTIR to identify the mid- to far infrared (5 to 20 μm) spectral signature of the basalts and dacites, which contain feldspar, pyroxene and magnetite as major mineral phases. Thin sections of every sample were analysed using petrographic microscopy, a scanning electron microscope (SEM) fitted with an EDAX energy dispersive spectrometer (EDS), as well as a Bruker Hyperion microscope connected to the FTIR.

2.1 Scanning Electron Microscope (SEM) with Energy Dispersive Spectroscopy (EDS)

A scanning electron microscope is used to determine the topographical image or make-up of a sample. It has a greater depth of field, higher resolution and higher magnification than an ordinary optical microscope. The SEM produces high-resolution images of the sample surface, derived from a narrow stream of electrons, which is accelerated towards a specimen. Penetration into the sample material is only minimal. Electrons interact and scatter when they impact the sample (HARDING, 2002). Images are made by scanning the specimen and mapping the intensity of corresponding scattered electrons and other energy signals.

The three signals which provide the greatest amount of information in SEM are the secondary electrons, the backscattered electrons, and X-rays. Secondary electrons are emitted from the atoms occupying the top surface and produce a readily interpretable image of the surface. Backscattered electrons are primary beam electrons which are ‘reflected’ from atoms in the solid. The contrast in the image produced, is determined by the atomic number of the elements in the sample. The image will therefore show the distribution of different chemical phases in the sample, if the mean atomic number of those chemical phases varies. Interaction of the primary beam with atoms in the sample causes shell transitions which results in the emission of an X-ray. The emitted X-ray has an energy characteristic of the parent element. Direction and measurement of the energy permits elemental analysis, Energy Dispersive Spectroscopy (EDS), which can provide rapid qualitative, or with adequate standards, quantitative analysis of elemental composition with a sampling depth of 1-2 microns.
2.2 Fourier Transform Infrared Spectroscopy (FTIR)

Infrared spectroscopy is a technique based on the vibrations of the atoms of a molecule at specific frequencies related to the structure, composition and mode of vibration of the elements of the analysed object (STUART, 2004). For geological mapping and mineral exploration of volcanic rocks, for example, the thermal infrared region shows well-defined features since silicate minerals display strong fundamental molecular vibration bands in the 8 to 14 µm wavelength range, such as the Si-O stretching vibrations (CLARK et al., 1990).

In infrared reflectance spectroscopy, radiation is passed through the surficial layers of a sample or reflected from its surface. Some of the infrared radiation is absorbed by the sample and some of it is passed through (transmitted). The resulting spectrum represents the molecular absorption and transmission, creating a molecular fingerprint of the sample. Like a fingerprint, no two unique molecular structures produce the same infrared spectrum.

The determination of the reflectance for directional irradiation of diffusely reflecting samples requires measurement of the radiation reflected into the whole hemisphere (GINDELE et al., 1985). For this, integrating spheres are used, which are spheres whose interior wall has a perfectly diffusing and highly reflecting surface. These properties and the spherical shape of the integrator cause a homogeneous distribution of the enclosed flux over the wall by multi reflections, so that the brightness of any spot on the wall is proportional to the reflected flux. The Bruker FT-IR spectrometer utilised in this work is equipped with a diffuse gold integrating sphere accessory, which was used to obtain the reflectance spectra of the whole rock samples between 5 µm to 20 µm.

To measure the spectra of single minerals in the thin sections after the previous petrographic identification of the minerals, the Bruker Hyperion microscope was used, which is a high performance infrared microscope with transmission and reflection capabilities. The microscope has a transparent knife-edge aperture and is equipped with a nose piece with 15x casse grain, 4x visible, ATR and GAO objectives, as well as binocular and video viewing. The carbon coating of the thin sections, which was required for the SEM analyses, was removed prior to the measurements under the infrared microscope.
3 Results

3.1 Whole rock spectral signatures

The first stage of this study was to characterise the minerals present and investigate the infrared spectral signature of the whole rock samples. From the 11 samples that were analysed, only results for two representative samples will be presented here, one of high TiO$_2$ content (PD03) and one of low TiO$_2$ content (MM007), for a better visualization. Data for the remaining nine samples can be found in the folder "EP136935" as outlined in Appendix 1. Figures 3 shows images of sample PD03 (high TiO$_2$) taken with the polarizing microscope for plane polarized light (Figure 3a) and for crossed polarized light (Figure 3b). The images show feldspars, pyroxenes, brownish glass and some opaque phases. The same type of photomicrograph is shown for the sample MM007 (low TiO$_2$), showing altered feldspar and pyroxene, as well as fewer opaques embedded in a fine intergranular matrix (Figure 4). The images of the entire thin sections are shown in Appendix 2.

Figure 3 Photomicrograph showing textural aspects of sample PD03 (TiO$_2$, 3.82 wt. %): (a) plane polarized light, and (b) crossed polarized light (fsp – feldspar, px – pyroxene).

Figure 4 Photomicrograph showing textural aspect of sample MM007 (TiO$_2$, 0.93 wt. %): (a) plane polarized light, and (b) crossed polarized light (fsp – feldspar, px – pyroxene).
Figure 5 displays TIR reflectance spectra of the same samples (PD03 in green and MM007 in pink) measured with the Bruker FT-IR Integrating Sphere. Reference curves for the three main silicate minerals identified in the samples, obtained from the JPL (Jet Propulsion Laboratory) Spectral Library, are plotted (pyroxene (blue), feldspar (red) and quartz (black)) together with the representative sample scans.

This comparison allows visualizing the shift in the wavelength of the Christiansen Frequency Feature, the minimum in reflectance indicated by black arrow in Figure 5, which depends on the content of SiO₂ of major minerals in the sample. The Christiansen frequency feature occurs in a wavelength region where the real part of the refractive index undergoes rapid change and thus may approach the refractive index of the medium surrounding the mineral grains, resulting in minimal scattering (SALISBURY & WALTER, 1989). Because this takes place at a slightly shorter wavelength than the fundamental molecular vibration, absorption is still relatively low. With little backscattering and little absorption, infrared radiation can pass through a sample relatively easily, resulting in a minimum in reflectance.

Figure 5  Reflectance spectra for a high-TiO₂ sample (red), low-TiO₂ sample (pink), and for three reference silicate minerals. Black arrow indicates the location of the Christiansen Feature.
Another way to visualize the comparison of spectral signature and chemical composition is presented in Figure 6, where the chemical index SCFM (SiO₂/(SiO₂ + CaO + FeO+ MgO)) is plotted vs. the wavelength value of the Christiansen Feature (SALISBURY & WALTER, 1989, COOPER et al., 2002). Whole rock geochemical data from the Parana Basin (PEATE et al., 1992) are compared with data from SALISBURY & WALTER (1989). The classification is made on the basis of wt. % SiO₂ utilized by SALISBURY & WALTER (1989) with acidic (>63% SiO₂), intermediate (52-63% SiO₂), basic (45-52% SiO₂), and ultrabasic (<45% SiO₂) rocks. The wavelength position of the Christiansen Feature shifts to shorter wavelengths (i.e. higher frequencies) with increasing acidity of the rock. The principal Christiansen Feature is associated with the strongest molecular vibration band and varied for different silicate minerals. This spectral feature, combined with the SCFM chemical index serves as a good indicator of the rock type.

Figure 6  SCFM (SiO₂/(SiO₂ + CaO + FeO+ MgO)) vs. Christiansen Frequency (CF) for samples belonging to the Paranapanema Formation (high TiO₂) and for the Caxias and Gramado Formations (low TiO₂). Samples presented as points are from SALISBURY & WALTER (1989), triangles from PEATE et al. (1992).
### 3.2 Mineral spectral signatures

The second part of the work was to understand the spectral signatures of the individual minerals in both samples with the Bruker Hyperion microscope connected to the FTIR. Grains of each of the key minerals (i.e. feldspar, pyroxene, opaque phase) analysed by FTIR in the high-TiO$_2$ (Figure 7) and low-TiO$_2$ (Figure 8) were selected using plane polarised light (coloured circles in Figures 7 and 8). Their compositions and chemical variability were verified by EDX measurements (Appendix 1) before the same grains were found using the Hyperion infrared microscope. It should be noted that for this report the use of the term "opaque" concerns only mineral phases that are opaque in the visible part of the spectrum, such as magnetite or ilmenite. Other minerals can be opaque in other wavelength regions of the electromagnetic spectrum, such as quartz, which is opaque in the thermal infrared wavelength region.

<table>
<thead>
<tr>
<th>PLANE POLARIZED LIGHT IMAGE</th>
<th>SEM IMAGE</th>
<th>HYPERION IMAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FELDSPAR</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>![Feldspar Image]</td>
<td>![SEM Image]</td>
</tr>
<tr>
<td><strong>PYROXENE</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>![Pyroxene Image]</td>
<td>![SEM Image]</td>
</tr>
<tr>
<td><strong>OPAQUE</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>![Opaque Image]</td>
<td>![SEM Image]</td>
</tr>
</tbody>
</table>

*Figure 7 Images from transmitted light, SEM and infrared microscopic measurements of feldspar, pyroxene and an opaque phase from the high-TiO$_2$ sample PD03 (TiO$_2$ of 3.82 %). Green points were measured using EDX (see Appendix 1 for respective results).*
Figure 8 Images from transmitted light, SEM and infrared microscopic measurements of altered pyroxene, matrix and an opaque phase from the low-TiO$_2$ sample MM007 (TiO$_2$ 0.93 %).

Figure 9 and Figure 10 show the reflectance spectra of the minerals shown in Figure 7 and Figure 8 respectively, where they are compared with references curves from the JPL spectral library for each type of mineral. The spectral signatures of feldspar and pyroxene from the high-TiO$_2$ sample ("f3" and "p3" respectively) are in broad agreement with the reference curves from the JPL spectral library ("Feldspar" and "Pyroxene"). No attempt was made to identify the feldspar or pyroxene species. The main point was to confirm the broad agreement of the spectral curve and to highlight the shift of the Christiansen Feature to longer wavelengths in feldspar, when compared to pyroxene. The spectral signature of the opaque phase in the high-TiO$_2$ sample (op4) resembles largely the reference curve of ilmenite, especially when considering the position of the Christiansen Feature at around 13µm. The whole rock spectrum ("Rock") shows a less characteristic shape. However, the broad increase of reflectance values in the wavelength
region from ca. 8 to 12 µm is probably due to a mixed response from feldspars and pyroxene, which have been identified in the single mineral spectra. The slight increase in reflectance to the longer wavelengths (i.e. from 15.5 µm) can be attributed to the silicates and ilmenite.

Reflectance spectra of silicates in the low-TiO₂ sample MM007 (Figure 10) are very different, when compared to the high-TiO₂ sample PD03 (Figure 9). This could be due to the high degree of alteration of the pyroxene (P3 in Figure 8 and 10) into secondary minerals, such as phyllosilicates, and the finer crystal size of the feldspar laths (A2 in Figure 8 and 10) in the low-TiO₂ sample. The spectral signature of the finecrystalline, possibly partly amorphous matrix (A1 in Figure 8 and 10) suggests a composition similar to the major silicates. The Fe-Ti oxide (Op2 in Figure 8 and 10) shows a typical spectral signature with elevated reflectance values in the 15 to 20 µm wavelength region.

Figure 9 Reflectance spectra of minerals in the high-TiO₂ sample compared with references spectra from the JPL Spectral Library PD03 (TiO₂ of 3.82 %).
From the petrographic, EDX and infrared microscope data it can be observed that samples with high TiO₂ values contain ilmenite (Figure 11a) and titano-magnetite (Figure 11b), whereas the low-TiO₂ rocks contain only titano-magnetite as the main Ti-bearing phase (Figure 12). Also, the titano-magnetite belonging to the low TiO₂ samples has more FeO than the high-TiO₂ ones.

Titano-magnetite and ilmenite show distinct spectral signatures in the thermal infrared wavelength range. The pink spectrum in Figure 13 belongs to the titano-magnetite indicated in Figure 11 (area b), and the red spectrum to the ilmenite in Figure 11 (area a), both from the high-TiO₂ sample PD03. The black spectrum in Figure 13 belongs to the titano-magnetite of the low-TiO₂ sample MM007. These three curves were compared with the ilmenite and magnetite spectra from the JPL Spectral Library. It can be appreciated that the Christiansen Feature shifts to longer wavelengths with increasing FeO content. Reflectance spectra showing a shorter wavelength position of the reflectance minimum at around 12 to 15 μm corresponds to ilmenite (highest titanium content).
Figure 11  Opaque mineral belonging to one high-TiO₂ sample PD03. The image in the middle corresponds to the SEM image showing ilmenite (a) and titano-magnetite (b), both with their respective compositional data. In the right corner is the FTIR Hyperion image of area b. Green points were measured using EDX (see Appendix 1 for respective results).

Figure 12  Opaque mineral belonging to low-TiO₂ sample MM007. The image in the middle corresponds to the SEM image showing the titano-magnetite with the geochemical data. In the right corner is the FTIR Hyperion image.
Figure 13  Map TIR reflectance spectra of opaque minerals in the high-TiO$_2$ samples (pink – Ti-magnetite; red - ilmenite) and the low-TiO$_2$ samples (black), compared with ilmenite and magnetite spectra from the JPL Spectral Library. The grey shaded band indicates the position of the Fe-O Bending in magnetite.
4 Discussion and Conclusions

Eleven samples from the Paraná Basin belonging to two different groups (high-TiO$_2$ and low-TiO$_2$) were selected and analysed to correlate their thermal infrared signatures with petrographic and geochemical data.

The results show that the wavelength position of the Christiansen Frequency in TIR spectral signatures of igneous rocks is useful for rock type classification based on SiO$_2$ content (SALISBURY & WALTER, 1989; COOPER ET AL., 2002). This has implications for classification of igneous rocks using hyperspectral drill core logging data (e.g. HyLogging™) and even hyper and multispectral remote sensing data. For the latter technologies, further studies should evaluate whether the location of the Christiansen Feature can still be accurately determined when considering the lower spectral resolution.

Similar to the wavelength position of the Christiansen Feature and its relationship to the SiO$_2$ content of igneous rocks, the wavelength position of the reflectance minimum at shorter wavelengths compared to the fundamental Fe-O and possible Ti-O bands can be used to estimate the TiO$_2$ content. A shift of this reflectance minimum to higher wavelengths (lower frequencies) correlates with decreasing TiO$_2$ content and increasing total iron content, due to compositional changes of titano-magnetite series minerals (compare pink and black spectra in Figure 13). It is proposed that changes of the Fe/Ti ratio in the ilmenite-ulvöspinel-magnetite series may be observed in the thermal to far infrared wavelength range of the electromagnetic spectrum. However, spectral signatures of the rock samples were complicated by overlapping spectral signatures of the single mineral components. The more coarse crystalline samples allow better separation of the single components when compared to the more fine crystalline samples (Figure 9 and 10). Up to now, it was only possible to estimate the TiO$_2$ content from the infrared microscopic analysis of single minerals, but not from the whole rock spectra. Therefore, more research of spectral parameters other than the Christiansen feature that may be useful for estimating the TiO$_2$ content is necessary. During future work, one way to test the ability of measuring the TiO$_2$ content or Ti/Fe ratio in rocks could be the development of an algorithm that traces the slope of the 10 to 14 µm region in HyLogging™ data. Our preliminary studies suggest that an increase in the incline of this slope is correlated with the abundance and/or composition of Fe-Ti-oxides.

The preliminary results suggest that there may be scope to develop thermal infrared spectroscopy as a fast method for estimating the TiO$_2$ content of igneous rocks, and therefore lithostratigraphic classification of rocks from the Paraná Basin and other volcanic suites worldwide.
References


Appendix 1: associated files in folder EP136935

<table>
<thead>
<tr>
<th>Name</th>
<th>Date modified</th>
<th>Type</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bruker FTIR</td>
<td>19/06/2013 10:59 AM</td>
<td>File folder</td>
<td></td>
</tr>
<tr>
<td>Images_OpticalMicroscope</td>
<td>19/06/2013 10:59 AM</td>
<td>File folder</td>
<td></td>
</tr>
<tr>
<td>Images_Zeiss</td>
<td>19/06/2013 10:42 AM</td>
<td>File folder</td>
<td></td>
</tr>
<tr>
<td>ParanaBasin_Literature</td>
<td>19/06/2013 10:39 AM</td>
<td>File folder</td>
<td></td>
</tr>
<tr>
<td>SBM</td>
<td>19/06/2013 10:43 AM</td>
<td>File folder</td>
<td></td>
</tr>
<tr>
<td>whole rock geochemistry</td>
<td>19/06/2013 10:37 AM</td>
<td>File folder</td>
<td></td>
</tr>
<tr>
<td>correlation.xlsx</td>
<td>13/02/2013 4:39 PM</td>
<td>Microsoft Office Excel</td>
<td>37 KB</td>
</tr>
<tr>
<td>feldspars.xlsx</td>
<td>28/02/2013 1:29 PM</td>
<td>Microsoft Office Excel</td>
<td>18 KB</td>
</tr>
<tr>
<td>Salisbury_Data.xlsx</td>
<td>20/02/2013 5:54 PM</td>
<td>Microsoft Office Excel</td>
<td>35 KB</td>
</tr>
</tbody>
</table>
Appendix 2a: Thin Section Image MM007
Appendix 2b: Thin Section Image PD03 (fresh rock and weathering surface)
Appendix 2c: Thin Section Image PD03A (fresh rock)