**PHYSICAL VOLCANOLOGY AND
LITHOGEOCHEMISTRY OF THE MATA DA CORDA
FORMATION, MINAS GERAIS, BRAZIL**

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Thesis submitted to the Faculty of Graduate Studies and Research in partial
fulfilment of the requirements for the degree of Doctor of Philosophy

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ABSTRACT

Between May 1995 and July 1996 detailed geological mapping programs were carried out on ten selective Upper Cretaceous mafic potassic/ultrapotassic volcanic centres within the Mata da Corda Formation, Minas Gerais, Brazil. As one of the largest, yet least understood, mafic ultrapotassic igneous provinces, it covers an area of about 4,500 km² in east-southern Brazil, and forms part of the Alto Paranaíba Igneous Province, one of several alkaline igneous provinces occurring around the margins of the sedimentary Parana Basin. Approximately 80-85 million years ago, an episode of mafic potassic and mafic ultrapotassic volcanism, believed to be the product of mantle plume-related alkalic magmatism, produced this suite of alkalic rocks. Presented herein is a model for the volcanological evolution and reconstruction of the Mata da Corda, as well as an accounting of its petrology, lithogeochemistry, mineralogy, and mineral chemistry.

The dominant eruptive style was passive, fissure fed, eruptions of low viscosity magmas, akin to flood basalt-type eruptions, that lead to the creation of the now largely eroded Mata da Corda lava plain. The onset of volcanism was characterized by hundreds or perhaps thousands of brief phreatomagmatic and/or magmatic eruptions forming maar-type volcanoes. Initial eruptions were centred within the Areado sandstone, excavating maar-type craters below the pre-eruptive surface. However, craters failed to develop further as continued maar forming eruptions were arrested. Thus, in this volcanic field's current eroded state, vent systems are marked by maar-type craters.

A typical Mata da Corda volcanic centre was fed by one, or several, polyphase intrusive pipes. Two types of kamafugites may be present, an older, weakly silicified, brecciated intrusion, and a later, massive, non-silicified intrusion. Lamproite intrusions, when present, typically occur close to the kamafugites. Ultramafic xenolith-rich breccia pipes can occupy the same pipes as the kamafugites, or, more commonly, lie along the margins of the volcanic edifice. Within the central portion of the edifice, lower crater facies rocks are dominated by volcanic intrusions, kamafugite flows, and minor lapilli tuffs. Pyroclastic rocks are not present in the underlying vent, evidence that a downward propagation of a prototypical maar

diatreme did not develop beneath some Mata da Corda volcanoes.

The sequence of flows at Fazenda Andorinha represents the only known occurrence of flows outside a crater setting, and is considered, in part, representative of the once extensive Mata da Corda lava plain. Flow thicknesses vary from < 2 m to 10 m, consistent with low viscosity lavas. Given a conservative estimate that the pre-eroded Mata da Corda once spanned $40,000 \text{ km}^2$, and that the lava plain was at least 250 m thick, then a volume of at least $10,000 \text{ km}^3$ would have been erupted. In comparison, considerably less than the $195,000 \text{ km}^3$ calculated for the Columbia River flood basalts. The geochemical evolution of the flows documented at Fazenda Andorinha, in accordance with their crystal-rich nature, suggests that the magmas originated from a fractionating source. Presumably, this hypabyssal magma chamber was an open system allowing the influx of compositionally homogeneous magma between eruptions, leading to the distinctive flow cycles preserved at Fazenda Andorinha.

On geochemical discrimination diagrams most Mata da Corda samples plot consistently within the kamafugite field and a few within the lamproite field, showing that they have a strong kamafugitic affinity, and some lamproitic characteristics. Although, it is currently accepted that kamafugites and lamproites are derived from distinct mantle sources, Mata da Corda rocks are not geochemically consistent with this model. In fact the compositional similarities and common occurrences of kamafugites and lamproites are best explained if they are viewed as fractionated products derived from a common source. The volcanological evidence presented herein is consistent with this interpretation.

Compared with most other ultrapotassic volcanic provinces, Mata da Corda rocks are mineralogically similar, but different, as they contain higher percentages of diopside, perovskite and zeolites. However, they are similar in terms of some accessory minerals. In particular are the rare occurrences of kalsilite (the second known occurrence reported in the Mata da Corda), wadeite (the first known occurrences in South America), shcherbakovite (the first known occurrence in the Mata da Corda), and melilite. Furthermore, two potentially new minerals were identified.

The lamproite mineralogical classification scheme of Woolley et al. (1996) cannot be

practically applied to Mata da Corda rocks, as kamafugites are mineralogically similar to lamproites except that they lack forsterite. Thus, a forsterite bearing kamafugite, by virtue of their definition, would be a lamproite. Therefore, the only major mineralogical differences between the two rock types are in the presence or absence of typomorphic minerals such as wadeite, shcherbakovite, and kalsilite, yet according to current thought this is sufficient evidence for two separate magma sources.

Results of the perovskite laser ablation ICP-MS study in conjunction with the detailed mapping of seven volcanic centres are consistent with this argument, and reveal that:

- 1) perovskite REE content is effective for identifying coeval flows and feeder intrusions, thus constituting an effective mapping aid in confirming similarities defined by geological mapping and petrography.
- 2) perovskite REE can be used to help distinguish cognate xenoliths from accidental xenoliths.
- 3) differences between two distinctive kamafugite intrusions, and their relative timings of emplacements, are reflected in perovskite REE contents.
- 4) perovskite REE suggests that Mata da Corda kamafugites and lamproites are genetically related, and are best explained as products of fractionation from a common magma source.
- 5) Mata da Corda kimberlites have drastically different perovskite REE contents than associated lithologies of kamafugitic and lamproitic affinities. This last observation may have merit as an exploration tool, as only kimberlites and olivine lamproites are hosts to economic concentrations of diamonds. Perhaps perovskites can be used to discriminate rocks with diamond bearing potential from those that have no potential, such as the kamafugites. Thus, there exists the possibility that perovskite might be a useful complement to other more traditional diamond indicator minerals.

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Between May 1995 and July 1996 a detailed geological mapping program was carried out on ten selective mafic potassic/ultrapotassic volcanic centres within the Mata da Corda Formation, Minas Gerais, Brazil (Figs. 1, 2). Presented in this thesis are the results of that mapping program as well as extensive laboratory studies.

In early 1995 an agreement was reached with Canabrava Diamond Corporation (CDC) for which funding and logistical support would be provided towards a PhD project on their diamond concessions in Minas Gerais, Brazil. In

Figure 1. Study Area Location Map

return, they required that detailed mapping and analytical work be done on some high priority diamond exploration target areas, and that the data be processed and presented expediently. In conforming to their needs, it was decided that complete reports would be prepared upon completion of each of the map areas. These are comprehensive documents presenting all aspects of investigation including, detailed surface geology maps, whole rock and trace element lithogeochemical analyses, petrology, mineralogy and mineral chemistry, physical volcanology, structural analyses, geophysical analyses and interpretation, and exploration recommendations.

A trade-off with CDC regarding suitable map areas was agreed upon, resulting in ten localities chosen that not only addressed the company's exploration needs, but also ensured thesis requirements would be met. Six were chosen to best describe and document the geology of a Mata da Corda volcanic complex. Because of the volcanic field's severely eroded state, no one volcanic centre makes up a complete, archetypical, edifice. However,

the six map areas were selected to ensure that collectively they would illustrate the volcanic evolution of the Mata da Corda.

Property reports form the foundation of the thesis, and are presented in Appendices one to five, with subsequent chapters borrowing heavily upon the core information they all contain. Chapter three delves into the volcanological setting of the Mata da Corda. Chapter four deals with geochemical, and mineralogical comparisons between the Mata da Corda volcanic field and other mafic ultrapotassic provinces. Chapter five presents details of a laser ablation microprobe ICP-MS study on perovskite (REE), including comments on its use in discriminating rock types. A general conclusion is contained in Chapter six, summarizing the main characteristics of the Mata da Corda volcanic field, and comparisons with other mafic ultrapotassic volcanic provinces. Also included are discussions on mafic ultrapotassic magma genesis, mantle sources of Mata da Corda lamproites and kamafugites, and some contributions to the ongoing debate on whether or not lamproites and kamafugites are derived from separate sources, or represent fractionated products sharing one common ancestry.

In respect to the exploration program, the mapping project is to provide detailed information on the rocks, structure, and volcanic setting surrounding each of the map areas. This data, and interpretations, in conjunction with the ground magnetic survey carried out by the company, will help to assess each property's potential for hosting diamond bearing pipes. Thus, the primary exploration objectives were to investigate for kimberlite or lamproite intrusive pipes, and to determine if structural features were a controlling factor in the emplacement of intrusive pipes. It was foreseen, that the information obtained would help better understand some of the volcanic and chemical characteristics of this unique province, and in the process, aid the ongoing diamond exploration program.

Figure 2. Mata da Corda Formation simplified regional geology map and map area location map.

Very little is known concerning the lithogeochemistry and physical volcanology of the Mata da Corda volcanic field, yet this part of western Minas Gerais has produced diamonds for more than one hundred years. The detailed work presented in property reports on Fazenda Ribeirao da Mata, (Appendix 5), Fazenda Bananal (Appendix 4), Agua Limpa (Appendix 3), Fazenda Grotao (Appendix 2), and the Quintinos pipe (Appendix 1) represent some of the first in-depth studies ever done on Mata da Corda volcanic complexes. No other studies have provided such comprehension coverage, or endeavoured to test interpretations based on analytical data in light of sound geological mapping control. These works have been followed up with detailed mapping at several other volcanic centres (Fig. 2), including: Fazenda Andorinha (~4 km north of Presidente Olegario); Fazenda da Serra; and the Pântano intrusion. Although information from these areas will be cited, individual property reports were not generated.

1.2 LOCATION AND REGIONAL GEOLOGY

The Mata da Corda Formation covers an area of about 4,500 sq. km. in east-southern Brazil (Fig. 2), forming part of the Alto Paranaíba Igneous Province (APIP), one of several alkaline igneous provinces occurring around the margins of the sedimentary Parana Basin (Fig. 3). About 80-85 million years ago (Gibson *et al.*, 1995; Card, 1996) a large episode of mafic potassic and mafic ultrapotassic volcanism, believed to be the product of mantle plume-related alkalic magmatism (Herz, 1977; Gibson *et al.* 1995), produced this suite of alkalic rocks.

Mata da Corda Formation volcanic rocks intruded sequences belonging to the Upper Proterozoic Brasilia Belt, a 1,500 km long by 100-200 km wide fold belt formed during the Brasiliano tectonic cycle (600 ± 100 Ma) . Units within the belt consist of low-grade metamorphic rocks (quartzite, metapelite, limestone, dolomite, chert), believed to have been thrust on top of the basement rocks (Archean) of the Sao Francisco Craton, which borders to the east. This was achieved by means of a compressional tectonic event resulting in the collision of two cratons, the Sao Francisco and Amazonia and/or the Rio de la Plata craton during the consolidation of the Gondwana super-continent (Ramos, 1988; Pimentel and

Fuck, 1992; Unrug, 1992; Storey, 1993). A well developed west-southwest foliation, and the interpretation of several regional NW/SE striking thrust faults is evidence of this event. However, not all workers believe the belt resulted from thin-skinned tectonics. There is evidence that sialic basement was affected by the Brasiliano orogeny (Gonzaga et al., 1994). Debate is currently ongoing regarding the thickness of the Proterozoic package, as well as the existence of craton beneath the belt. Leonardos et al. (1996) propose that at least 150 kilometres of lithosphere lie beneath the Alto Paranaíba Igneous Province (APIP), separating it from the Sao

Francisco craton. However, Gonzaga et al. (1996) contest this arguing that the teleseismic data are preliminary and inconclusive. They maintain that within the Western Minas Gerais part of the APIP the kimberlites lie off craton, and as such, are poor targets for primary diamond recovery. On the other hand, Leonardos et al. (1996) defend that the Mata da Corda diamonds are primary, and the existence of underlying craton help support this.

The Sao Francisco craton represents the oldest, most stable, mid to late Archean crustal terrain in east central Brazil. Basement rocks consist of migmatites, gneisses, schists, gabbros, phyllites, conglomerates, and metavolcanics (Teixera, 1982). As stated previously, much speculation exists regarding the limits of the craton (Tomakin and Gonzaga, 1989). The western extent is particularly dubious as much of the area is overlain by Upper

Figure 3. Location of the Alto Paranaíba Igneous Province, and the distribution of other Cretaceous igneous provinces around the margin of the Parana Basin. (modified after Gibson et al., 1995)

Proterozoic Bambui Group metasedimentary rocks of the Brasília Belt, and overprinted by Brasiliano-age (400-750 Ma; Almeida, 1978) tectonism. Middle Proterozoic cover rocks of the Chapada Diamantina Group onlap the Sao Francisco craton within its central portions. Silicic volcanic rocks form the base of this group, and are overlain by eolian, fluvial, alluvial fan and marine facies strata. Radiometric

Figure 4. Main geotectonic units of east central Brazil. (modified after Gonzaga et al., 1994)

U/Pb dating indicates the craton had stabilized at ~2720 Ma

(Machado et al., 1992). This was followed by a period of relative crustal stability until around 2.2-1.7 Ga, when thermo-tectonic events related to the Early Proterozoic Trans-Amazonian orogeny affected the craton's southern margin.

The Aracuaí Belt wraps around the eastern and southern border of the Sao Francisco craton (Fig. 4). Basement and supracrustal sequences of sedimentary rocks were thrust toward the craton resulting in several major structural discontinuities (Delgado et al. 1994). Central portions of the belt contain strongly deformed, high grade metamorphic rocks (mica schists, quartzite, amphibolite). Overlying these units are Late Proterozoic glacial and marine sedimentary rocks. Granitoid intrusions related to the Brasiliano event are common within the internal zone of the belt.

During the Middle Proterozoic, igneous and sedimentary rocks of the Araxa Group were deposited along the southwest margin of the craton. These were in turn overlain by Bambui Group (~640 ± 15 Ma) shallow marine clastic sediments. By the Late Proterozoic, tectonic events of the Brasiliano orogeny thrust Araxa and Bambui Group rocks eastward

over the Sao Francisco Craton. This succession of Proterozoic thrust slices is known as the Brasilia Belt (Almeida, 1967; Schobbenhaus et al., 1984). Proterozoic basement rocks consist of thrust slices of sheared granitic rocks and amphibolites of the Araxa Group (Leonardos and Meyer, 1991). The Canastra formation is considered the uppermost formation of the Araxa Group, and consists of quartzite, phyllites, and chlorite-sericite schist units. Ibia Formation rocks of strongly foliated green phyllites with quartz stringers and carbonate, forms the base of the Bambui Group. The remainder of the Bambui Group is composed of slates and arkosic meta-sediments.

The Parana Basin formed at the end of the Brasiliano orogeny (Ordovician-Silurian) and consists of a large sedimentary basin bordering the Brasilia Belt to the west (Figs. 3, 4). It covers more than 1,000,000 km² in Brazil, and extends farther to the south into Paraguay and Argentina. Currently, the mechanism for basin subsidence remains unresolved. The oldest rocks within the basin are Silurian continental and marine clastic deposits and overlying Devonian marine shales (Delgado et al. 1994). Deposition throughout the remainder of the Paleozoic consisted of fluvial, lacustrine, glacial, and marine styles of sedimentation. Sedimentation continued until the Mesozoic when approximately two-thirds of the sedimentary rocks were covered by tholeiitic lava flows (Parana continental flood basalts) erupted during the Triassic and Jurassic (between 138 and 127 Ma; Turner et al., 1994). It is believed the magmatism was triggered by lithospheric extension related to the rise of the Tristan plume and the subsequent opening of the Atlantic Ocean (White and McKenzie, 1989; O'Connor and Duncan, 1990; Peate et al. 1990). From Cretaceous to Quaternary continental type deposition dominated. The Parnaiba basin is the second of two major Phanerozoic sedimentary protobasins within this part of Brazil (Fig. 4).

The Lower Cretaceous Areado Formation unconformably overlies the Bambui Group, which has been subdivided into three sedimentary members, the Quirico Member (lacustrine; siltstones and argillites), Tres Barras (fluvial; arenites), and Abaete (alluvial fan; conglomeratic). Pebble to boulder sized conglomerates occur locally at the base and the top of the formation, and are an indication of a high energy fluvial environment.

Areado Formation rocks are overlain by Upper Cretaceous volcanic rocks of the Mata

da Corda Formation. Outcrop geology consists of intrusions, flows, pyroclastic, and epiclastic deposits of ultramafic/mafic alkaline composition. Exposures are intensely weathered, and fresh outcrops are exceedingly rare. Typically, volcanic rocks are spatially related to intrusive bodies, commonly in the form of necks, dykes, and severely eroded maars.

Figure 5. Brazil's Regional Structural Lineaments

Several ultramafic and alkaline intrusions of Cretaceous age lie along a series of parallel NW trending lineaments within the Brasilia belt (Fig. 5). Ulbrich and Gomes (1981) believe the lineaments have been in existence since Late Precambrian, and represent zones of crustal weakness instrumental in the emplacement of subsequent alkaline intrusions. The lineament of interest is labelled "lineament 125°" in Figure 5, also known as the Alto Parnaiba uplift (Ulbrich and Gomes, 1981). Where the lineament intersects the northeast corner of the Parana Basin, in the Alto Paranaiba-Presidente Olegario provinces, it is called the Alto Paranaiba Arc. The lineament constitutes both a structural and gravimetric high.

Locally, intrusions are well defined on magnetic maps. During the Cretaceous, uplift of the arch formed a natural topographic barrier separating the Parana from the San Franciscana basin (Costa and Sad, 1968; Leonardos and Meyer, 1993). Gibson *et al.* (1995) attribute this to an upwelling of the Trinidad mantle plume beneath the Brazilian continent, and that volcanism associated with this event lead to the formation of the Mata da Corda Formation of intrusive rocks and related flows and pyroclastics.

1.2.1 Geology of Western Minas Gerais (Alto Paranaíba region)

The Alto Paranaíba magmatic province is outlined in Figure 3. Within this region of western Minas Gerais State, Proterozoic rocks of the Brasilia fold belt have been intruded by Cretaceous age alkaline

bodies. In Figure 6 the distribution of the main kimberlitic and kamafugitic pipes, and the regional supracrustal geology is shown. Locations of the intrusions appear strongly influenced by the Alto Paranaíba arc, a 125° trending lineament reactivated during a period of Cretaceous magmatic activity. Rocks of the Brasilia belt consist of thrust sheets of meta-volcanic sedimentary material of the Araxa Group, and psammitic pelitic sedimentary sequences of the Canastra and Ibia Formation, and Bambui Group.

Figure 6. Geology map of western Minas Gerais (modified after Gonzaga et al. 1994).

This eastward succession of thrust slices is a product of the compressional tectonic forces of the Brasiliano event (600 ± 100 Ma).

The Lower Cretaceous Areado Formation unconformably overlies the Bambui Group. It has been subdivided into three sedimentary members, the Quirico Member (lacustrine; siltstones and argillites), Tres Barras (fluvial; arenites), and Abaete (alluvial fan; conglomeratic). Planar bedding, cross bedding, and desiccation cracks are common features present in the fluvial facies rocks, while the lacustrine facies is characterized by shales exhibiting ripple marks and mud cracks. Areado deposition within the study area appears to have been greatly influenced by periods of regional uplift and faulting (Winter, 1996).

Upper Cretaceous volcanic rocks of the Mata da Corda Formation overly the Areado Formation. However, recent work by Gibson (1995) in the Tiros area, indicates that the contact between the Mata da Corda and Areado is gradational, thus implying that in some areas the Areado may be younger than Lower Cretaceous. Mata da Corda volcanic rocks cover an area of about 4,500 sq. km (Figs. 2, 6), and are considered the stratigraphic equivalent of the Bauru volcanic rocks farther to the west (Fig. 6). Both formations are intensely weathered. Thus, fresh exposures are exceedingly rare, if not non-existent. Outcrop geology consists of flows, pyroclastic, and epiclastic deposits of ultramafic/mafic alkaline composition. Volcanic rocks are spatially related to intrusive bodies, commonly in the form of necks, dykes, flows, and maar complexes. In areas where the feeders have intruded the Areado Tres Barras Member, sandstones appear disrupted, brecciated, fluidized, and silicified. These disturbance features are usually within a few hundred metres of the vent. However, when pipes have intruded Proterozoic basement rock those features are absent, perhaps due to the different physical characteristics of the more competent, undeformed Areado sandstones, and the strongly schistose Bambui Group phyllites and slates. It is generally believed that phreatomagmatic and magmatic volcanism were the dominant volcanic processes at work forming the various centres. Explosive events occurred either when rising magma contacted groundwater within the Areado sandstone aquifer, or when exsolved magmatic gas pressures exceeded the confining pressure of the overlying Areado sandstone.

1.3 ORIGINAL WORK

The following table lists the thesis work done by the Ph.D. candidate, and that which was done by others. Although some of the analyses were done at commercial and government laboratories, only the analytical data was provided. The Ph.D. candidate was solely responsible for sample selection, data processing, interpretation, and presentation.

Table 1. Original Work Content.

Type of Work	Done by Candidate	Done by Others
Geological Mapping	✓	
Sample collection	✓	
AutoCAD drafting and plotting	✓	
SEM-EDS analyses	✓	
LAM ICP-MS trace element analyses	✓	
Electron Microprobe analyses	✓	
Lithogeochemical data processing	✓	
Geophysical data processing & map production	✓	
Mineral chemistry data processing	✓	
Photomicrographs & SEM backscatter images	✓	
Computer generated diagrams and maps	✓	
Writing property reports	✓	
Making thin sections & polished thin sections		✓
XRF whole rock & trace element analyses		✓
REE whole rock analyses		✓
Sm-Nd whole rock analyses		✓
Rb-Sr & U-Pb mineral ages		✓
Airborne and ground geophysical surveys		✓
XRD mineral analyses		✓

CHAPTER 2

MATA DA CORDA FORMATION VOLCANIC EDIFICES

2.1 MAP AREAS

Formal property reports were written and submitted to Canabrava Diamond Corporation for five of the areas mapped within the Mata da Corda Formation between May 1995 to June 1996. Information on the remaining five map areas was either presented in short communications to the company or incorporated into chapters of this thesis. However, the ideas presented herein are largely based on the work done on all the areas.

Chapter 2 begins with brief summaries of the five areas, and introduces a sixth area consisting of the kamafugite flow sequence at Fazenda Andorinha. All areas are located on a schematic cross-section of the Mata da Corda (Figure 7), showing the general, yet varied, anatomy of the volcanic centres. Each area is placed on the diagram at its perceived stratigraphic position and erosional level. The ensuing discussion on their general geological and geochemical characteristics, will help set the stage for the volcanic reconstruction of the Mata da Corda to be presented in Chapter 3.

Complete map area reports are presented in Appendices 1 to 5, and 11 (Appendix 1 - Quintinos pipe; Appendix 2 - Fazenda Grotao; Appendix 3 - Agua Limpa; Appendix 4 - Fazenda Bananal; Appendix 5 - Fazenda Ribeirao da Mata; Appendix 11 - kamafugite flows at Fazenda Andorinha). Due to the advanced erosional state of the Mata da Corda a complete volcanic edifice has probably not been preserved. However, an idealized model has been constructed based on the available exposure. The six mentioned areas possess many unique features not seen at any of the other sites, yet collectively, they provide the information needed to understand the general geological and geochemical characteristics of Mata da Corda volcanism better.

Figure 7. Schematic cross section showing the locations and stratigraphic positions of the six map areas as they pertain to the overall model for the Mata da Corda.

2.1.1 Quintinos Pipe (X433)

The volcanic edifice at Quintinos (see Appendix 1 for complete property report) forms a distinct topographical feature 80m east-west by 140m north-south, as defined by the volcanic rock - sedimentary rock (Areado) contact. A vertical difference of 45 metres separates this contact from the structure's highest point. The present erosional level has exposed an upper section of a single polyphase pipe, occupied by two different Upper Cretaceous Mata da Corda Formation kamaufugite intrusions and an ultramafic xenolith-rich

intrusion that has intruded country-rock of Lower Cretaceous Areado Formation (Quiricó Member) intercalated quartz arenites and siltstones (Fig. 8). Marginal sections of the volcanic edifice, as well as all crater facies material, have been completely removed by erosion.

Figure 8. Property geology map of the Quintinos Pipe (X433) and sample location map.

Quintinos is recognised as a composite pipe, consisting of three distinct intrusions. Field relationships indicate that the breccia, rich in ultramafic xenoliths, is the latest. The first intrusion, one of two kamafugites, consists of silicified blocks that form the highest part of the pipe. The second kamafugite intruded the first, filling interstitial spaces between the brecciated and silicified blocks. In terms of their lithogeochemistry, mineralogy, and mineral chemistry the volcanic rocks are identical to those observed at the other volcanic centres.

The absence of pyroclastic rocks within the pipe suggests that a typical maar diatreme did not develop, and that initial crater forming phreatomagmatic and/or magmatic eruptions were short lived. It is proposed that the Quintinos pipe is typical of pipes that underly and fed the volcanic activities at the other centres, and may be representative of most Mata da Corda vent systems.

The quantity of ultramafic xenoliths observed at Quintinos suggests the breccia pipe sampled deep source regions, of which two samples, in particular, contained forsteritic olivine hosting inclusions of euhedral chromites rich in MgO and Cr₂O₃ (Cr-Ti chromites: a lamproite diamond indicator mineral). Olivines and chromites from known lamproites possess similar concentrations. Both minerals are characteristic of deeper mantle sources. In addition, the mineral wadeite was found in one of the ultramafic xenoliths. Wadeite is recognized as a positive phase for lamproite recognition, in which it occurs as a common accessory mineral.

2.1.2 Fazenda Grotão (X348)

Bedrock geology at Fazenda Grotão (X348), Minas Gerais, Brazil (Figs. 2, 7) consists of Lower Cretaceous Areado Formation (Quiricó Member) intercalated quartz arenites and siltstones (see Appendix 2 for complete property report) . Upper Cretaceous porphyritic intrusive kamafugitic rocks, an olivine-diopside-phlogopite lamproite intrusion, and ultramafic xenolith-rich breccia pipes intruded the country-rock (Fig. 9; Map 2). Extrusive rocks consist of porphyritic flows, flow top breccias, sandy tuffs, and minor lapilli tuffs. Exposures of flows and pyroclastic rocks are intensely weathered to a dark coloured soft “soil-like” material, whereas the intrusions and ultramafic xenoliths are much fresher.

Figure 9. Property geology of Fazenda Grotao (X348) and sample location map

The volcanic edifice lies within a topographical depression about 1.2 km east-west by 2.0 km north-south, as defined by the volcanic rock - sedimentary rock (Areado) contact. A vertical difference of 120 metres separates this contact from the structure's highest point. The erosional level has exposed a central section of the maar crater, occupied by two different phases of kamafugite intrusion, while marginal sections of the volcanic edifice have been completely eroded (Fig. 7). As shown in Figure 7, Fazenda Grotao is believed to represent the lower crater facies of a maar crater as evidenced by the presence of subaerial flows and airfall lapilli tuff.

Grotao is recognised as a composite pipe, consisting of four intrusive types. The first of two kamafugite intrusions makes up the main body of the volcanic edifice, occupying the central region of the map area. The second phase intruded the first, filling interstitial spaces between the brecciated and silicified kamafugite blocks, in effect, cementing the blocks in place. Field relationships at Agua Limpa, the Quintinos pipe, and Fazenda Grotao indicate the last intrusive phase is the breccia, rich in ultramafic xenoliths. Field evidence regarding the lamproite's timing of emplacement is lacking, however, the fact that it lies near the country-rock contact, wedged between the sedimentary rocks and the central kamafugite intrusion, may indicate it intruded last and came up along the structure's boundary, the most obvious point of crustal weakness.

In plan view, distributions of the three main rock types are remarkably consistent (Fig. 9; Map 2), in that exposures of ultramafic xenolith-rich breccia pipes occur as discontinuous outcrops around the periphery of the volcanic structure, next to the Areado/volcanic contact. Kamafugites, on the other hand, occupy the central core of the edifice, suggesting the later breccia pipes intruded along concentric faults, marking the contact between the vent and the surrounding country rock. Similar distribution patterns were observed at Agua Limpa, Fazenda Bananal, Ribeirao da Mata and the Quintinos pipe.

Geochemical analyses have shown that volcanic rocks at Fazenda Grotao are similar to kamafugites, and, to a lesser degree, lamproites. Similar observations were recorded at all other volcanic centres mapped to date. This commonality is also reflected in the mineralogy and mineral chemistry, a topic that will be discussed in greater detail in Chapter 4. Overall,

Mata da Corda kamafulgites have similar mineral chemistry to olivine-diopside phlogopite lamproites but they lack the required forsteritic olivine. Simply put, according to the current proposed lamproite definition (Woolley et al.,1996), a typical Mata da Corda kamafulgite would be classified as a lamproite if it contained forsteritic olivine.

Although flows are intensely weathered, their chemistry is still useful in characterizing rock types. By using molecular proportion ratio plots, it has been shown that certain elements have remained relatively immobile. As to be expected, mobility is greatest in the highly weathered flows, and much less among the moderately weathered intrusions and relatively fresh xenoliths.

In all map areas there is also a strong chemical association between porphyritic intrusions, flows, and some xenoliths. It is believed that their chemical congruities reflect a common source region. In particular, the strong evolutionary trend in incompatible elements, with the flows representing the most evolved, suggests that porphyritic intrusions, flows, and some xenoliths (cognate xenoliths) were derived from the same source region. Cognate xenoliths bear some magmatic relationship to the host rock. Therefore, they probably represent the composition of the source region from which intrusions and flows have evolved.

The presence of pyroclastic rocks at Fazenda Grotao is evidence of initial maar forming magmatic and/or phreatomagmatic eruptions. Glauconite alteration of sedimentary country rock and ultramafic xenolith breccia pipe material attests to the area's once shallow marine setting, conditions suitable for phreatomagmatic eruptions. We know that the ascent of ultramafic xenolith-rich magma to the earth's surface must be rapid, otherwise the xenoliths will be dissolved back into the melt. The abundance of xenoliths and pyroclastic rocks at Fazenda Grotao supports a model of rapidly ascending magma explosively emplaced upon reaching the surface. In addition, the quantity of ultramafic xenoliths also suggests that some breccia pipes have sampled deeper source regions. In particular, one xenolith contains abundant forsteritic olivine, hosting inclusions of euhedral chromites rich in MgO and Cr₂O₃ (a diamond indicator mineral), similar to olivines and chromites from lamproites. Both minerals are characteristic of deeper mantle sources.

Although, four distinct types of intrusions are present at Fazenda Grotao, they are not distinguished based on the ground magnetic survey. In fact, similar magnetic surveys were performed at four of the six map areas, and in all instances individual intrusions could not be recognized. Therefore, geological mapping remains the best method of establishing the existence of breccia pipes, as well as their spatial relationships to the other rock types present.

2.1.3 Agua Limpa (X276 & X277)

Agua Limpa outcrop geology consists of Lower Cretaceous Areado Formation (Quiricó Member) intercalated quartz arenites and siltstones that have been intruded by Upper Cretaceous porphyritic intrusive kamafugitic rocks, and ultramafic xenolith-rich breccia pipes of the Mata da Corda Formation (Fig. 10; Map 3). Extrusive rocks consist of intensely weathered porphyritic flows, flow top breccias, and lapilli tuffs (see Appendix 3 for complete property report).

The volcanic edifice is an inverted “L” shaped topographical high feature about 1.8 km east-west by 2.0 km north-south, as defined by the volcanic rock - sedimentary rock (Areado) contact. A vertical difference of 120 metres separates this contact from the structure’s highest point. The current erosional level has exposed a central section of the maar crater (Fig. 7), similar to that observed at Fazenda Grotao, and occupied by two different types of kamafugite intrusion. Marginal sections of the volcanic edifice have been completely eroded.

Agua Limpa is a composite volcanic centre, consisting of three intrusive phases. Field relationships at Agua Limpa, as well as Fazenda Grotao and the Quintinos pipe, indicate that the last phase was the ultramafic xenolith-rich breccia. The first of two kamafugite intrusions makes up the main body of the volcanic edifice, forming the topographical high ridge. The second phase intruded the first, filling interstitial spaces between the brecciated and silicified kamafugite blocks, cementing the blocks in place.

Kamafugites occupy the central core of the edifice (Fig. 10; Map 3), while the exposures of ultramafic xenolith-rich breccia pipe occur as discontinuous outcrops around the periphery of the volcanic structure, next to the Areado/volcanic rock contact. It is believed they

intruded last and came up along concentric faults marking the structure's boundary. Similar distribution patterns were observed at Fazenda Grotao, Fazenda Bananal, Ribeirao da Mata and the Quintinos pipe.

Figure 10. Agua Limpa property geology and sample location map.

The best outcrops of kamafugite flows are located within the central section of the map area (Fig. 10; Map 3). Here four complete subaerial cycles are preserved. Each cycle consists of a thin porphyritic flow that grades into an overlying well-developed flow-top breccia, that is in turn capped by a thin unit of graded, airfall, lapilli tuff (Appendix 3, Plates 16, 17). Thus demonstrating that pyroclastic deposition was a common part of the eruption sequence, and that the sequence repeated itself several times. The same association was observed at Fazenda Grotao, except there flows and lapilli tuffs are much rarer. However, the rock types present at both centres are essentially identical.

Typically, individual flows are <2m thick, contain 3 to 10% euhedral, 1-3mm, phenocrysts of altered pyroxene, perovskite, magnetite and ilmenite, set in a fine grained matrix. Vesicles occur in any shape (most are rounded and oblong), size (up to 3mm), and quantity. Most of their cores have been weathered out, leaving a fine grained chalk white material encrusting the cavity (probably an altered zeolite). Only the heavy minerals (perovskite, ilmenite, magnetite, and titanomagnetite) have survived the intensive weathering. The overlying lapilli tuff units have an average thickness of about 30 cm. They consist of rounded to subrounded volcanic lapilli fragments, ranging in size from 1 mm to 5 mm, and are highly vesicular.

The quantity of ultramafic xenoliths also suggests that some breccia pipes have sampled deep source regions. One exposure, in particular, contained a xenolith with abundant Mg-rich (fresh) olivine (Fo_{91}), hosting inclusions of euhedral chromites rich in MgO and Cr_2O_3 (a diamond indicator mineral). Both species are characteristic of deeper mantle sources.

2.1.4 Fazenda Bananal (X162)

Fazenda Bananal is located within western Minas Gerais, Brazil, approximately 12 km northeast of the city of Carmo do Paranaíba, in the east-central portion of Block L (Figs. 2, 7). The map area defines a horse shoe shaped topographical high, about 1.6 km east-west by 2.0 km north-south. Outcrop geology consists of Lower Cretaceous Areado Formation (Quiricó Member) quartz arenites and siltstones intruded by Upper Cretaceous porphyritic kamafugitic/lamproitic pipes, and ultramafic xenolith-rich breccia pipes, of the Mata da

Corda Formation, resulting in intense, localized, disruption of the sandstone country rock (see Appendix 4 for complete property report). Subsequent flows and pyroclastic rocks were deposited within the maar-type crater thus helping to preserve them (Fig. 11).

Figure 11. Fazenda Bananal simplified surface geology and sample location map.

The current erosion level has exposed a marginal section of the maar-type crater (Fig. 7), while the rest has either been removed by erosion or is covered by the laterite cap to the west. Occurrences of silicified Areado blocks, porphyritic intrusions, ultramafic xenolith-rich breccia pipes, outcrops of garnet-rich lapilli tuff, and blocks of silex lie along arcuate features, parallel to the volcanic/sedimentary contact (Fig. 11; Map 4). It is believed these features are concentric faults, similar to those described at Ribeirao da Mata, and represent centres of caldera collapse or crater rim slumping. They also represent centres of intrusive activity within the volcanic structure.

At Fazenda Bananal two distinct types of intrusive pipes are present. Porphyritic, sometimes brecciated, relatively fresh lamproite/kamafugite pipes are the most common. Breccia pipes are rarer, and much smaller than the porphyritic intrusions, but they always occur in association with them. Missing is the massive kamafugite intrusion observed at Agua Limpa, Fazenda Grotao, and the Quintinos pipe.

Intrusive rocks are fine to medium grained, porphyritic, and vesicular to varying degrees. Euhedral to subhedral phenocrysts range in size from 1 to 4 mm, and crystal contents range between 10 and 25%. Mineralogy consists of fine grained phenocrysts of diopside, hyalophane (barium, potassium feldspar), an iron magnesium rich alteration product, and perovskite. The groundmass consists of a very fine grained, lime green, altered mass. Optical recognition of constituents is limited due to the extent of weathering. However, perovskite grains have survived. Other lath shaped grains (0.25mm long) are scattered throughout the groundmass. Their crystal habit is similar to mellilite, but there is no means by which to verify this, as they have been completely altered and replaced by fine grained secondary products.

Extrusive volcanic rocks consist of porphyritic, vesicular, flows (and associated flow top breccias), and pyroclastic rocks. Usually, individual flows are <2m thick, contain 3 to 10% euhedral, 1-3mm, phenocrysts of altered pyroxene, perovskite, magnetite and ilmenite, set in a fine grained matrix.

Flowtop breccias are commonly thicker than the accompanying massive section of the flow. Moreover, there exists a gradational transition from massive flow, to angular breccia

fragments with minor matrix material, to rounded fragments resting in a matrix supported medium. On the surface, flowtop breccias are readily identifiable. Because of their brecciated nature, they are more susceptible to alteration (silicified, feldspathised, apatitized), and being a more resistant layer, they stick out on the topographic surface.

Fourteen outcrops of intensely weathered pyroclastic rocks were found in association with outcrops of kamafugite flows. However, unlike the exposures described at Agua Limpa and Fazenda Grotao, direct contact between flows and overlying pyroclastics was not observed. Volcanic fragments are rounded to subrounded, ranging in size from 1 mm to 2 mm. One outcrop area contained finely laminated, near vertical beds of garnet-rich lapilli tuff.

Breccia pipes are less resistant to weathering than the other intrusions, therefore, good outcrop exposures are difficult to find. However, they often host ultramafic xenoliths which are more resistant to weathering. These are found lying on the weathered surface above the breccia pipes. They are generally oblong to rounded in shape and vary in size up to 1m. However, the majority are less than 20cm, relatively unaltered, and represent the freshest material collected. Although xenoliths include the following mineralogical types: diopside-rich pyroxenite; diopside-phlogopite pyroxenite; diopside-kalsilite pyroxenite; diopside-phlogopite-leucite pyroxenite; and diopside-phlogopite-olivine pyroxenite, their geochemistry indicates a kamafugite affinity.

Geochemical analyses show that volcanic rocks at Fazenda Bananal have chemical characteristics similar to kamafugites and phlogopite lamproites, and are best described as a hybrid species. There is also a strong chemical association between the porphyritic intrusions, flows, tuffs, and some xenoliths, and that the chemical similarities may reflect a common source region.

2.1.5 Ribeirao Da Mata Volcanic Complex

The Ribeirao da Mata volcanic complex is located approximately 10 km north of the city of Patos de Minas, within western Minas Gerais, Brazil (Fig. 2, 7). The volcanic complex, is a 1.8 km long and 1.3 km wide topographic high feature standing 125 m above the surrounding countryside (Fig 12). Outcrop geology consists of Upper Cretaceous kamafugite

porphyritic intrusions and flows, an olivine lamproite intrusion, and ultramafic xenolith-rich breccia pipes that have intruded, and overlying, Late Proterozoic basement Bambui Group phyllites and Lower Cretaceous Areado Formation (Quiricó Member) quartz arenites (see Appendix 5 for complete property report).

Like the other volcanic centres, the intrusions at Ribeirao da Mata are polyphase. Lithogeochemical analyses and mineralogical data suggest that most intrusions have a kamafugitic affinity. However, also present are an olivine lamproite intrusion, and several lamproite xenoliths (recovered from ultramafic xenolith-rich breccia pipes). The olivine lamproite intrusion contains forsteritic olivine, aluminum-poor and sodium-poor diopside, and titanian and aluminum-poor phenocrystic phlogopite, thus confirming its lamproite classification. This kamafugite-lamproite association is fairly common, and examples of it were found at all other map areas, either as separate intrusions sharing the same centre, or as lamproite xenoliths scattered about kamafugite centres.

Ribeirao da Mata was not formed by volcanic activity restricted to one large center. Instead, several pipes of variable sizes, shapes, and emplacement times, are responsible. To date, twelve pipes have been found from all areas of the complex. The largest has dimensions of 280m x 180m, while the smallest are localized pipes of less than 10m in diameter. All are spatially associated with volcanic flows.

Intrusive rocks are fine to medium grained, porphyritic and vesicular to varying degrees. Euhedral to subhedral phenocrysts range in size from 1 to 4 mm. These are crystal rich rocks, with phenocryst contents ranging between 20 and 55%. Most exposures are relatively fresh, but the more vesicular and brecciated outcrops are generally more weathered, and show evidence of hydrothermal alteration (minor silicification, secondary potassium feldspar and apatite). Mineralogy consists of phenocrysts of diopside, zeolite (phillipsite), perovskite, serpentine pseudomorphs of olivine, and altered melilite, set in a fine grained matrix of diopside, zeolite and opaques, with accessory apatite, calcite, phlogopite, barite, potassium feldspar, and barium feldspar (celsian). The opaque minerals are predominantly ilmenite, magnetite and titanomagnetite.

Figure 12. Ribeirao da Mata simplified geology map.

Extrusive volcanic rocks consist of porphyritic, vesicular, flows with associated flow top and foot breccias. Pyroclastic rocks were not observed. Usually, individual flows are <2m thick, contain 10 to 15% euhedral, 1-3mm, phenocrysts of altered olivine, perovskite, and pyroxene, set in a fine grained matrix. Weathering has progressed to the stage that fresh outcrop no longer exists on the surface. All that is remaining is a soft “soil-like” material in which the primary textures and mineral shapes have been preserved. Only the heavy minerals such as perovskite, ilmenite, magnetite, and titanomagnetite have survived.

Although flows are more abundant at Ribeirao da Mata than at any of the other map areas, well-preserved flow exposures are not common. The easily eroded flows typically form gently sloping, relatively flat, surfaces, recognizable by their characteristic black soils. Where erosion has cut a steeper path (gullies and cliff faces), flow textures and morphologies can be observed. When preserved, flowtop and foot breccias provide good stratigraphic top indicators. Most flowtop breccias are thicker than the accompanying massive section of the flow, while the foot breccias are much thinner, and are not always present.

Kamafugite flows and intrusions contain a high percentage of phenocrysts, suggesting they originated from highly crystallised magmas. It is considered unlikely that highly crystallized magmas, or their extrusive derivatives, will have risen in their highly crystallized state from depths >4 km. Instead, they would have crystallised wholly or partially in relatively shallow magma chambers.

Ultramafic xenoliths are found associated with breccia pipes, either within the pipes themselves, or as loose fragments scattered on the surface effectively marking the underlying pipes location. Xenolith types include diopside-leucite lamproite, diopside-rich pyroxenite, peridotite, and rounded sandstone nodules. To date, most of those recovered are kamafugitic, while diopside-leucite lamproite xenoliths are next in abundance. One ultramafic xenolith sample, collected from a breccia pipe located in the north-east section of the map area, contains the mineral wadeite, a typomorphic phase for lamproite recognition.

Regional structural control on the emplacement of pipes and dykes is shown on the property geology map (Fig. 12, Map 5), where everything has a southeast orientation roughly parallel to the regional 125° lineament, or the trend of the Alto Parnaiba Arch. However, on

a local scale, concentric and radial faults are the dominant structural features. Concentric faults represent centres of caldera collapse or crater rim slumping, and are also often associated with breccia pipe intrusions, silicification and fluidization of the country-rocks. Although early magmatic and/or phreatomagmatic maar forming eruptions excavated the crater down into the preeruption surface, the lack of pyroclastic deposits indicates that continued maar forming eruptions were arrested, and that more passive emplacements dominated. Subsequent flows infilled the crater, effectively protecting them from being completely removed by erosion. The current erosional level has exposed the basal section of a maar-type crater (Fig. 7), consisting of the main central vent complex and a portion of the crater's eastern margin. The rest of the edifice has been eroded. In comparison to the other map areas, Ribeirao da Mata is unique in terms of the abundance of subaerial flows, yet total lack of pyroclastic deposits. The significance of this observation will be elaborated on in Chapter 3, dealing with the volcanic reconstruction of the Mata da Corda.

2.1.6 Fazenda Andorinha

The flows at Fazenda Andorinha represent the best examples of Mata da Corda kamafugite flows found to date (Fig. 2, 7). Their physical characteristics are similar to those already described for the other map areas, and like all other Mata da Corda flows, they are intensely weathered, and except for the oxides, all primary minerals have been replaced by secondary phases (see Appendix 11 for complete property report) . On the other hand, at Fazenda Andorinha primary flow textures and relict mineral shapes have been largely preserved. Twenty-two individual flows, with associated flow-top and foot breccias, are exposed along a 210 m road section (Map 6). On average, flow thicknesses vary from two to three metres, as do the overlying flow-top breccias, while the foot breccias are much thinner, averaging about 15 cm. Dips varying from 32° within the southeast part of the section (Map 6), to 60° at the northeast end. Assuming that faulting did not produce a duplication of flow units in the section, then a true thickness of approximately 150 m of relatively uninterrupted volcanic stratigraphy has been preserved. A plan map of the immediate outcrop geology surrounding the road section was produced to establish whether

fault duplication did occur (Appendix 11, Fig. 1). No evidence was found to suggest that was the case.

Prior to Fazenda Andorinha, flows were found exclusively within a maar crater setting. However, at Fazenda Andorinha intrusive rocks were not observed, nor were the ultramafic xenoliths that are usually found in abundance within volcanic centres. Furthermore, flow units within the maar-type craters at Agua Limpa and Fazenda Grotao are capped by air-fall lapilli tuff units, yet lapilli tuffs were not observed at Fazenda Andorinha. The possibility that Fazenda Andorinha represents a more distal setting, could explain the absence of pyroclastic deposits, as these would be thickest and most prevalent closer to the eruptive centres. Accordingly, it is believed that this package of flows represents extensive flood basalt type eruptions that accumulated in some form of structural depression or valley, thus leading to their well-preserved state. This would place the Fazenda Andorinha flows stratigraphically above the other map areas shown in Figure 7, and thus representative of Mata da Corda flood basalt-type eruptions.

Flows are typically porphyritic (phenocryst-rich - 10-25%) with upwards of 8% subhedral (relict) olivine (ranging in size from 1-9 mm). Most of the relict phases are euhedral and tabular (~3.0 mm) diopsides, minor melilite laths, while fine-grained magnetite accounts for the rocks' moderately magnetic character. Euhedral perovskites (2-3 mm) occur in variably amounts. Vesicle contents are also variable ranging from 0% to 15%. They are typically 1-2 mm in size, rounded to elongate in shape, and filled with a chalky-white soft material (probably zeolite).

Sixteen samples of massive flows, spanning the entire road section, were submitted for whole-rock and trace element analyses (Appendix 11, Table 1). Flow-top and foot breccias were not sampled as they show signs of limited hydrothermal alteration (e.g., silicification). Although the flows are intensely weathered, it is assumed that the entire section has been weathered uniformly, therefore, geochemical variations between flows should be a primary phenomenon and not a weathering overprint. To check for such variations, samples were first assigned a stratigraphic location based on their distance (up section) from the base the section. They were then plotted on scatter diagrams. Sample numbers on the diagrams can

be matched to their positions on the section as shown in Map 6. Five plots are presented in Appendix 11 (Figs. 2 to 6), showing that temporal changes in composition (evidence for geochemical evolution) exist. In particular, there appears to be two, and possibly three, distinctive cycles preserved in the section as defined by compatible elements Cr and Ni, and incompatible elements, such as Ba and P_2O_5 . From the base of the section upwards, Ni contents steadily increase until sample FA29 (Appendix 11, Fig. 2). The cycle then repeats itself from samples FA33 to FA46, thus defining two distinct sample groupings. Three possible cycles (of up to seven flows in each) are shown on the three remaining diagrams (Appendix 11, Figs. 3, 4, 5) in which Ba contents progressively increases throughout each cycle, as do K_2O/P_2O_5 and Ni/P_2O_5 ratios. Geochemically evolution of successive flows, in association with their crystal-rich nature, agrees with a model involving fractionation of a hypabyssal magma chamber.

Ni is typically concentrated within olivine, however, olivine is only a minor phase in these flows, as it is in all Mata da Corda kamaufugites. Instead, Ni is accommodated by diopside, which has a much lower partition coefficient. Therefore, with the onset of each cycle, Ni would become progressively concentrated in the melt, thus early diopsides would not contain significant Ni. With continued fractionation, the Ni content of the melt would steadily increase, such that later diopsides would have higher Ni contents. The same explanation is proposed for the incompatible elements. At the end of the eruptive cycle, extrusive activities would cease, fractionated materials would no longer be removed from the source, thus allowing the addition of new magma to rejuvenate it. With the next eruptive cycle the whole process would repeat itself, thus producing the cyclical geochemical variations observed at Fazenda Andorinha.

CHAPTER 3

VOLCANOLOGICAL RECONSTRUCTION OF

ERUPTIVE EVENTS

DURING CONSTRUCTION OF THE MATA DA CORDA

Figure 13. Schematic cross section showing the locations and stratigraphic positions of the six map areas as they pertain to the overall model for the Mata da Corda.

3.1 INTRODUCTION

This chapter outlines the volcanic evolution of the Mata da Corda. The six map areas shown on Figure 13, occur at different erosional levels, and provide views of the different stages of development of the Mata da Corda, that collectively forms the basis of the volcanic reconstruction presented herein.

3.2 VOLCANIC RECONSTRUCTION OF THE MATA DA CORDA

About 80 million years ago (Gibson et al., 1995; Card, 1996), in southern Brazil (Fig. 2), a large episode of mafic potassic and mafic ultrapotassic volcanism created the rocks of the Mata da Corda Formation. Onset of volcanism was characterized by hundreds or perhaps thousands of explosive eruptions that resulted in the formation of maar-type volcanoes. The resulting maar-type volcanoes of this field are much older than others they have been compared to and described in Appendix 6. Typically, younger maars are better preserved than those older than Quaternary and Tertiary (Lorenz, 1985). Older structures are generally highly eroded, and often only deeper sections of the edifice are exposed (diatreme), as most rim deposits have been eroded off. Rock composition also has an adverse effect on preservation. For instance, the work of Ufnar et al. (1995) emphasizes the low preservation potential of ultrabasic rocks, even in arid, intraplate tectonic settings, conditions similar to those present at the time of Mata da Corda volcanism.

According to Lorenz (1985, 1986) maars are underlain by a well-developed diatreme. With continued phreatomagmatic eruptions they deepen as eruption foci migrate downward in response to the development of a hydraulic cone of decompression that lowers the hydrostatic pressure on the detonation level. The presence of lithic fragments from deeper stratigraphic levels in the pyroclastic deposits reveals diatreme development. However, no such evidence has been found in any of the map areas, suggesting that diatremes were not developed, or they are shallow and poorly developed. The small Quintinos pipe (Fig. 14, 15) may represent the type of upper-level feeder underlying these volcanoes. All overlying crater facies material has been eroded, such that only the weakly silicified feeder pipe is left, standing about 45 m above the surrounding country side (Fig. 14). Exposed is an excellent three-dimensional view of a shallow stratigraphic level (Fig. 15). This interpretation is partially based on the pipe's many similarities with the Agua Limpa volcanic centre (Fig. 7, Appendix 3), located 8 km to the northwest. At both localities the Bambui/Areado contact lies at almost identical elevations, thus implying a similar topographic elevation prior to eruptions. Therefore, both landforms were probably constructed upon a common datum, except that at Quintinos, the much smaller intrusion, erosion had less material to deal with.

Both locations are host to intrusions of the same composition with the same intrusive timing relationships. Given these commonalities, a pipe similar to Quintinos must exist beneath Agua Limpa, and probably the three other edifices. As outlined by Lorenz (1985, 1986) upper diatreme facies should consist principally of bedded pyroclastic rocks. However, Quintinos is a polyphase intrusive pipe completely lacking pyroclastic materials. Based on these observations it seems that not even a shallow, poorly developed diatreme exists below these maar-type craters.

Figure 14. Quintinos pipe surface elevation map (looking northeast).

Figure 15. Quintinos pipe surface elevation map overlain with simplified geology map (looking northeast). See Figure 8 regarding detailed geology.

The relict maar-type edifices at Fazenda Grotao, Fazenda Bananal, Agua Limpa, and Ribeirao da Mata represent higher stratigraphic sections than the Quintinos pipe (Fig. 13) as evidenced by the occurrence of subaerial flows and pyroclastic rocks. In particular, the exposures at Fazenda Grotao (Appendix 2, Fig. 7) and Agua Limpa (Appendix 3, Fig. 7) are of lower crater facies rocks lying within the volcanic edifices' central cores. At each locality kamafugite intrusions are the dominant rock types, with subordinate ultramafic xenolith-rich breccia pipes, kamafugite flows and airfall lapilli tuffs. The flows and tuffs are confined to the central portion of the crater, where they have been preserved. All other parts of the maar-type craters, if developed, were removed by erosion. However, unlike Agua Limpa, Fazenda Grotao occurs within a low lying topographical setting (Fig. 16, 17), whereas the former is a topographically high feature standing 110 m above the surrounding countryside. It is believed this difference is largely a function of differential erosion, as the weakly silicified kamafugite breccias at Agua Limpa eroded slower than the non-silicified intrusions at Fazenda Grotao.

Figure 16. Contoured surface elevation map of Fazenda Grotao (looking southwest).

Figure 17. Fazenda Grotao surface elevation map overlain with simplified property geology. See Figure 7 Appendix 2 regarding property geology. (Looking southwest)

Fazenda Bananal and Ribeirao da Mata occupy marginal sections of eroded craters (Fig. 13), offering insight into the role concentric faults (ring faults caused by crater subsidence) had on the emplacement of subsequent intrusions. They are also the only two areas in which extensive exposures of fluidized Areado sandstone breccia occur. Fluidization is caused by the explosive disruption of the sandstone country rock. At Fazenda Bananal a section through the eastern and southeastern portion of the eroded crater is exposed. Here outcrops of intrusive volcanic rock and outcrop areas of fluidized sandstone define the arcuate trend of the concentric faults. The rest of the edifice, including the main eruptive centre, has either been eroded off or lies under an extensive laterite cap. Lower crater facies rocks consist of kamafugite intrusive rocks, ultramafic xenolith-rich breccia pipes, kamafugite flows and associated lapilli tuffs.

Ribeirao da Mata provides exposures through the central core of a maar-type crater as well as its eastern margin (Fig. 13). Outcrop geology consists of lower crater facies kamafugite intrusions, an olivine-phlogopite intrusion, ultramafic xenolith-rich breccia pipes, extensive kamafugite flows, and several areas of fluidized sandstone breccia. Pyroclastic rocks were not observed. However, similar to Fazenda Bananal, concentric faults are delineated by outcrops of intrusive rocks and fluidized sandstone breccia.

3.2.1 Discussion

In summary, a typical Mata da Corda volcanic centre was fed by one, or several, polyphase intrusive pipes similar to that described at Quintinos. Two types of kamafugites may be present, an older, weakly silicified, brecciated intrusion, and a later, massive, non-silicified intrusion. Lamproite intrusions may also be present (Fazenda Grotao and Ribeirao da Mata), and typically occur close to the kamafugites. Ultramafic xenolith-rich breccia pipes occur at all five centres, and as seen at Quintinos, they can occupy the same pipe as the kamafugites, or, more commonly, lie along the margins of the edifice. Pyroclastic rocks are not present in the underlying pipe, evidence that a downward propagation of a prototypical maar diatreme did not develop beneath some Mata da Corda volcanoes. The reasons for this will be addressed later in the chapter. Within the central portion of the

edifice, lower crater facies rocks are dominated by volcanic intrusions, kamaugite flows, and minor lapilli tuffs. Intrusions are less common within marginal sections of the crater, where flows and fluidized Areado sandstone breccias dominate. At all centres the overlying crater facies materials have been eroded, thus evidence establishing the lateral extensiveness of the flows is lacking. Nevertheless, there can be little doubt that volcanic activity within this field was voluminous and widespread, as there are literally thousands of Mata da Corda volcanic centres (their distinctive airborne dipolar magnetic anomalies confirm this) similar to those described herein.

Plate 1. A linear array of six blind pipes. Evidence of structurally controlled emplacement in the Mata da Corda. A closeup of pipe "A" is shown in Plate 2.

Plate 2. Closeup of two blind pipes shown in Plate 1, consisting of intensely silicified Areado sandstone surrounded by non-silicified sandstone and Bambui Group phyllite. Associated dipolar airborne magnetic anomalies confirms the presence of underlying intrusions.

Although most of the evidence has long since been removed by erosion, the most dominant eruptive style is passive, fissure fed, eruptions of low viscosity alkaline magmas,

akin to flood basalt-type eruptions. The fact that this volcanic field falls along the Alto Paranaíba Arc, a major transcontinental lineament, is evidence of regional scale structural control. Its dominant influence is evident within individual volcanic centres, such as

Figure 18. Block diagram illustrating the model for reconstruction and volcanic evolution of the Mata da Corda from initial explosive maar-type eruptions to voluminous eruptions of alkaline lavas.

Ribeirao da Mata, where the intrusions, and even the overall shape of the complex, conforms to the Arc's 125° orientation. On a local scale, evidence of fissures, or laterally continuous fractures, are shown in Plates 1 and 2, where several blind pipes are aligned along an underlying structure controlling their emplacement.

The sequence of flows at Fazenda Andorinha is the only known example of flows to occur outside the crater setting, and as such, are considered, in part, representative of the once extensive Mata da Corda lava plain (Fig. 13). Preserved in the 210 m road section is 22 individual kamaugite flows, with associated flow-top and foot breccias. Flow thicknesses vary from < 2 m to 10 m. Columbia River flood basalts range in thickness from 15-35 m, while less viscous ultramafic komatiites typically range in thickness from <1 m to > 10 m (Cas and Wright, 1993). Thus, the consistency of flow thicknesses at Fazenda Andorinha, as well as those described within the Mata da Corda maar-type craters, is consistent with low viscosity lavas.

It is believed that fissure fed eruptions of voluminous alkaline magmas, originated from hundreds, and possibly thousands, of Mata da Corda maar-type volcanoes. Thus forming a laterally extensive lava plain consisting of thousands of low viscosity flows similar in morphology to those described at Fazenda Andorinha. Furthermore, the geochemical evolution of the flows documented at Fazenda Andorinha, in accordance with their crystal-rich nature, suggests that the magmas originated from a fractionating source. Presumably, this hypabyssal magma chamber was an open system allowing the influx of compositionally homogeneous magma between eruptions, leading to the distinctive flow cycles preserved at Fazenda Andorinha. The characteristics of this unique volcanic field are summarized in Figure 18, a block diagram which illustrates the reconstruction and volcanic evolution of the Mata da Corda from initial explosive maar-type eruptions to voluminous eruptions of alkaline lavas. Given a conservative estimate that the pre-eroded Mata da Corda once spanned 40,000 km², and that the lava plain was at least 250 m thick (twice the known thickness of the Fazenda Andorinha flow sequence), then a volume of at least 10,000 km³ would have been erupted. Considerably less than the 195,000 km³ calculated for the Columbia River flood basalts.

3.3 MAAR VOLCANOES

3.3.1 Introduction

Recognition of eruptive fissures is difficult in flood basalt-type settings. Especially, for younger provinces in which immense outpourings of magma tend to cover the vent systems. Swanson et al. (1975), recognized vent and near-vent areas in the Columbia River Plateau based on the occurrences of remnant spatter cones, spatter ramparts, agglutinates, and welded scoria. However, in older volcanic terrains that have been substantially eroded, these relatively fragile features may not survive. On the other hand, the Mata da Corda volcanic field is different in that vent systems are marked by maar-type volcanoes. The presence of maar craters implies explosive volcanic eruptions, and not the type of passive volcanism needed to create huge laterally extensive lava plains. Yet, it has been proposed that the Mata da Corda is analogous to a flood basalt province. To address this contradiction, it is helpful to take a close look at a typical Mata da Corda volcano, as the evidence indicates that early crater forming phreatomagmatic and/or magmatic eruptions were quickly arrested, and immediately followed by passive eruptions of low-viscosity kamafugite flows. These flows emanated from hundreds, or perhaps thousands, of centres, collectively forming the Mata da Corda lava plain. The maar-type volcano at Ribeirao da Mata (Appendix 5, Fig. 7) represents the best preserved edifice of its type known to occur within the Mata da Corda, and is presented here as a typical volcanic centre.

3.3.2 Maar Definition

A maar is essentially an explosively excavated volcanic crater with most of its structure lying below the pre-eruption surface, resulting in the older country rocks being exposed in the crater walls. Contrary to most volcanic edifices, which are positive landforms, maar craters possess a negative relief. Not surprisingly, many quickly become filled with water forming distinctive circular lakes. Although most maars are associated with mafic volcanic fields (all types of basalts, nephelinites, leucitites, olivine melilitites, kamafugites, lamproites, and kimberlites), magma composition is not believed to be a determining factor (Lorenz, 1985). For instance, maars have also been found associated with other types of

subaerial volcanism, such as of rhyolitic, dacitic, andesitic, trachytic, phonolitic, and carbonatitic affinity.

Since the early 1800s geologists have recognized and described these unique volcanic landforms. One of the most intensely studied areas, the Eifel region in Germany, is commonly regarded as the type locality for maar volcanoes. The word "maar" was initially used in this region for volcanic crater lakes. Subsequently, its meaning has evolved to today's universally accepted usage when referring to the entire volcanic landform, with or without the enclosed lake.

Appendix 6 contains a summary of the processes involved in the formation of maar volcanoes, as well as a description of their general characteristics. Included also, is a brief description of selective maar volcanoes from around the world. Information contained therein is provided as a complement to the discussion, in this chapter, on how Mata da Corda maar-type edifices. The ensuing analysis of Mata da Corda volcanic landforms is based on comparison with the information summarized in Appendix 6.

Maars, tuff rings, and tuff cones are all products of phreatomagmatic eruptions. According to experimental studies, magma/water mass ratios largely determine the resulting landforms, in which a ratio of 0.35 is considered optimal for the development of maar volcanoes, and is typical of the interaction between magma and ground water (see Appendix 6, pp. 2-7). Examples of wetter environments, in which tuff cones and tuff rings dominate, include magma interaction with free water in the form of lakes, swamps, shallow marine, or water-rich fluvial gravel beds. If water is lacking, then phreatomagmatic eruptions will not develop. Instead, strombolian or hawaiian styles of volcanism will prevail. Any factor that affects the availability of water will have a direct influence on the type of eruption, and consequently, the resulting landform, of which some likely candidates include geology, topography, hydrology, and even climate.

The Eifel district in Germany (Appendix 6, p. 18) is the classic maar volcano locality, and much of our knowledge regarding maars was derived from studies in this region. However, as a group, maars should not be misconstrued as being identical to those of the Eifel region. By definition, their craters must lie below the pre-eruption surface so that bed rock is

exposed within the crater walls. Yet, from this point onward they can differ considerably. Variations seem to be dependant upon the physical characteristics present at the site prior to eruption. For instance, in the Eifel district hydraulically active fault zones underlying the valleys held the water necessary to initiate phreatomagmatic eruptions. On the other hand, the maars at Hopi Buttes, Arizona (Appendix 6, p. 21) formed from the explosive interaction between wet muds and magma. Topography was not a limiting factor concerning the formation of the two Ukinrek maars in Alaska (Appendix 6, p. 25). They formed along a 100 m high ridge of glacial till that happened to house an elevated aquifer. The Joya Honda maar in central Mexico (Appendix 6, p. 27) is a classic example of the relationship between aquifer dynamics and deposit stratigraphy. Lake Nyos maar in northwest Cameroon (Appendix 6, p. 29) seems to defy a phreatomagmatic origin, as its maar crater appears to have been excavated by magmatic eruptions.

At 80 million years old, maars of the Mata da Corda Formation, Minas Gerais, Brazil are the oldest and most denudated. Of the five areas mapped in detail, only the basal sections of the volcanic edifices are left intact, and they lack the deposits and features indicating that prolonged hydrovolcanic eruptions were responsible for their creation. The lack of definitive evidence for sustained phreatomagmatism suggests that brief phreatomagmatic and/or magmatic eruptions were responsible for crater formation. These were immediately followed by flood basalt type eruptions. Although sustained interaction between water and ascending magma does not appear to have occurred in the areas studied, there are hundreds of other volcanic centres in this field where suitable conditions may have existed. Thus, the presence of typical maar volcanoes in the Mata da Corda, and their associated underlying well-developed diatremes, cannot be ruled out.

3.4 MAARS OF THE MATA DA CORDA FORMATION

Mata da Corda maar-type volcanoes have few similarities with the classic examples discussed in Appendix 6. Other than the fact that bed rock is exposed within the walls of the craters, none of the other typical maar characteristics are present. For example, pyroclastic rocks make up only a very small part of deposit strata. Only at Agua Limpa (Appendix 3,

Fig. 7) and Fazenda Grotao (Appendix 2, Fig. 7) were primary pyroclastic deposits found. There they occur as bedded air-fall lapilli units capping successive subaerial flows, their interstratified occurrence suggesting that weakly explosive magmatic eruptions preceded each flow. Invariably, centres are dominated by intrusive rocks and flows, lacking pyroclastic fall deposits and surge or base surge deposits that typically construct the basal section of classical maar deposits. In fact, basal sections are dominated by intrusions and flows. Accretionary lapilli, armoured lapilli, vesiculated tuffs, lahars, slumping, and bomb impact sags, all indicative of wet eruptions, were not found (see Appendix 6, pp. 7-9). Neither was sideromelane, nor its hydrous alteration product palagonite.

Juvenile materials found within a prototypic maar are nonvesicular and quenched, evidence of rapid cooling presumably from interaction with water. On the other hand, juvenile material found within Mata da Corda type maars is highly vesicular and porphyritic. Such a state suggests that magmas may have erupted in a supersaturated condition with respect to volatile content, and that substantial amounts of free water did not have a significant influence on eruptions.

Alkaline magmas are CO_2 -rich, and as in the case of the Lake Nyos maar (Appendix 6, p. 29), rapid exsolution of CO_2 in a near surface environment can result in explosive crater forming magmatic eruptions. Kamafugite magmas are considered to be CO_2 -rich, therefore it is possible that, along with phreatomagmatism, magmatic eruptions may have played an important role in Mata da Corda volcanism.

The depth at which exsolution commences differs depending on the composition of volatile phase. CO_2 , being less soluble in silicate melts, begins to exsolve at much greater depths than either H_2O or SO_2 . Exsolution of CO_2 is believed to begin at pressures >300 bars and depths $>4\text{km}$, while most H_2O and SO_2 are exsolved below 20-30 bars ($\sim 120\text{m}$ to 10m depth), but it is not until about 6 to 10 bars that major outgassing and disruption of magma occurs (Gerlach, 1986; Mangan et al., 1993). Proussevitch and Sahagian (1996) modelled magma ascent rates between 0.1 and 100 m/s. Their results show that for typical rates of ascent, a few metres a second to tens of metres a second, melts could maintain a state of equilibrium between diminishing ambient pressure and volatile diffusion. They found that

only for extreme rates, on the order of 100 m/s, is there any significant oversaturation. Therefore, rapidly ascending alkaline magmas, similar to those of the Mata da Corda Formation (indicated by the abundance of ultramafic xenoliths present) could retain much of their volatile content until reaching the near surface environment.

Should the above conditions prevail, then rapidly ascending mafic ultrapotassic magmas would arrive at the surface in a supersaturated state. Volatile pressure would be high and would increase with time due to crystallization. The stage would then be set for “oversaturation degassing” where the rate of decompression to atmospheric pressures is so high that volatile degassing processes cannot keep pace with reductions in ambient pressure, resulting in extreme expansion of the near vent eruption column, and possibly, explosive eruptions similar to those attributed to the formation of Lake Nyos Maar in northwestern Cameroon (Appendix 6, p. 29). Initial magmatic eruptions would effectively degas the melt allowing for coherent flows to follow.

3.4.1 Ribeirao da Mata

The maar-type crater at Fazenda Ribeirao da Mata (Appendix 5, Fig. 7) represents the best preserved edifice of its type known to occur within the Mata da Corda. Present day erosional level reveals a basal section through the edifice with dimensions of 2.0 km NW-SE and 1.6 km NE-SW. Emplacement of pipes and dykes roughly parallels the regional 125° lineament, or the trend of the Alto Paranaiba Arch, as does the general outcrop pattern and the overall shape of the edifice.

Ribeirao da Mata stands approximately 125 m above the surrounding countryside (Fig. 19, 20, 21). A vertical difference of 110 m separates the volcanic/sandstone contact from the highest point within the crater. In cross-section the complex would have a relatively thin veneer of volcanic material on top of relatively flat lying Areado sandstone (Fig. 22). Volcanic rocks of kamaflagitic affinity have intruded bed rock consisting of Upper Proterozoic Bambui Group phyllites unconformably overlain by a thin unit of Upper Cretaceous Areado Formation sandstone. The resulting structure resembles the eroded remnants of an immature maar-type volcano, in which a combination of early explosive

events, and later crater subsidence and fluidization processes have excavated the crater. Subsequent intrusions and flows filled the crater, while down faulting of the rims of the crater, along radial and concentric faults, provided structures that later flows have ponded against, leading to a complex internal morphology.

Figure 19. Ribeirao da Mata contoured elevation map.

Figure 20. Contoured elevation map of Ribeirao da Mata overlain with simplified geology map. See Figure 7, Appendix 5 regarding detailed geology.

Ribeirao da Mata Looking North

Figure 21. Contoured surface plot of Ribeirao da Mata (looking northeast)

Figure 22. Ribeirao da Mata surface elevation map overlain with simplified geology map (looking northeast). See Figure 7, Appendix 5 regarding detailed geology.

The proximal facies at Ribeirao da Mata is dominated by several porphyritic intrusions spatially associated with porphyritic volcanic flows. Geochemical evidence supports their comagmatic affiliation (Chapter 4). Evidence of prolonged hydrovolcanic and/or magmatic eruptions was not observed, such as pyroclastic rocks, either air fall or surge deposits. Also absent at Ribeirao da Mata are indicators of phreatomagmatic eruptions or volcanic environments where water was in abundance, including accretionary lapilli, armoured lapilli, sideromelane, palagonite, ballistic impact sags, vesiculated tuff, lahars, base surge deposits and associated bed forms, lacustrine deposits, reworked pyroclastic deposits, and marine fossils.

Within most maars basal strata are deposits of heterolithic breccia, whose principal component is of pre-eruptive bed rock (Lorenz, 1985, 1986). This records the initial hydrovolcanic explosions responsible for the creation of a young crater. Intercalated

pyroclastic fall and surge deposits overlie the breccias denoting continued melt-water explosive interaction. Flows are not usually seen until the upper levels of deposit stratigraphy. Their presence signals the onset of dry, less energetic strombolian or hawaiian eruptions. At Ribeirao da Mata we are looking at the basal portion of the edifice, yet flows dominate. The observance of flows so early in the eruptive sequence suggests that water was not present in sufficient quantity to propagate a long-lived episode of phreatomagmatic activity. Therefore, soon after the initial crater forming eruptions, passive flood basalt-type eruptions of low viscosity alkaline lavas dominated, and quickly filled the crater.

At Ribeirao da Mata Upper Proterozoic basement rocks of the Bambui Group consist of phyllite unconformably overlain by relatively flat lying Lower Cretaceous Areado Formation quartz arenites. It is believed that explosive activities took place above the Bambui rocks, within the Areado Formation sandstones, as the sandstones show considerable signs of disruption, whereas the phyllites lack recognizable signs of disturbance due to the intrusive events. Furthermore, there is an overall lack of Bambui fragments in any of the breccia pipes or fluidized materials. Lorenz (1985, 1986) proposed that diatremes deepen with continued phreatomagmatic activity. Excavation process is revealed by the occurrence of clasts from stratigraphically lower units. If a diatreme were to exist beneath Ribeirao da Mata, one created and evolved due to prolonged episodes of phreatomagmatism, then fragments of Bambui rocks should be present. This is not so. Bambui fragments were not observed within any of the breccia pipes, or the silicified and fluidized sandstone breccia. The lack of Bambui deformation and contribution to the overlying deposits strongly suggests that explosive activities were centred within Areado Formation rocks, and that an underlying diatreme did not extend down into Bambui Group rocks.

Areado sandstone exhibits many different modes of occurrence. At a distance from vent areas (>200m) it is flat lying and undisturbed, essentially a planar bedded to massive sandstone void of texture except the occasional polygonal mud crack. Closer to the complex, outcrops show signs of physical disturbance, dips are steep, and large blocks within outcrop areas possess drastically different strikes and dips (denoting large breccia fragments or rotated blocks). Within about 75 m of known vents, outcrop areas of fluidized

sandstone are present. The best examples are found at the eastern edge of the complex, the south-central contact, and the southwestern border (Fig. 22). All localities are related to concentric faults, and fluidization, breccia pipe intrusion, and hydrothermal alteration are centred on these structures. Francis (1970) reports similar findings of basaltic dykes and tuffsite intruded along ring fractures in six Scottish tuff-pipes.

Fluidized outcrop areas contain large fragments of sandstone set in a fluidized sandstone matrix. Fluidization refers to a mixture of solid particles suspended in a turbulent gas. In some locations the matrix is intensely flow banded and wraps around larger fragments, clearly demonstrating its once fluid character. Rocks are silicified to the point that some outcrops resemble metaquartzites more than quartz arenites. These features make the Areado sandstone an important geological marker within the complex. Different styles of deformation and intensities of silicification provide useful information regarding proximity to the complex, and the location of major, internal, fault structures.

There is little doubt that fluidized sandstone breccias, and the maar-type crater were formed by explosive volcanism. Instead, the uncertainty centres on the type of eruption responsible. Four possibilities are explored: 1) explosive interaction between magma and abundant, replenishable, near surface water; 2) explosive interaction between magma and a non-replenishable smaller volume water source; 3) explosive interaction between magma and wet, unconsolidated, sand or mud; and 4) explosive magmatic eruptions in which magma/water interaction was either absent or played a minor role.

If fluidized sandstones were produced by appreciable phreatomagmatic eruptions centred within the sandstone units themselves, then one might expect to see a significant juvenile magmatic component. However, juvenile material within the fluidized sandstone is very rare. In fact, at Ribeirao da Mata it was not observed. This, coupled with the absence of wet eruption indicators, suggests that, at this location, the Areado was not a robust aquifer, thus negating the first possibility.

The third scenario speculates that unconsolidated sands may have contained interstitial water, similar to the Bidahochi Formation muds at Hopi Buttes (Appendix 6, p. 21). Therefore, initial crater forming eruptions would have resulted from the interaction of

rapidly rising magma and near surface, unconsolidated wet sands. According to White's (1991) model for Hopi Buttes, initial, none explosive, interaction with rising magma and wet muds occurred at shallow depths. A peperite-like mixture of melt and wet mud resulted in response to the addition of magma from below. "When the top of the growing peperitic mass closely approached ground level, its top explosively broke through to the surface. At this point rarefaction waves passed downward through the peperitic zone, and explosive expansion behind the shock waves ejected the remainder of the peperitized zone to form a dense, mud-rich pyroclastic flow" (White, 1991, pp.247-248). He describes basal maar units consisting of mud-rich pyroclastic surge and flow deposits with prominent lenses of vesicular juvenile lapilli, accretionary lapilli, and cauliflower bombs. None of these features were observed at Ribeirao da Mata. There is no evidence of a peperitic mixture of magma and sand or of sandstone-rich pyroclastic deposits of any description. Thus, it appears that the Areado sandstone was lithified prior to eruption activities, and if phreatomagmatic eruptions did occur, they were short-lived and involved magma interaction with a weak (poorly charged) aquifer.

The fourth possibility involves processes similar to those described for the formation of Lake Nyos maar (Appendix 6, p. 29). Perhaps at Ribeirao da Mata the first eruptions were magmatic. Rapidly ascending magma could not maintain equilibrium with falling ambient pressure and volatile diffusion; thus, volatile pressure would steadily build. Once close to surface, rapid degassing occurred resulting in extreme expansion of the near vent eruption column, and possibly, explosive eruptions. The Areado may have acted like a cap rock, sealing pre-Areado vent systems in the underlying Bambui, thus allowing underlying volatile pressure to build. Its competency was reenforced due to pre-eruptive silicification. When volatile pressure exceeded the confinement capabilities of the cap rock, it ruptured explosively, producing a basal explosion breccia of fluidized sandstone. Magmatic eruptions could also account for the absence of Bambui, juvenile, and pyroclastic materials, the lack of evidence for phreatomagmatism, the presence of flows within the basal portion of the stratigraphy, and the large outcrop areas of fluidized sandstone lacking a juvenile component. Wright and Bowes (1967) describe a similar process for the formation of

explosion breccias that appear comparable to the fluidized Areado breccia at Ribeirao da Mata: “Explosive activity takes place due to increases in gas pressure related to the sudden release of gas when gas-charged magma moves into zones of fractured rock below structural traps of impervious rock units. Explosion breccias form as a result of the shattering of the rocks forming the traps, the brecciation usually being the result of a number of successive explosions (gas rushes). With the breaching of the trap, gases escape and the column of already brecciated rock may be carried up with the gas streams to form intrusive breccia. Fluidization, which results in the rounding of pebbles and the erosion of the pipe, is the operative stage”.

When the cap rock ruptured, streams of fluidized sand flowed around larger fractured blocks. Evidence of this chaotic activity is preserved within a large outcrop area at the eastern edge of the map area (Fig. 22). There, huge blocks of silicified deformed sandstone are set in flow banded fluidized sand (Plate 3). Thin section analyses reveals that the fluidized material was injected in a relatively cool state. There are no signs of thermal metamorphism or melting of the primary grains. Such cool emplacement conditions are consistent with a CO₂-rich gas charged medium (Lockwood and Rubin, 1989). In summary, the evidence suggests that initial, short-lived, phreatomagmatic and/or magmatic eruptions were responsible for excavating the maar-type crater and producing fluidized sandstone breccias.

Within the west-central part of Ribeirao da Mata (Fig. 22) lies a circular, bowl shaped, feature (cut by the western most concentric fault). The western half consists of inward dipping blocks (several metres in size) of Areado sandstone (Plate 4). Immediately northwest of this is a long, narrow outcrop of kamaugite intrusion (Fig. 22). It appears on the cliff face below the circular structure. This semicircular arrangement of inward dipping blocks resembles a collapse feature in which overlying Areado rock caved in due to the evacuation of underlying magma. Such a situation would only exist if the Areado was at its original stratigraphic position. Otherwise, relatively flat lying bedrock would have to be transported, by some unknown means, to its current elevated position.

There is also the possibility that areas of concentrated, silicified sandstone blocks have

slumped into the maar-type crater along concentric or ring faults. As such, they would be evidence of pre-eruptive country rock exposed within the crater wall. However, all three large areas of silicified and fluidized sandstone, covering the length of the volcanic edifice, lie between 930 m to 940 m above sea level. Should such conformity of movement along separate fault planes be expected? Or perhaps this not a coincidence, but an artifact of a pre-eruptive paleosurface. If this is the case, then there must not have been much vertical movement along the faults.

Concentric faults are readily recognized in the field due to their spatial association with areas of intensely silicified, fluidized and deformed blocks of Areado sandstone. In addition, they define sharp structural contacts between flows and regions of fluidized Areado, where flows appear to terminate abruptly. Intrusive activity has also occurred along the faults. However, they cannot be true ring faults in the classic sense as applied to maar volcanoes, as those faults developed as a direct result of continued phreatomagmatic activities expanding the underlying diatreme causing instabilities in the overlying strata, and ultimately collapse of bed rock and rim deposits into the crater and diatreme. Since it is unlikely that a diatreme exists beneath Ribeirao da Mata, concentric faults may owe their origin to other means. Perhaps they are products of crater subsidence brought about by the eruption of large amounts of material from an relatively shallow, underlying magma chamber. A similar mechanism was proposed by Francis (1970) to explain how the Scottish tuff-pipes came to resemble maars. The sheer number of vents present at Ribeirao da Mata leaves little doubt that a considerable amount of material was erupted. Evidence of limited subsidence regarding the small circular collapse feature was previously discussed. Similarly, mapping at Quintinos (Appendix 1, Fig. 7) revealed that the local country rock, immediately surrounding the pipe, dip inward towards the central edifice. In effect, forming a small, localized, basinal depression around the vent.

The complex at Ribeirao da Mata exhibits an asymmetrical symmetry, in which most of the intrusions and outcrops of flow material lie within the western section (Fig. 22), and the concentric faults in the eastern section. These geological differences reflect the geology of those parts of the maar complex. For instance, the abundant intrusions and flows marks the

central part of the complex, where most of the volcanic activity originated from. It is also apparent, from the pipe distribution that there was not one main vent, but a coalescing of several smaller pipes. To the east, away from the main centre, but still within the crater, the incidence of pipes and flows diminishes, and the number of fault structures increases.

Plate 3. Large outcrop area of fluidized Areado sandstone.

Plate 4. Small localized collapse feature. Note the inward dipping blocks of silicified sandstone. (See text for explanation)

3.4.2 Summary

The maar-type crater at Ribeirao da Mata is believed to be characteristic of most volcanic centres within the Mata da Corda. Thus, this flood basalt-type province is unique in that eruptive centres are marked by maar-type craters. Voluminous eruptions of alkaline lavas emanated from perhaps thousands of these centres, collectively forming the, now eroded, Mata da Corda lava plain.

At Ribeirao da Mata, evidence is completely lacking to suggest that water was present in sufficient quantity to propagate long-lived hydrovolcanic eruptions. Instead, it is believed that brief phreatomagmatic and/or magmatic eruptions were responsible for the formation of the maar-type crater. These were immediately followed by voluminous flood basalt-type eruptions, emanating from several small vents, that quickly filled the crater (thus preserving the lower crater facies rocks) and generated laterally extensive alkaline flows. There is also a lack of physical evidence to indicate the existence of a well-developed maar crater and underlying diatreme. Initial eruptions, being centred within the sandstones excavated a crater below the pre-eruptive surface, and a maar-type crater was formed. However, it failed to develop further, and was quickly filled with flows. Continued maar forming eruptions were arrested either because the local aquifer was unable to recharge, thus explosive interaction of magma and water could not take place, the aquifer was effectively sealed by the enormous outpouring of lava, or once the cap rock was explosively breached, conditions were no longer suitable for violent magmatic eruptions.

CHAPTER 4
LITHOGEOCHEMISTRY AND MINERALOGY OF
MATA DA CORDA FORMATION ROCKS:
A COMPARATIVE STUDY

4.1 INTRODUCTION

A comparison of the chemical composition, mineralogy (Table 3), and physical volcanology (Table 4), of mafic ultrapotassic rocks from around the world with those of the Mata da Corda Formation in Brazil, is presented. Few topics in igneous petrology have attracted as much attention, yet continue to baffle geoscientists, as has our understanding and genesis of these exotic rocks. They are the rarest of all igneous rock types, yet are widely distributed, occurring in several different tectonic environments, including continental rift valley, continental intraplate, and subduction zones.

Volcanic provinces referred to in this chapter include the Mata da Corda Formation, Brazil; the Toro-Ankole region, southwest Uganda (Appendix 7, p. 13); Leucite Hills, Wyoming (Appendix 7, p. 25); the West Kimberly Region, western Australia (Appendix 7, p. 19); and the Roman Volcanic Province, Italy (Appendix 7, p. 30). The last four locations are considered type localities, and as such, have attracted considerable attention, while the Mata da Corda Formation has been the least studied. Very few papers have been published on this area (see Gibson et al., 1995, and references therein), which is surprising since it is perhaps the largest of all the regions, contains the greatest number of outcrop exposures, and the most intrusive bodies.

Despite their worldwide distribution, there exist strong chemical similarities among the lithologies of the volcanic provinces, possibly an indication of similar genetic processes. In particular, they possess both the chemical characteristics of mafic rocks (high Mg, Cr, and Ni; low Si), and features typical of more felsic rocks (elevated incompatible element contents and K). This compositional paradox has contributed much to the debate concerning their classification and origin. Their abundance in alkalis, combined with their silica deficiency, has lead to the generation of several unusual minerals. This extraordinary mineralogical diversity has attracted the interests of petrologist and mineralogist, and ultimately has lead to a cluttered petrological nomenclature.

Mafic ultrapotassic rocks are defined as having $K_2O > 3$ wt.%, $MgO > 3.0$ wt.%, and $K_2O/Na_2O > 2$ (Foley et al., 1987; Table 2). Some other characteristic compositional traits are their high to extreme enrichment in incompatible elements, especially the large ion

lithophile elements (LILE: K, Rb, Cs, Ba, Th, U), light rare-earth elements (LREE: La, Ce, Pr, and Nd), and volatile species (H₂O, CO₂, F, Cl, SO₂). They also possess an extremely wide range of Sr, Nd, and Pb isotopic characteristics, requiring complex parent-daughter fractionation histories (Foley et al., 1987). In addition, they tend to have high Mg-numbers [Mg/(Mg+Fe)], and are enriched in some high field strength elements (Ni and Cr).

Table 2. Summary table of Group I, II & III mafic ultrapotassic rocks (Foley et al., 1987).

	I Lamproites	II Kamafugites	III Plagioleucitites
Major Elements	Low Al ₂ O ₃ , CaO, Na ₂ O High K ₂ O/Al ₂ O ₃ (>0.7) Variable TiO ₂ Extremely high K/Na	Low Al ₂ O ₃ , Na ₂ O High CaO Low SiO ₂ (<45 wt.%) Variable K ₂ O/Al ₂ O ₃	High Al ₂ O ₃ Low TiO ₂ "low" K ₂ O/Al ₂ O ₃
Trace Elements	Most extreme incompatible elements and LREE enrichments. Variable Nb, Ta, Zr Often negative Sr anomaly.	Incompatible elements relatively anomaly-free. High Nb, Ta, Zr No negative Sr anomaly	Negative anomalies for Ti, Nb, Ta, Zr, Ba
Volatiles	High H ₂ O, Low CO ₂ , Highest F (0.2 - 0.6 wt.%)	High CO ₂ , high H ₂ O High or moderate F	Moderate H ₂ O Low to moderate CO ₂ Moderate F
Tectonic setting	Continental mild extension	Continental rift	Collisional setting (subduction)
Ultramafic xenoliths	Depleted types (dunite, harzburgite) > fertile types (spinel lherzolite)	Pyroxenite, mica bearing xenoliths > lherzolite, harzburgite	Dominantly pyroxenite, including mica-bearing types
Primitive magma character	High K/Al Low Ca, Al, and Na Extremely high Mg-number (often 70-85) Variable SiO ₂ (~43-53 wt.%) ? reduced source	Low SiO ₂ High Ca/Al ? oxidized source	High Al ₂ O ₃ No extreme Mg-number (≤70) ? oxidized

Four main groups are recognized within the mafic ultrapotassic umbrella: Group I (lamproites), Group II (kamafugites), Group III (plagioleucitites), and those of transitional composition between the groups (in particular groups I and III) Group IV. The first three represent end-member compositions, while the fourth is a transitional group. In general tectonic terms, Group I rocks occur in either stable continental areas or in orogenic areas. Group II rocks are found in rift environments, while Group III occurs exclusively in active orogenic zones. Because of the extreme mineralogical diversity characteristic of potassic and ultrapotassic rocks, this chemical-based system, recognizing the transitional nature of the rocks between end member compositions, has been adopted; petrographic and mineralogical classifications only add to an already cluttered and confusing nomenclature. This idea of a chemical continuum among ultrapotassic rocks is consistent with observations regarding the Mata da Corda Formation rocks.

Mata da Corda Formation rocks possess some mineralogical characteristics not shared by any of the other volcanic provinces (Table 3); in particular, are the greater abundances of diopside, perovskite, and zeolites. In addition, perovskites from ultramafic xenoliths typically form euhedral crystals, thus their morphology and mode of occurrence suggests a mantle origin. Perovskite abundance is manifested in the whole rock incompatible trace element concentrations by elevated Nb concentrations, an element that readily substitutes for Ti into the perovskite structure. Accordingly, the niobium content of Mata da Corda rocks is much greater than those reported for any of the other areas referred to earlier, indicating that the Cretaceous mantle that fed Mata da Corda volcanism was different from any of the other ultrapotassic provinces with respect to this element. These mineralogical and compositional characteristics make the Mata da Corda Formation rocks truly unique, and the larger Alto Paranaíba Igneous Province, to which they belong, atypical.

The Alto Paranaíba Igneous Province is the oldest (~85 Ma) of the ultrapotassic provinces, whereas the West Kimberley province is next closest in age at 17-24 Ma. There are many physical volcanological similarities between these two regions (Table 4), more so than between any of the other volcanic provinces. No doubt, much of that can be attributed to similar erosional levels. In both settings the volcanic fields are sufficiently denuded such

that most large volcanic edifices no longer exist. Instead, the dominant features are intrusive pipes, various types of volcanic breccias, flows and rare pyroclastic rocks. Flows and pyroclastics are less resistant to weathering, so with time they are effectively removed unless capped by subsequent extrusive activity or are hydrothermally altered (e.g. silicification). The two regions also share similar tectonic environments, where intrusions have bored through a mobile belt adjacent to an Archean craton. Nevertheless, given all their similarities, they also have some important differences. For instance, their volcanic rocks bear little resemblance in terms of their geochemistry and mineralogical composition. There are also some important petrological differences. Although kimberlites, lamproites, and carbonatites occur within both provinces, kamaugites are found only within the Mata da Corda Formation. Furthermore, ultramafic xenoliths are relatively rare within the West Kimberley district but incredibly abundant in the Mata da Corda.

The other volcanic provinces are younger (3.1 Ma to recent), and this is reflected in their state of preservation. Large, well-preserved volcanic centres are common, and in some areas active volcanism is ongoing (Roman Volcanic Province: Beccaluva et al., 1991; and southwest Uganda: Barker and Nixon, 1989). Lava flows are particularly abundant at Leucite Hills (Carmichael, 1967), and within the Roman Province where they have associated volcanic centres. On the other hand, pyroclastic rocks are more prevalent within the volcanic fields of southwest Uganda. The following comparative generalizations between provinces are presented:

- 1) In terms of basic rock forming mineralogy, Mata da Corda rocks are most like the kamaugites from southwest Uganda, but regarding volcanic structures they most resemble the volcanic fields of West Kimberley, Australia; 2) The Roman Volcanic Province exhibits the greatest variety of rock types; only the Alto Paranaíba Province in Brazil shows a similar diversity, whereas their volcanic features are comparable to the Toro-Ankole region, but only in their gross morphology, not in their rock type compositions or volcanic products; 3) The mineralogy and petrology of Leucite Hills rocks closely matches those of West Kimberley, Australia, but in terms of their volcanic structures (i.e., abundance of lava flows) they are similar to the Roman Province.

There are many similarities and differences between the five mafic ultrapotassic provinces described in Appendix 7 and in this chapter, but in many ways each is unique. However, it can be said with confidence that the Mata da Corda Formation rocks are distinctive in terms of their mineralogy and geochemistry.

The earliest theories on the origin of potassium-rich magmas suggested that potassic magmas were generated by the assimilation of carbonate rocks by basalts (Gibson et al., 1995, and references therein). Today the most popular theories involve various processes of mantle metasomatism; the overall consensus being that ultrapotassic magmas are mantle-derived.

Table 3. Ultrapotassic Volcanic Province Mineralogy Compilation Table.

ULTRAPOTASSIC PROVINCES																					
	BRAZIL																				
	olivine	leucite	phlogopite	augite	diopside	kalsilite	melilitre	glass	amphibole	plagioclase	sanidine	apatite	perovskite	priderite	wadeite	ti-magnetite	chromite	ilmenite	rutile	zeolite	hyalophane
Fazenda Bananal	R					R						A				A	R	A	R		A
Ribeirao da Mata	A	R										A			R	A	R	A	R		A
Agua Limpa	R						A					A				A	R		R		R
Fazenda Grotao	A			R					R			A			R	A	R	A	R		R
Quintinos Pipe	A											A				A	R	A	R		R
other areas	A	R				R		R				A				A	R	A	R		R
WEST KIMBERELY, AUSTRALIA																					
wollgildite												A		A	A						
fitzroyite	A								A					A	A				A		
cederite	R																		R		
maimillite	R		R									A	A	A	A		A				
olivine lamproite									A			A	A	A	A		A		R		
TORO-ANKOLE, UGANDA																					
ugandite																					
mafurite																					
katungite																					
LEUCITE HILLS, WYOMING																					
wyomingite												A									
orendite		A					R														
madupite		A					A					A									
ROMAN PROVINCE, ITALY																					
lamproite									A			A						A	A		
kamafugite		A											A								
KS	A	A										A				A					
HKS	A											A				A					
OTHERS																					
Gaussberg, Antarctica			A									A									
Jumillite, Spain		R		A														A			

Rock Forming Minerals				
				dominant
				abundant
				common
	A			accessory
	R			rare

Table 4. Compilation of Ultrapotassic Volcanic Province Characteristics.

ULTRAPOTASSIC PROVINCES	LITHOLOGIES	AGE	INTRUSIVE/EXTRUSIVE FORMS	VOLCANIC PRODUCTS	STRUCTURE	COUNTRY ROCK	ALTERATION	TECTONIC SETTING
BRAZIL <i>MATA DA CORDA FORMATION</i> (Gibson, 1995, Gibson et al., 1995, Sgarbi and Valença, 1993, Byron, 1995, 1996a, 1996b, 1997a, 1997b)	kimberlites, lamproites, kamafugites, carbonatites, melilitolites	~85 Ma	maar volcanoes and tuft cones, erosional necks, plugs, dykes, blind pipes, diatremes, sills, flows, minor pyroclastics, intrusive pipes, breccia pipes	intrusions, porphyritic flows, pyroclastics, tufts, lapilli tufts, volcanic breccias, diatreme breccias, fluidized sandstone country rock, epiclastics, abundant ultramafic xenoliths, porphyritic flows, porphyritic intrusions, siles, country rock (tuffisite), tuffisitic breccia	volcanism related to regional structural lineament - Alto Paranaíba Arc concentric faults, radial faults	Areado sandstone, Bambuí phyllite	silicification & carbonatization	continental rift, intraplate hotspot activity??
WEST KIMBERLEY, AUSTRALIA (Jaques et al., 1984, Atkinson et al., 1984, Prider, 1982, Prider and Cole, 1942, Wade and Prider, 1940)	Group I (olivine lamproite, leucite lamproites)	17-24 Ma	intrusive pipes, flows, plugs, diatremes, sills, tufts, rare dykes, blind pipes	intrusives are far more common than flows, abundant pyroclastics, tufts, lapilli tuft, tuft-breccia, xeno-tuft-breccia, autolithic breccia, tuffisite, tuffisitic breccia, rare ultramafic xenoliths, pyroclastic flow and surge deposits	emplacement controlled by preexisting west-north-westerly trending structures	sedimentary and metamorphic rocks, limestone, sandstone, mudstone	silicification, chloritization	lamproite intrusion into a mobile belt adjacent to a craton, hotspot activity
TORO-ANKOLE, UGANDA (Holmes and Harwood, 1932, Holmes, 1942, Holmes, 1950, Vollmer and Norry, 1983, Sahama, 1962, Barker and Nixon, 1989)	Group II (kamafugites)	0-5 Ma	tuft cones, explosion craters (maars?), rare flows	mostly pyroclastic, tufts, lapilli tufts, agglomerates, volcanic breccias, bombs and blocks, flows are very rare, abundant ultramafic xenoliths	emplacement related to East African rift system	argillites, phyllites, quartzites		continental rift, intraplate hotspot activity??
LEUCITE HILLS, WYOMING (Carmichael, 1967, Kuehner et al., 1981, Mitchell and Steele, 1992, Vollmer et al., 1984)	Group I (lamproites)	1-3.1 Ma	lava flows, dykes, plugs, cinder or pumice cones, rare pyroclastics	vesicular lavas make up bulk of volcanic materials, lesser amounts of scoria, autolithic intrusive breccia, lapilli tuft, tuft-breccia, agglomerate, country rock and ultramafic xenoliths	volcanic field occurs along northeast side of Laramide basement uplift, emplacement influenced by local features parallel to older Laramide structures	sandstone, siltstone, coal, shale, mudstone		continental, intraplate hotspot activity??, postorogenic
ROMAN PROVINCE, ITALY (Beccaluva et al., 1991, Peccerillo et al., 1988, Savelli, 1967)	Group I, II, III	<0.9 Ma	well preserved volcanic edifices, lava flows, tephra cones, cinder cones, pyroclastics	abundant flows, pyroclastics, ignimbrites, rare ultramafic xenoliths		carbonates		collisional, underlain by subducted lithosphere

4.2 MAFIC ULTRAPOTASSIC ROCK GEOCHEMISTRY AND MINERALOGY

4.2.1 Chemical Composition and Comparisons of Mafic Ultrapotassic Rocks

The extreme compositional variability of potassic rocks has made it difficult for geoscientists to reach any consensus on their classification. However, based on some of the proposed classification schemes (Sahama, 1974; Barton, 1979; Mitchell, 1985; Foley et al., 1987; and Mitchell and Bergman, 1991), four main groups of potassic and ultrapotassic rocks are recognized (Peccerillo, 1992): shoshonites, Roman-type ultrapotassic rocks, lamproites, and kamafugites. Except for shoshonites, these groups correspond to Foley et al. (1987) Group I, Group II, and Group III ultrapotassic rock types. Shoshonites are not part of this study as they do not fit the chemical criteria for ultrapotassic recognition ($K_2O > 3.0$ wt.%, $MgO > 3.0$ wt.%, and $K_2O/Na_2O > 2$). They are the least enriched in potassium and have K_2O/Na_2O around unity. However, a couple of samples have been included on some geochemical diagrams to permit comparisons.

In this section, the lithogeochemical characteristics of five ultrapotassic type localities are summarized, categorized, and compared according to the classification scheme of Foley et al. (1987), using various whole rock, trace element, and stable isotope diagrams. Detailed descriptions of each of the four areas are given in Appendix 7 (southwest Uganda, p. 13; West Kimberley, Australia, p. 19; Leucite Hills, Wyoming, p. 25; Roman Volcanic Province, Italy, p. 30), while special emphasis is placed on the Mata da Corda Formation, as it is the least-known of all the ultrapotassic igneous provinces. It is demonstrated that each of the four well-known volcanic provinces consistently plot within their own geochemically designated fields on various lithogeochemical discrimination diagrams, and that the Mata da Corda samples predominantly cluster within the kamafugite fields, and to a lesser extent, within some lamproites fields.

Comparative data presented on lithogeochemical diagrams has been compiled from several published sources: East African Rift - Holmes (1950), Sahama (1962), Peccerillo (1992); West Kimberly, Australia - Jacques et al. (1984), Peccerillo (1992); Leucite Hills, Wyoming - Carmichael (1967), Peccerillo et al. (1988), Peccerillo (1992); Roman Volcanic

Province, Italy - Peccerillo et al. (1988), Peccerillo (1992), Conticelli and Peccerillo (1992).

4.2.1.1 Discrimination Diagrams

Figures 23 to 30 are modified after Foley et al. 1987, data from five mafic ultrapotassic provinces are plotted on major oxide scatter diagrams and categorized as either Group I, II or III.

Figure 23 illustrates the ultrapotassic character of the four volcanic province rocks. Group I, II, and III rock type fields are outlined on this Na_2O vs K_2O diagram. All melilitite samples from Uganda fall outside the ultrapotassic boundary, and except for being enriched in Na_2O , they are silica undersaturated rocks that closely resemble Group II rocks. According to the classification scheme of Foley et al. (1987), lamproite samples from Leucite Hills, West Kimberley, Roman Province, and Gaussberg (Antarctica) fall within the Group I field. However, Jumillite lamproites of southeastern Spain exhibit K_2O contents more in line with Group II rocks. Mata da Corda Formation samples are presented in Figure 24. The ultrapotassic character of these rocks is clearly shown, as is their Group II (kamafugitic) affinity.

Kamafugites from East Africa and Italy cluster within the Group II field on an Al_2O_3 vs CaO plot (Fig. 25). Madupites and lamproites from Leucite Hills fall within both Group I and II, while West Kimberley lamproites lie exclusively within Group I. Most of the Roman Province K-rich and transitional rocks concentrate within Group III. Whereas, the transitional Group I-II nature of the Jumillite lamproites is evident. This transitional theme is even stronger within Mata da Corda rocks, as samples in Figure 26 show a continuum in CaO and Al_2O_3 contents between the different igneous rocks of the volcanic edifices. Mata da Corda Formation intrusions are predominantly Group II, while the flows are transitional between Groups I and II, with the majority plotting within the Group I field. Element mobility due to intense tropical weathering (and/or hydrothermal alteration) can also influence the positioning of samples on these types of diagrams, and one must be especially cautious with the alkali metals. The MPR plot technique for judging element mobility is

reviewed in Appendix 1 (Figs. 15, 16) and the results summarized (Appendix 1, Table 3), revealing that element mobility is greatest in the deeply weathered kamafugite flows (in particular CaO and MgO). It is believed that CaO mobility in the weathered kamafugite flows, best explains their spread of data depicted in Figure 26.

Figure 23. Na₂O vs. K₂O plot of Mata da Corda samples and other mafic ultrapotassic provinces. I = Group I lamproites; II = Group II kamafugites; III = Group III plagioclinites. The dashed line refers to K₂O/Na₂O = 2, the lower limit for ultrapotassic rocks as defined by Foley et al. (1987). (modified after Foley, 1992)

Figure 24. Na_2O vs. K_2O plot of Mata da Corda samples and other mafic ultrapotassic provinces. I = Group I lamproites; II = Group II kamafugites; III = Group III plagioclucitites. The dashed line refers to $\text{K}_2\text{O}/\text{Na}_2\text{O} = 2$, the lower limit for ultrapotassic rocks as defined by Foley et al. (1987). (modified after Foley, 1992)

Figure 25. Ultrapotassic volcanic province rock CaO vs. Al_2O_3 diagram of Group I, II, III fields (after Foley, 1992).

Figure 26. Mata da Corda Formation CaO vs. Al_2O_3 plot. Shaded areas represent the Group II and Group I lamproite fields of Foley, 1992.

Perhaps the most interesting feature of Figure 26 is that samples from different Mata da Corda volcanos (separated by distances in excess of 80 km) display such a good correlation, perhaps an indication that they share a common source. In the plots to follow, this is a recurring theme.

As mentioned previously, SiO_2 contents vary considerably within, and between, groups. This is illustrated in Figure 27, a SiO_2 vs $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ plot. As shown in the preceding plots, each volcanic region appears to plot consistently within a certain field. Although some spread in data does occur, generally there is good agreement between diagrams. Mata da Corda rock samples are plotted on Figure 28, illustrating their silica undersaturated kamafugitic character as compared to that of the other volcanic provinces (Fig. 27). Also of note is the clustering of kamafugite flow samples, believed to be a result of SiO_2 and K_2O depletions due to intense weathering.

Figures 29 and 30 categorize samples based on their SiO_2 and K_2O contents. Although Groups I and III cannot be distinguished on this diagram (Fig. 29), there is good separation of Group II rocks. Mata da Corda samples fall predominantly within Group II (Fig. 30), further demonstrating their major oxide kamafugitic affinity.

Figures 31 and 32 are SiO_2 vs. $\text{Na}_2\text{O}+\text{K}_2\text{O}$ rock type discrimination diagrams. Superimposed over the two plots are lamproite fields from West Kimberly, Australia; Leucite Hills, Wyoming; and the kamafugite field. Data compiled from published sources are plotted on Figure 31, further demonstrating the K_2O and Na_2O rich nature of these rocks. Mata da Corda Formation samples (Fig. 32) fall predominantly within, and below, the kamafugite field. The intense SiO_2 -poor weathered flows are in striking contrast to the more typical kamafugitic concentrations of the intrusions and xenoliths.

CaO and SiO_2 contents of volcanic province rocks are depicted on Figures 33 and 34. Of note is the good separation of Group II rocks based on their high CaO contents. Figure 34 compares CaO and SiO_2 contents of Mata da Corda samples to established kamafugite and lamproite fields. As a group, only the Mata da Corda weathered flows plot outside of the kamafugite field, as they are depleted in both CaO and SiO_2 .

Figure 27. Ultrapotassic volcanic province rock SiO_2 vs. $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ diagram of Group I, II, III fields (after Foley, 1992).

Figure 28. SiO_2 vs. $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ plot of Mata da Corda rocks. The shaded area represents the Group II kamafugite field of Foley, 1992.

Figure 29. Ultrapotassic volcanic rock SiO_2 vs. K_2O plot of Group I, II, III rocks. Rock type fields are after Foley, 1992.

Figure 30. SiO_2 vs. K_2O plot of Mata da Corda Formation rocks. Rock type fields are after Foley, 1992.

Figure 31. SiO_2 vs $\text{Na}_2\text{O} + \text{K}_2\text{O}$ diagram comparing ultrapotassic volcanic province rocks to established rock type composition fields (modified after Mitchell and Bergman, 1991).

Figure 32. SiO_2 vs $\text{Na}_2\text{O} + \text{K}_2\text{O}$ plot comparing Mata da Corda area rocks to established rock type compositional fields. (modified after Mitchell and Bergman, 1991)

Figure 33. SiO₂ vs. CaO plot of ultrapotassic volcanic province rocks.

Figure 34. SiO₂ vs. CaO plot of Mata da Corda samples. Note the SiO₂ and CaO depleted weathered flows.

Lamproites, kimberlites, and kamafugites contain the highest concentrations of compatible trace elements compared with other types of ultrapotassic rocks. Their Ni and Cr contents are often greater than 1000 ppm. Yet, Sc generally does not exceed 20-25 ppm. Figure 35 is a log Cr vs log Ni plot outlining kimberlite, lamproite, and kamafugite fields. Included on the diagram are the samples from various ultrapotassic volcanic provinces. Mata da Corda Formation samples are presented on Figure 36, showing that the majority fall within the lamproite fields, similar to values reported for West Kimberley lamproites, and phlogopite lamproites (Mitchell and Bergman, 1991, p.318), while only a few possess low concentrations, similar to the Roman Province kamafugites.

As stated previously, ultrapotassic rocks are characterized by high to extreme enrichment in incompatible elements, especially the large ion lithophile elements (LILE). A Ba vs Sr plot (Fig. 37) illustrates the higher barium values of lamproite provinces (especially the West Kimberley lamproites) compared with the other ultrapotassic provinces. The average Ba value of Mata da Corda rocks is 6,984 ppm (range = 808 to 45,817 ppm). These values overlap with reported values for lamproites (Fig. 38), and are much greater than those reported for kimberlites and kamafugites (Mitchell, 1986, p.290).

Roman volcanic province rocks are depleted in high field-strength elements (HFSE). According to Pearce (1982) the deficiency is typical of subduction-related rocks. Zr and Nb contents are presented in Figures 39 and 40. The distinctive lower Nb and Zr contents of Roman province rocks are clearly shown in Figure 39. On the other hand, Mata da Corda rocks have Zr values similar to lamproites, which typically exceed 1000 ppm, but greater than kimberlites (mean of 184 ppm), while their average Nb values are much greater than either of the other two rock types (Fig. 40). Niobium is concentrated within the perovskite structure. Since this mineral is very common within all the volcanic rocks of the Mata da Corda volcanoes, niobium whole rock values can be accounted for. Extreme niobium enrichment is a feature unique to Mata da Corda rocks, as nothing comparable has been observed in any of the other ultrapotassic volcanic provinces.

Figure 35. Cr vs. Ni plot of ultrapotassic volcanic province rocks (modified after Mitchell and Bergman, 1991).

Figure 36. Cr vs. Ni plot of Mata da Corda rocks. Samples of the Tres Ranchos kimberlite (Brazil, see Fig. 2), and the Monestary kimberlite (South Africa) were analysed and included on the diagram for comparison. Note the higher Cr and Ni contents of the intensely weathered kamaufugite flows, perhaps a supergene effect. (Modified after Mitchell and Bergman, 1991).

Figure 37. Ba vs. Sr plot of ultrapotassic volcanic province rocks.

Figure 38. Ba vs. Sr plot of study area rocks.

Figure 39. Zr vs. Nb plot of ultrapotassic volcanic province rocks, and various kimberlite, lamproite, and kamafugite composition fields.

Figure 40. Zr vs. Nb plot of Mata da Corda Formation volcanic rocks, and various kimberlite, lamproite, and kamafugite composition fields. Anomalous samples M-162 & M-170 are from Ribeirao da Mata (Appendix 5), and FB-46 from Fazenda Bananal (Appendix 4).

In comparison to other mafic ultrapotassic volcanic provinces, most Mata da Corda volcanic rocks typically exhibit kamafugite compositions (with the exception of Ba concentrations, which are typical of lamproites).

4.2.1.2 Isotopes

In recent years the number of isotopic studies on ultrapotassic rocks has steadily increased, in part because of their unusual isotopic characteristics. They typically possess extremely wide ranges in lead (Pb), neodymium (Nd), and strontium (Sr) isotopic characteristics, a feature attributed to long and complex parent-daughter (Rb/Sr, Sm/Nd, and U-Th/Pb) fractionation histories (Nelsen, 1992). Of the three main groups, Group I rocks (lamproites) have attracted the most attention, concerning their isotopic compositions (Nelson et al., 1986). Isotopic studies on Group II and Group III rocks are rare (especially Pb and Nd data). Only $^{87}\text{Sr}/^{86}\text{Sr}$ data are abundant enough to allow reasonable comparisons to be made between groups. For this report investigations are restricted to initial strontium isotopic ratios.

Group I rocks show considerable variation in $^{87}\text{Sr}/^{86}\text{Sr}$ (Fig. 39). These rocks occur within stable Archean or Proterozoic continental (or anorogenic) settings. Nelson (1992) believes the variability in isotopic character of anorogenic potassic magmas can be explained by contamination of the mantle source by subducted lithosphere. Crustal materials would contribute the high K and incompatible element contents, whereas the enriched Mg#, Ni, Cr, Co, and Sc contents are indicative of their mantle source. To explain their extremely wide range of Pb, Nd, and Sr isotopic characteristics, Nelsen (1992) suggests that the contaminated mantle source has had a long fractionation history within the subcontinental lithosphere (perhaps greater than 1 Ga). This long term storage period would explain the fact that anorogenic potassic magmatism is not associated with recent subduction processes. Hotspot magma generation processes eventually produce melts that upon eruption, form the intraplate continental ultrapotassic provinces designated as Group I.

Most Group II rocks are believed to be associated with rifting in an intraplate continental setting. Examples from Toro-Ankole, Batbjerg, and the Mata da Corda have low $^{87}\text{Sr}/^{86}\text{Sr}$

ratios, perhaps an indication that subduction related contamination was not a factor. In particular, Mata da Corda rocks possess initial $^{87}\text{Sr}/^{86}\text{Sr}$ from 0.7045 to 0.7058 (Gibson *et al.*, 1995), values in line with the present-day mantle value of 0.704 ± 0.002 (Zindler *et al.*, 1982; Allegre *et al.*, 1983; Taylor and McLennan, 1985; DePaolo, 1988). Yet, Group II samples from the Roman volcanic province (San Venanzo and Cupaello) have higher ratios, more in line with Roman Province rocks in Group III (Fig. 41).

Roman province Group III rocks show a trend of increasing $^{87}\text{Sr}/^{86}\text{Sr}$ from south

to north (Fig. 41). Although considerable isotopic work has been done on the topic of magma geneses, the trend remains a mystery. Another earmark of Group III rocks is their relatively large range of initial Sr isotopic ratios. Conticelli and Peccerillo (1992) consider this phenomenon to be a function of source heterogeneity, presumably due to addition of upper crustal material to the mantle via plate subduction.

4.2.1.3 Mata da Corda Formation

In each of the five detailed map areas (Appendices 1 to 5) it was shown that there exists a common geochemical link between most flows, intrusions, and xenoliths, possibly indicative of a common source. To investigate possible associations beyond the five areas, and in an attempt to arrive at more regionally significant conclusions, several major oxide and trace element diagrams, involving samples collected from five additional Mata da Corda areas, as well as several drill core samples of intrusive pipe material, have been examined.

Figure 41. Sr isotope compositions and ranges for ultrapotassic rock localities (modified after Foley *et al.*, 1987)

In Appendices 1 to 5, modified molecular proportion ratio (MPR) plots are shown to be helpful in establishing relative element mobilities, indicating that the more highly weathered material (flows) possess the greatest number of mobile elements. These plots also show that volcanic rocks share a common major oxide composition, and that individual rock types group at different locations along the data trend. This grouping was found to occur on most MPR plots, weight percent ratio-ratio plots involving relatively immobile elements, and trace element diagrams. One possible interpretation is that the grouping illustrates a compositionally evolving, single system, in which the flows are the most evolved. This will be discussed in greater detail later in this chapter.

An inherent problem of depicting sample chemistry on ratio plots is that using ratios produces a stronger correlation among the samples, thus leading to spurious trends on the diagram. One must be careful when interpreting these diagrams, especially if they are to be used to make inferences concerning fractionation trends, source compositions, or other genetic conclusions. On the other hand, ratio plots can be useful, because they help minimize the problems of spurious correlations due to the effects of closure (the fact that whole rock data is presented relative to 100%).

Trace elements are more effective in discriminating between petrological processes than major elements (Rollinson, 1993). They are also much less influenced by the effects of closure. Several compatible and incompatible trace elements were looked at to further substantiate the co-magmatic relationship between map area rocks. Some comments concerning the source of the ultramafic xenoliths are also presented.

Data for two incompatible elements, Zr and Nb (Figure 42) illustrating a good correlation. Samples appear to cluster into two distinct groups. All but the kamafugite flows fall together along the trend closest to the origin. Flows are more evolved, possessing Zr and Nb concentrations greater than all other rock types. Xenolith samples that fall along the trend may represent samples of the source region (cognate xenoliths), while those that deviate from the central cluster may have originated from a completely different source region. This diagram may reveal an evolutionary trend of incompatible trace elements generated by the fractional crystallization or partial melting of a source region with initial Nb and Zr similar

to those of the cognate ultramafic xenoliths. Another possible explanation for the higher Nb and Zr contents of the flows is that the elements have been concentrated (supergene enriched) due to intense weathering processes akin to lateritization. As a result, most primary minerals have been broken down, while only a few of the more resistant minerals such as perovskite (Nb bearing), and Zr bearing phases including zircon, baddelyite and wadeite have endured.

"Ratio-ratio plots of incompatible elements minimize the effects of fractionation and can help examine the character of the mantle source" (p. 157, Rollinson, 1993). Different mantle sources plot on different correlation lines. Mata da Corda samples define a single cluster on ratio-ratio trace element plots (Fig. 43), thus suggesting a common source.

Because compatible trace element concentrations change markedly in an igneous melt as fractional crystallization proceeds, binary plots of such elements versus some index of fractionation are useful in testing for fractional crystallization. In Figure 44 Mg# is used as an index of fractionation plotted against the compatible element Cr. In Figures 44 to 46 the intensely weathered kamafugite flow samples consistently fall off the dominant data trends. As stated previously, it is believed this is a function of supergene enrichment and not totally due to fractionation. The samples plotting within the upper right portion of the figure contain abundant olivine phenocrysts. Mineral analyses of the samples has revealed that olivine accounts for most of the sample's Cr, Mg, and Fe. On the other hand, olivine is a minor constituent, or totally absent, in the rest of the samples (diopside accounts for their Mg#s). This observation is corroborated by their much lower Cr contents and Mg#. The fractionation of olivine and diopside is interpreted to control the trend depicted on the diagram. However, when Mg# is plotted against Nb (Fig. 45), one of the incompatible elements, the effect of perovskite fractionation is revealed. Detailed mineral analyses (laser ablation ICP-MS and SEM-EDS work) has shown that perovskite is the only mineral phase hosting significant Nb concentrations. Thus, the well defined negative correlation between Nb and Mg# is due to olivine, diopside, and perovskite fractionation. Figure 46 effectively summarizes the above statements. The Ni/Nb ratio, plotted on the Y axis, mimics the olivine+diopside/perovskite ratio in the rock. Olivine rich rocks have both elevated Ni/Nb

ratios and $Mg\#$, while olivine poor and perovskite rich rocks have low Ni/Nb ratios and $Mg\#$. Petrographic investigations support this observation. In general, rocks that are olivine bearing are perovskite deficient, and when they do co-exist, perovskites are very small crystals largely confined to the groundmass. Alternatively, rocks containing abundant perovskite phenocrysts generally lack olivine and are diopside-rich.

Figure 42. Zr vs. Nb plot of study area samples. Note the high correlation.

Figure 43. Zr/Nb vs Y/Nb of Mata da Corda samples, illustrating a well defined grouping, typical of rock types related to a common source.

Figure 44. Cr vs Mg-number of study area samples, illustrating a well defined fractional crystallization trend. See the text for explanation. Samples of the Tres Ranchos kimberlite (Brazil, see Fig. 2), Pantano olivine lamproite intrusion (see Fig. 2), and the Monestary kimberlite (South Africa) were analysed and included on the diagram for comparison.

Figure 45. Mg# vs Nb for study area samples. See text for detailed explanation.

Figure 46. Mg# vs Ni/Nb for study area samples. See text for detailed explanation.

4.2.1.4 Summary

Group I (lamproites) rocks vary from ultramafic to intermediate in composition, and are characterized by very high potassium concentrations and K_2O/Na_2O ratios, low contents of Al_2O_3 (<10 wt.%), Na_2O (1.5-2.0 wt.%), and CaO (6-8 wt.%). MgO can also be high, sometimes up to 25 wt.%. They are also distinguished by their high to extreme enrichment in incompatible elements (more than any of the other ultrapotassic rocks), and their extreme variability in $^{87}Sr/^{86}Sr$. The main compositional differences between Group I and Group II (kamafugites) rocks are that Group II are strongly undersaturated and highly enriched in CaO (up to 18 wt.%). Their initial Sr isotopic ratios are typically low, except for those within the Roman Volcanic Province which are enriched, presumably due to subduction related contamination. Group III rocks (Roman-type) are undersaturated in silica (but not as much as Group II rocks) and mafic to intermediate in composition. They are typically rich in Al_2O_3 (12-20 wt.%), and depleted in TiO_2 (<1.2 wt.%). More mafic varieties can have high CaO contents (10-13 wt.%), and Na_2O around 2-3 wt.%. Their large range, and generally enriched values of $^{87}Sr/^{86}Sr$ are thought to be due to contamination from subducted crustal lithosphere.

West Kimberley lamproites possess Group I major oxide compositions. However, a few samples have K_2O contents typical of Group II (Figs. 23, 29). They are enriched relative to the other volcanic provinces in the compatible elements, Cr and Ni (Fig. 35), and incompatible elements, Ba, Nb, and Zr (Figs. 37, 39). Samples from the East African Rift show greater variability, especially the Na_2O and Al_2O_3 rich melilitites (Figs. 23, 25), but generally, the more undersaturated rocks are clearly Group II members (Figs. 27, 29). Leucite Hills lamproites and madupites exhibit transitional chemistry between Group I and Group II. Overall, the lamproites plot as Group I members, but the madupites show a stronger affinity to Group II. Their CaO contents are higher, and their SiO_2 and K_2O contents lower than lamproites from the same province (Figs. 23, 25, 27, 29, 31, 33). Samples of Roman Volcanic Province rocks display the greatest compositional diversity (kamafugites, lamproites, tephrites, and transitional varieties), thus they plot across all the compositional fields. However, their characteristically high Al_2O_3 contents set them apart (Figure 25). Samples of the Jumillite lamproite from southeastern Spain, one sample of the Gaussberg

lamproite from Antarctica, and a couple of shoshonite samples from the Aeolian arc are included on most of the diagrams. Although the geology of these volcanic districts was not discussed, a few samples were included for comparison. The Gaussberg lamproite is similar to the Leucite Hills lamproites (they are also the closest in age), while the Jumillite samples show considerable variation in their major oxide lithogeochemistry (transitional between Groups I and II).

In summary, Mata da Corda volcanic rocks exhibit kamafugite compositions. On all the diagrams most Mata da Corda Formation samples plot consistently within the Group II field and a few within the Group I field, indicating that they have a strong kamafugitic affinity, and some lamproitic characteristics. However, the most distinguishing compositional feature of the Mata da Corda Formation rocks is their extremely elevated Nb values, making this mafic ultrapotassic volcanic province geochemically unique. It is believed that kamafugite and lamproite intrusions, kamafugite flows, and some ultramafic xenoliths share a similar source composition. Figures 42 to 73 suggest that most Mata da Corda Formation rocks have originated from a common source, and that fractional crystallization is the dominant process leading to magma evolution. The volcanological evidence presented in Chapter 3 is consistent with this interpretation. Although, it is currently accepted that kamafugites and lamproites are derived from distinct mantle sources, Mata da Corda rocks do not exhibit lithogeochemistries consistent with this model. In fact, as will be shown in Chapter 5, the compositional similarities and common occurrences of Mata da Corda kamafugites and lamproites is best explained if they are viewed as fractionated products derived from a common source.

4.2.2 Mineralogical Composition and Comparisons of Mafic Ultrapotassic Rocks

Ultrapotassic rocks are often characterised by an incredible diversity of unusual minerals both rock forming (e.g., kalsilite, melilite, perovskite, leucite) and accessory (e.g., wadeite, priderite, shcherbakovite). Yoder (1986) states, "The complex mineralogy and diversity of the potassium-rich rocks are attributed mainly to incomplete reactions, with or without volatiles, between critical phases of limited range of stability". Incomplete reactions are evidence of rapidly changing conditions as magmas rise to or near the surface. Early descriptive accounts proposed nomenclatures based on modal mineralogy, but the rock's inherently complex and diverse mineralogy lead to the generation of a voluminous nomenclature, predominantly "location specific", having little applicability to rocks outside their type areas.

There are two opposing camps regarding ultrapotassic rock classification. Foley et al. (1987) propose a petrochemical based scheme (Table 2), while Mitchell and Bergman (1991) stress a mineralogical classification based on typomorphic mineral assemblages (Table 5). Table 3 contains compiled rock type mineralogical comparisons for the five volcanic provinces referred to in this thesis, as well as the Jumillite lamproites of Spain and the Gaussberg lamproite in Antarctica. This table does not present the revised nomenclature of Mitchell and Bergman (1991), although comparisons can be made with Table 5. Original rock type names are firmly entrenched in the literature; some have been used for more than 100 years, as is the case for Leucite Hills rocks.

Table 5. Revised lamproite nomenclature (Mitchell and Bergman, 1991)

Historical name	Revised Name
Wyomingite	Diopside leucite phlogopite lamproite
Orendite	Diopside sanidine phlogopite lamproite
Madupite	Diopside madupitic lamproite
Cedricite	Diopside leucite lamproite
Mamilite	Leucite richterite lamproite
Wolgidite	Diopside leucite richterite madupitic lamproite

Historical name	Revised Name
Fitzroyite	Leucite phlogopite lamproite
Verite	Hyalo-olivine phlogopite lamproite
Jumillite	Olivine diopside richterite madupitic lamproite

Mata da Corda Formation rocks are mineralogically similar, yet distinct from all the other ultrapotassic volcanic provinces (Table 3), as they contain higher percentages of diopside, perovskite and zeolites. Also, two potentially new minerals were identified in a ultramafic xenolith collected from Fazenda Grotao (Plates 16 & 17). However, they are similar in terms of some of their accessory minerals. In particular, rare kalsilite was found at Fazenda Bananal (kamafugite affinity; Appendix 4, Plates 8-11 & 22-24); wadeite at Fazenda Grotao (Plates 13-15) Ribeirao da Mata, and the Quintinos pipe; and melilite at several other locations throughout the Mata da Corda (Plates 5 & 6).

Kalsilite and melilite bearing rocks are best known from the kamafugites of the Toro-Ankole region, southwest Uganda, and from the Roman Volcanic Province in Italy. Mitchell and Bergman (1991) state that wadeite had not been reported in any other lamproite province but West Kimberley (Australia), Leucite Hills (Wyoming), and the Francis occurrence (Utah). Two other non-lamproite occurrences are reported in that publication: the Khibina alkaline complex and the Kovdor carbonatite. Furthermore wadeite has also been found at Mont St.Hilaire, Quebec (personal communication A.M. McDonald, Laurentian University). To quote Mitchell and Bergman (1991), "The recognition of wadeite in these carbonatites, where it occurs in a completely different paragenesis and is a very rare mineral, does not diminish the importance of wadeite as a typomorphic phase for lamproite recognition". The occurrence of wadeite at three different Mata da Corda kamafugite volcanic centres, certainly brings into question this, seemingly, common association between lamproites and kamafugites.

Yet perhaps the most distinctive feature of the Mata da Corda rocks is their extremely high perovskite content. In some cases perovskite is abundant enough to be considered a

common rock forming mineral (some xenoliths contain up to 12%). On the other hand, perovskite is only reported as an accessory phase in rocks of the other ultrapotassic volcanic provinces .

Zeolite minerals (harmotome and phillipsite) are alteration products due to the breakdown of primary silicates such as kalsilite and melilite. They are particularly abundant in Mata da Corda rocks, a testament to the once greater abundance of kalsilite and melilite. Prior to the availability of drill hole samples, only one occurrence of melilite was found, and that was from a relatively fresh kamafugite intrusion at Ribeirao da Mata (Appendix 5, pp. 24 & 28). However, melilite is present in several drill hole samples. Thus, it appears, that the perceived abundance of melilite may be largely a function of weathering. Melilite weathers easily to zeolites, but since the drill holes penetrate below the more intensely weathered surface environment, melilite is better preserved.

4.2.2.1 Mineralogy and Mineral Chemistry: Mata da Corda Formation

Flow, intrusion, and xenolith mineralogy has been described in detail for each of the six main map areas in Appendices 1 to 5 and 11. The following account is a brief discussion on the general mineralogy and mineral chemistry of Mata da Corda Formation rocks. Examples from the five study areas will be cited, as well as drill core samples from locations across the Mata da Corda.

Detailed mineralogical work was not carried out on the kamafugite flows, as they are the most weathered of all the rock types. Although, given the proper exposure (e.g., steep slope sections) most primary flow textures are preserved (e.g., flow-top breccia, foot breccia), of the primary minerals only oxides have survived the extreme weathering conditions. Primary rock forming minerals have all been altered to clays, imparting a "soil-like" competency to the flow outcrops. A few samples were processed for perovskites that were subsequently analysed by laser ablation ICP-MS. The results of that study are discussed in Chapter 5. Of the three main rock type divisions, ultramafic xenoliths are the best preserved, with the intrusions falling somewhere between the xenoliths and flows in terms of their state of preservation.

4.2.2.1.1 Intrusions

Most Mata da Corda intrusions best fit a kamafugite geochemical and mineralogical classification. Three lamproite occurrences were also investigated, at Ribeirao da Mata (Appendix 5, Fig. 7), at Fazenda Grotao where it has intruded next to a central kamafugite body (Appendix 2, Fig. 7), and the Pantano intrusion (Fig. 2).

4.2.2.1.2 Kamafugites

Diopside is the dominant rock forming mineral in Mata da Corda kamafugite intrusions. It occurs as both euhedral (Appendix 2, Plate 8) phenocrysts and as euhedral crystals within the groundmass (Appendix 2, Plate 10). With the exception of perovskite, apatite, phlogopite, and titanomagnetite, most primary minerals have been altered leaving a groundmass rich in zeolite and clays. Altered melilite (Appendix 5, pp. 24 & 28) was first identified at Ribeirao da Mata. However, when fresher material was drilled and sampled (Plates. 5 & 6), it became apparent how abundant melilite is in these rocks, and that recognition of it is probably hampered by the highly weathered state of the surface exposures.

One of the proposed major differences between kamafugites and lamproites is in the degree of silica saturation which can be recognised by the presence of kalsilite and melilite in the more undersaturated kamafugites. Therefore, the melilite bearing intrusion at Ribeirao da Mata is, by definition, a kamafugite. The whole rock and trace element chemistry further supports this classification. However, an olivine lamproite intrusion and lamproite xenoliths are also present at Ribeirao da Mata (olivine-leucite lamproite), as well as pyroxenite xenoliths containing wadeite (a typomorphic lamproite accessory mineral). In fact, in almost every area of study, both lamproites and kamafugites were identified. In some instances, such as Fazenda Grotao (Appendix 2, Fig. 7) the two types of intrusions are almost in contact, while at others there is an abundance of lamproite xenoliths within volcanic centres dominated by kamafugite intrusions (Ribeirao da Mata, Appendix 5; and Quintinos, Appendix 1). This recurring spatial association raises the question that Mata da Corda lamproites and kamafugites may not have originated from two different, and mutually

exclusive, sources. Field relationships point to the possibility that they may share a common genesis, and that their chemical and mineralogical differences are a function of magma fractionation. This topic is explored in greater detail in Chapter 5.

Plate 5. Drill core sample of melilite-rich pelletal lapilli (melilitolite). Sample X074/1b

Plate 6. Drill core sample of altered melilite and hauyne-bearing intrusion (melilitolite). Sample X053.

4.2.2.1.3 Lamproites

Three lamproite intrusions, the Pantanô intrusion (Fig. 2) the occurrence at Fazenda Grotao (Appendix 2, Fig. 7), and the one at Ribeirao da Mata (Appendix 5, Fig. 7) were mapped and studied (see Appendix 2 for a comparison on their mineral assemblage and mineral chemistry). All are diopside-olivine-phlogopite lamproites, containing abundant groundmass perovskite. They have been classified based on the recently proposed lamproite definition from Woolley et al. (1996):

"Lamproites are characterized by the presence of widely varying amounts (5-90 vol.%) of the following primary phases: (1) titanian (2-10 wt% TiO₂), aluminum-poor (5-12 wt.% Al₂O₃) phenocrystic phlogopite, (2) titanian (5-10 wt.% TiO₂) groundmass poikilitic "tetraferriphlogopite, (3) titanian (3-5 wt% TiO₂) potassium (4-6 wt% K₂O) richterite, (4) forsteritic olivine, (5) aluminum-poor (<1 wt% Al₂O₃) sodium-poor (<1 wt% Na₂O) diopside, (6) non-stoichiometric iron-rich (1-4 wt% Fe₂O₃) leucite, and (7) iron-rich sanidine (typically 1-5 wt% Fe₂O₃). The presence of all the above phases is not required in order to classify a rock as a lamproite. Any one mineral may be dominant, and this, together with the two or three other major minerals present, suffices to determine the petrographic name."

Mata da Corda kamafugites have a similar mineralogy to the lamproites except that they lack olivine. There is no difference in diopside or phlogopite composition between the two (see Table 6, and the mineral chemistry sections of Appendices 1 to 5). Thus, a forsterite bearing kamafugite, by virtue of the above definition, would be a lamproite. Samples FB27 and FB46 (Appendix 4, Fazenda Bananal) are excellent examples of this. Phlogopite and diopside compositions of FB27 fall within the lamproite thresholds given above, yet they also host kalsilite, whose presence dictates a kamafugite designation. In addition, the kalsilitolite xenolith FB46 (Appendix 4, Fazenda Bananal) contains Na and Al deficient diopside, typical of lamproitic diopsides. To confuse matters further, three xenolith samples QP12 (Quintinos Pipe, Appendix 1), M170 and RBD (Ribeirao da Mata, Appendix 5) contain phlogopite and diopside in accordance with the lamproite definition, but a third primary phase is lacking (such as forsterite); therefore, they were classified as kamafugites. However, subsequent SEM-EDS work revealed the presence of wadeite, thereby changing their classification from kamafugite to lamproite. In essence, the only major mineralogical difference between these rocks is the presence or absence of the typomorphic minerals

wadeite and kalsilite, yet according to current thought this is sufficient evidence for two separate magma sources. Sample GR23 is a kalsilitolite xenolith collected from Fazenda Grotao (Appendix 2, Plates 37, 38, 40, 41), that contains more wadeite than any other sample yet known from the Mata da Corda, yet other than the presence of wadeite, it does not conform to the lamproite definition. Of the seven primary lamproite minerals only diopside is present and it is Na-rich, not Na-poor. In fact, they plot as aegirine-augite on a Ca-Mg-Fe-Na pyroxene classification diagram (Appendix 2, Fig. 25).

Sample	Diopside (wt%)		Phlogopite (wt%)		Forsterite	Wadeite	Shcherbakovite	Leucite Fe-rich	Richterite	Kalsilite	Melilite
	Na ₂ O	Al ₂ O ₃	TiO ₂	Al ₂ O ₃							
M72 ^a	0.56	0.67	2.68	9.92	✓	✓					
M170 ^a	1.26	0.07	1.83	5.4		✓					
M159 ^b	0.41	0.77	4.79	13.58				✓			
M160 ^b	1.11	0.2						✓			
M78 ^c	0.5	0.08									✓
FB27 ^c	0.84	0.05	2.4	9.03						✓	
FB46 ^c	0.44	0.58								✓	
GR10 ^a	0.53	0.09	5.14	13.66	✓						
GR17 ^d	0.66	0.07	1.81	5.44							
GR23 ^d	0.46	0.46				✓	✓		✓	✓	
QP12 ^a	0.60	0.53	7.21	8.54		✓					
QP7 ^a	0.11	1.41			✓						
QP33 ^c	1.05	0.66									
AL9 ^c	0.52	0.38	0.54	4.8							
P2 ^a	0.42	0.0			✓						
Kam	0.1-1.1	0.05-2.0	0.5-8.0	4.5-10.0							

Table 6. Comparison table of lamproite vs kamafugite determinant minerals. Mineral chemistry limits are given in the above lamproite definition. Samples marked: "a" = olivine-phlogopite lamproites; "b" = olivine-leucite lamproites; "c" = kamafugites; "d" = kalsilitolites. Samples are from the following areas: M - Ribeirao da Mata; FB - Fazenda Bananal; GR - Fazenda Grotao; QP - Quintinos pipe; AL - Agua Limpa; P2 - Pantano intrusion; Kam - range of values for typical Mata da Corda kamafugites.

Several other lamproite examples were discovered as a result of the drilling program. To date, the olivine-phlogopite variety is the most common. In some occurrences classic “dog-tooth” olivine was observed (Plate 7). Resorption of olivine produces the characteristic serrate crystal margins. Madupitic olivine lamproites have been identified in several locations. These possess olivines that are typically anhedral and variably serpentinized, poikilitic groundmass titanian phlogopite, and smaller prismatic diopside crystals (Plate 8). Relatively fresh leucite-olivine lamproite was found in a couple of localities (Plates 9 to 12). The leucite is uncharacteristically fresh with only the margins showing signs of alteration (Plates 11 & 12). Anhedral olivine occurs as larger grains set in a groundmass of diopside microlites, perovskite, minor groundmass apatite and phlogopite.

Plate 7. Large “dog-tooth” olivine. Olivine lamproite. Drill core sample X348/3.

Plate 8. Madupitic olivine lamproite. Drill core sample X001/5.

Plate 9 Leucite-olivine lamproite. Leucites are the small, clear, roughly rounded, crystals. Drill core sample X559/3.

Plate 10 SEM backscatter image of leucite-olivine lamproite with composition of olivine. Drill core sample X559/3.

Plate 11 SEM backscatter image. Leucite-olivine lamproite. Drill core sample X559/3. Note the fresh core of the leucite crystal, and the abundance of diopside microlites in the groundmass.

Plate 12 SEM backscatter image. Leucite-olivine lamproite. Note the iron-rich leucite, typical of leucite lamproites. Drill core sample X559/3.

4.2.2.1.4 Ultramafic Xenoliths

Ultramafic xenoliths occur in abundance at every volcanic centre. They principally occur in breccia pipe intrusions, or as ovoid shaped rocks of various sizes lying loose on surface in close proximity to the pipe. Rarely do they occur within kamafugite intrusions. They also represent the freshest material available for analyses, thus more data was generated on these than either the flows or intrusions. Kamafugite, lamproite, pyroxenite, and kalsilitolite xenoliths were collected and studied. Of these, the vast majority are pyroxenites, consisting of diopside, minor perovskite, titanomagnetite, phlogopite, and apatite. Only the identifiable accessory minerals determine whether they are of kamafugitic or lamproitic affinity, and in most instances such judgements are far from conclusive. Several mineral varieties of lamproites have also been identified, including olivine lamproites, olivine-phlogopite lamproites, and olivine-leucite lamproites.

Sgarbi and Valenca (1993) first recognised kalsilite in Mata da Corda Formation rocks. Although the crystals were too small to facilitate conclusive X-ray diffraction data, the mineral chemistry compares well with kalsilites from other localities around the world. In

stark contrast are the kalsilites analysed as part of this study. A kalsilite-rich kamafugite xenolith (FB46) was collected from Fazenda Bananal (Appendix 4, Plates 8-11 & 22-24). It represents the freshest and coarsest grained occurrence known to exist within the Mata da Corda (see Appendix 4 for a more complete description of the sample). Both mineral chemistry and X-ray diffraction analyses firmly establish its identity. Kalsilite readily alters to zeolite (Appendix 4, Plates 23, 24), therefore, its presence in surface exposures is probably greatly underestimated, much the same as it probably is for melilite.

Plate 13. Euhedral wadeite crystal. Ultramafic xenolith sample GR23 (Fazenda Grotao). The black patch to the left of the picture is marker ink.

Prior to this study, wadeite had not been described in rocks of the Mata da Corda Formation. In fact, this represents the first known occurrences of wadeite in South America. Wadeite was found in four different ultramafic xenolith samples from three different map areas (see Fig. 2, Ribeirao da Mata - 2 samples, Fazenda Grotao, and the Quintinos pipe). The presence of wadeite in samples spanning half the areal extent of the Mata da Corda Formation demonstrates the province's lamproitic affinity. The most notable of these samples is GR23 (Plate 13), a kalsilitolite xenolith composed of euhedral kalsilite

pseudomorphs altered to potassium feldspar, anhedral diopside (Appendix 2, Plates 32, 33, 34, 35, 36), aegirine-augite (Appendix 2, Plates 37, 38), poikilitic phlogopite (Appendix 2, Plates 33, 34), perovskite (Appendix 2, Plates 35, 36, 39), apatite, secondary potassium feldspar (Appendix 2, Plates 40, 41), and many large wadeite crystals (confirmed by SEM-EDS and X-ray diffraction analyses), as well as two unknowns which maybe potentially new minerals. It is one of only three kalsilitolite xenoliths found to date. None of the areas mapped so far contain morphologically similar kalsilite or aegirine-augite bearing rocks, nor is there a record of any Mata da Corda rocks of similar composition.

Wadeite typically occurs in two forms, either as euhedral crystals (Plates 13 & 15), or as late stage anhedral crystals interstitial to earlier formed minerals (Plate 14). Shcherbakovite was found in sample GR23 where it occurs as euhedral prismatic crystals (Fig. 16). This represents the first known occurrence of this mineral in the Mata da Corda. Two unknown minerals were also found in GR23. One of the unknown phases is essentially an Ti, K silicate (Plate 17) while the second has a composition grossly similar to annite (Plate 17). The unknown minerals are currently under investigation.

Plate 14 SEM backscatter image of late stage wadeite interstitial to kalsilite pseudomorphs. Sample GR23.

Plate 15. SEM backscatter image of the euhedral wadeite crystal in Plate 13.

Plate 16. SEM backscatter image of shcherbakovite. Sample GR23.

Plate 17. SEM backscatter image of two unknown minerals (Ti,Na-silicate and Fe,Mg-silicate). Sample GR23.

4.3 DISCUSSION

4.3.1 Ultrapotassic Magma Genesis

The genesis of ultrapotassic rocks is one of the most debated topics in igneous petrology. A good deal of this controversy can be attributed to the bizarre chemical compositions they possess; they are enriched in elements typically concentrated in crustal rocks (incompatible elements such as K, Rb, Th, U, REE), and have high concentrations of some compatible elements (Ni, Cr, Mg) indicative of mafic rocks. Several theories have been advanced to explain this chemical paradox. Daly (1910) argued that potassic magmas were produced by the assimilation of carbonate rocks by "normal" sodium-alkaline basalts. Rittman (1933) expanded on this idea by proposing that potassic magmas are products of the assimilation of carbonate rocks by trachytic magmas, which were in turn derived from sodium-alkaline basalt by fractional crystallization processes. In another contribution, Holmes (1950) proposed that the spatial relationship between mafic alkaline rocks of the Toro-Ankole region, Uganda, and carbonatite rocks was suggestive of a common source. He believed that African volcanic rocks were produced due to the assimilation of granites by carbonatitic magmas.

Various forms of the syntectonic theme were popular until Savelli (1967) demonstrated that potassic magmas have higher incompatible element concentrations than crustal rocks, and that the assimilation of carbonatitic melt does not explain the high contents of ferromagnesian elements in the most primitive rocks. Furthermore, there is also the problem of differences in melting temperatures. Carbonatitic melts have temperatures between 600°-800°C. These values are similar to, or lower than, the granite solidus, and thus they probably cannot assimilate granitic rocks. In summary, the consensus is that assimilation theories can not effectively explain the formation of potassic and ultrapotassic rocks.

The next generation of hypotheses was based on gaseous transfer and metasomatic changes of either mantle- or crust-derived magmas. Harris (1957) proposed a zone refining process by which a diapir of molten material ascending through the mantle would rise adiabatically by melting the roof rocks at its top and crystallizing minerals at its base. Supposedly, all impurities (i.e., incompatible elements) would be swept up from the part of

the mantle that was traversed by the diapir. Consequently, the migrating melt would become enriched in incompatible elements and would attain ultrapotassic composition. O'Hara and Yoder (1967) suggested that potassium and incompatible element enrichment in subcrustal magmas might be derived from intramantle fractional crystallization of omphacitic pyroxene and garnet (eclogite fractionation) from a basaltic magma. Kay and Gast (1973), based on trace element quantitative modelling, concluded that enrichment of incompatible elements and REE in potassic melts was due to very low degrees of partial melting of garnet-bearing peridotitic mantle. They calculated that <1% partial melting of a normal mantle was necessary to explain the LREE enrichment.

However, the strongest drawback to most of these hypotheses is the high and variable strontium isotopic signatures of mafic potassic magmas. Initial $^{87}\text{Sr}/^{86}\text{Sr}$ of the mantle is about 0.703-0.704. To produce values reported for mafic-potassic magmas by crustal assimilation, 70-80% of upper crustal material would have to be assimilated (Peccerillo, 1992). This conflicts with the undersaturated character of the rocks and the mafic composition of many of them.

4.3.1.1 Mantle Metasomatism and Potassic Magmatism

Ultramafic xenoliths brought to the surface by deep-seated pipes, such as lamproites and kimberlites, establishes the existence of incompatible element enriched minerals in the upper mantle (phlogopite, apatite, amphibole, and perovskite), suggesting that the upper mantle is heterogeneous at a small scale. The obvious question is by what process, or processes, was this accomplished. Experimental studies on ultrapotassic rocks began in the mid-1970s. From then on, knowledge of these rocks has steadily increased, culminating in the belief that mantle metasomatism is the likely process responsible for the genesis of potassic and ultrapotassic magmas (Edgar, 1996, and references therein).

Mantle metasomatism involves the introduction of incompatible element rich fluids or melts into the upper mantle, resulting in an enriched source region for the production of potassic and ultrapotassic rocks. However, the nature and origin of the metasomatizing agents are still actively debated. Perhaps the most accepted hypothesis requires the existence

of small scale, mobile, metasomatic melts. McKenzie (1989) commented on the movement of small scale melts within the upper mantle. He stated that partial melts of <1% of mantle peridotite may be mobile. They would also be enriched in incompatible elements, and being much less dense than the surrounding rocks, they would migrate toward the surface. Upon reaching the lithospheric mantle the melts would freeze into veins rich in minerals that contain incompatible elements (Foley, 1992). The resulting metasomatic minerals have lower melting temperatures than their mantle host rocks. Therefore, melting of the veins could be induced by crustal stretching, or elevated isotherms due to hotspot activity, resulting in the generation of potassic magmas.

Different tectonic environments are likely to influence the composition of metasomatic agents. Subduction related processes have been proposed to explain the potassic and ultrapotassic magmas of the Roman Volcanic Province (Peccerillo, 1990). In such orogenic areas, incompatible element enriched fluids or melts are released from the subducted slab. As metasomatic agents, they can have geochemical and isotopic compositions matching the subducted materials; these features will be passed on to the potassic magmas. Nelsen (1992) suggested that this process is responsible for the distinctive geochemical and isotopic characteristics of orogenic potassic magmatism (Sunda arc, Italy, and Southeastern Spain). He also believed that subduction processes were probably responsible for providing the incompatible elements within anorogenic tectonic settings in which the subduction zone setting is long gone. In this scenario, previously enriched, chemically anomalous, sources are isolated from the convecting mantle for long periods; probably within the subcontinental lithosphere. During this time their isotopic characteristics will evolve until, at some later time, potassic magmatism is triggered by either rifting or hotspot activity.

4.3.2 Conclusion

In general, there are a number of similarities between the major ultrapotassic volcanic provinces. In particular, the main characteristic is the potassic enrichment of these melts in conjunction with their clear mafic chemical traits. Some believe this chemical paradox is evidence of a heterogeneous upper mantle, and that the processes (and the mantle

composition) leading to the generation of potassic magmas are globally comparable. There is also agreement that subtle differences between ultrapotassic provinces are probably due to the influences of different tectonic settings, ultimately contributing to diverse metasomatic agent compositions. Nevertheless, the overall consensus is that ultrapotassic melts are derived from a metasomatised mantle enriched in certain elements characteristic of crustal rocks (Edgar, 1996).

Differences between volcanic provinces are just as enlightening, the consensus being that most of these disparities are greatly influenced by tectonic environment. A good example of this is the different $^{87}\text{Sr}/^{86}\text{Sr}$ values between the Toro-Ankole kamafugites and those of the Roman volcanic province. Though both possess chemical traits of kamafugites, there is a distinct difference in their isotopic signatures. It has been suggested that this is due to their different tectonic settings; Toro-Ankole volcanism is related to continental rifting and intraplate hotspot activities, while the Italian rocks lie within a collisional setting underlain by subducted lithosphere. The higher isotopic ratios of the Italian magmas were supposedly inherited from subducted crustal material. Table 4 is a compilation of ultrapotassic volcanic province characteristics illustrating many of these similarities and differences.

In a previous section, the chemical and mineralogical characteristics between the provinces are discussed. The petrochemical classification scheme of Foley et al. (1987) was used to categorize province rock types into four main groups: Group I (lamproites), Group II (kamafugites), Group III (plagiolecitites), Group IV (transitional). They proposed that because of the extreme mineralogical diversity characteristic of potassic and ultrapotassic rocks, a chemical-based system, recognizing the transitional nature of the rocks between end member compositions, is more effective, while petrographic and mineralogical classifications only add to an already cluttered and confusing nomenclature. Their idea of a chemical continuum among ultrapotassic rocks is consistent with observations made of Mata da Corda Formation rocks in this study. For example, most Mata da Corda Formation rocks are kamafugites in terms of their lithogeochemistry, mineralogy and mineral chemistry, yet some have compositional characteristics typical of both kamafugites and lamproites, and are best described as hybrids. Perhaps even more convincing is that when chemical data are plotted

on the same diagrams, sample distributions define a common trend. There is also evidence that a fractionation trend exists, as samples from each map area lie along their own section. Ratios of incompatible elements in igneous rocks are believed to be unaffected by partial melting or differentiation processes and closely resemble those of the mantle sources from which the melts were derived. Incompatible element ratio plots of Mata da Corda rocks data define a common trend, suggesting a common source, and the fact that the samples cluster on different parts of the trend indicates fractionation from a common source.

Yoder (1986) explained that the complex mineralogy of these rocks mainly depends on incomplete reactions, caused by a sequence of changing conditions as they are brought to or near the surface. Simply put, ultrapotassic rocks are especially responsive to changes in pressure and temperature. Therefore, the complexity of the final product, resulting from incomplete or failed reactions, often obscures the primary assemblage. It is the primary assemblage that provides the clues to the origins of the magma, and it is the primary assemblage that has to be deduced from the incomplete reactions. The mineralogy of the various type localities is compiled in Table 3. The results were dramatic in the sense that Brazilian rocks appear to possess mineralogical characteristics not shared by any of the other regions, in particular, the abundances of diopside, perovskite, and zeolites are the greater than the other provinces. Perovskites within mantle-derived ultramafic xenoliths are typically euhedral crystals. This suggests that the Cretaceous mantle that fed Mata da Corda volcanism was enriched in perovskite, more so than any of the other ultrapotassic provinces. Effects of abundant perovskite can be seen in the whole rock incompatible trace element concentrations, especially among elements such as Nb, which substitutes for Ti in the mineral structure. Niobium contents of Mata da Corda rocks are much greater than those reported for any of the other areas. These mineralogical and chemical traits make the Mata da Corda Formation rocks unique, and the larger Alto Paranaíba Igneous Province, to which they belong, atypical.

The Mata da Corda exhibits many volcanological similarities to the West Kimberley province of northwestern Australia. Both volcanic fields are sufficiently denuded such that most large volcanic edifices no longer exist. The dominant features remaining are intrusive

pipes, various types of volcanic breccias, flows and rare pyroclastic rocks (Table 4). Erosion has exposed deeper levels of the volcanic centres. In the Mata da Corda, the remnant maar-type volcanos at Ribeirao da Mata (Appendix 5), Fazenda Bananal (Appendix 4), Fazenda Grotao (Appendix 2), Agua Limpa (Appendix 3), and the Quintinos Pipe (Appendix 1) are all good examples of this. In some cases, such as Quintinos, all the overlying volcanic material has been eroded leaving only an intrusive pipe surrounded by country rock. Examples of this can be found in both volcanic provinces, but are especially abundant within the Mata da Corda, as are blind pipes that did not intrude all the way to the surface. There are many Mata da Corda examples of subsurface pipes, typified by topographic knolls (pyramid shaped) composed of intensely silicified sandstone. Not much is known of the Australian examples, although, in their accounts of Mt. Abbott, Wade and Prider (1940) described many features suggestive of a blind pipe.

Magmas in both provinces predominantly intruded sandstone causing intense disruption and alteration. The abundance of tuffisite, and tuffisitic breccia are evidence of the incorporation of bedrock material, and the destructive nature of the emplacements. In addition, sandstones close to the vents have been chloritized. Magnesium is believed to have been contributed by the intrusions. However, there is little documentation of silicification of the country rock. Intense silicification of the Areado sandstone surrounding Mata da Corda intrusions is ubiquitous, and used as an important guide in locating possible volcanic centres.

Fluidization has traditionally been viewed as one of the dominant processes responsible for the formation of maar volcanoes. Evidence of fluidized sandstone is found within most Mata da Corda volcanic centres. However, it either does not play such an important role in the West Kimberley fields, or fluidization, to date, has gone undetected.

The Australian and Brazilian provinces also share similar tectonic environments in which intrusions bored through a mobile belt adjacent to a craton. Nevertheless, with all their similarities, they do have some important differences. For example, their volcanic rocks bear little resemblance in composition and mineralogy. In addition, there are also some important petrological differences. For instance, although kimberlites, lamproites, and carbonatites

occur within both provinces, only kamaugites are found within the Mata da Corda. Furthermore, ultramafic xenoliths are relatively rare within the West Kimberley district but incredibly abundant in the Mata da Corda.

The other volcanic provinces are younger (3.1 Ma to recent), and this is reflected in their state of preservation. Large, well-preserved, volcanic centres are common, and in some areas, active volcanism is ongoing (Roman Volcanic Province, and southwest Uganda). Lava flows are particularly abundant at Leucite Hills, and within the Roman Province where they are associated with volcanic centres. On the other hand, pyroclastic rocks are more prevalent within the volcanic fields of southwest Uganda, and lava flows very rare.

Unfortunately, detailed descriptions on the physical volcanology of the type localities are not currently available. Most recent work has concentrated on their chemistry, mineralogy, and petrogenesis. Without detailed geological accounts covering the geology and volcanology between the provinces comprehensive comparisons are impossible. However, in its place the following generalizations can be made (Tables 3, 4):

- 1) In terms of primary mineralogy, Mata da Corda rocks are most like the kamaugites from southwest Uganda, but in volcanic events they most resemble the volcanic fields of West Kimberley, Australia.
- 2) The Roman Volcanic Province exhibits the greatest variety of rock types. Only the Alto Paranaíba Province in Brazil shows a similar diversity; whereas their volcanic features are comparable to the Toro-Ankole region, but only in gross morphology, not in their rock type compositions or volcanic products.
- 3) The mineralogy and petrology of Leucite Hills rocks closely match those of West Kimberley, Australia, but in terms of their volcanic structures (i.e., abundance of lava flows) they are similar to the Roman Province.

Structure has been a dominant influence in the localization of intrusions. Within the Alto Paranaíba Igneous Province, igneous activity is centred along the Alto Paranaíba Arc, a trans-Brazilian lineament. Within the West Kimberley lamproite fields, emplacements were controlled by west-north-westerly trending structures, while Ugandan volcanism is related

to the western arm of the East African rift system. The lamproite exposures at Leucite Hills lie along the northeast side of a Laramide basement uplift, with local emplacements influenced by older Laramide structures. Volcanic edifices within the Roman Volcanic Province are believed to have been emplaced in a post-collisional setting dominated by intense block faulting. On a local scale, intrusions within the maar craters of Brazil are spatially related to concentric faults. This relationship has not been reported for the other areas. In every one of the ultrapotassic provinces, structural controls are considered largely responsible for the emplacement of intrusions, and for influencing the overall shape of the volcanic fields.

If older structures play such a dominating role, then it may be possible that they are chronic features reactivated throughout time. Kostyuk (1993) believes that some present day rift belts show a relationship to older basement structures, and that major rift systems are inherited. He cites evidence from the Baikal-Stanovoy-rift system of East Siberia, suggesting that volcanic activity associated with continental rift zones is a recurring phenomenon. Similarly, evidence for at least two main episodes of volcanic activity is suggested for the Toro-Ankole region, with the later events destroying most of the former volcanic stratigraphy. Similarly, U-Pb dates on Mata da Corda perovskites suggest magmatic events at 80 Ma and 156 Ma (Card, 1996).

There are many similarities and differences among the five mafic ultrapotassic provinces, but in many ways each is unique. However, it is noted that Mata da Corda Formation rocks are distinctive in terms of their mineralogy and geochemistry. Consequently, if we were to side with those who support mineralogical classification schemes, there would be grounds for describing a new rock type regarding the sample with upwards of 12% modal perovskite.

The common association of kamafugites and lamproites within Mata da Corda volcanic centres, coupled with their similar mineralogy and mineral chemistries, brings into question the current belief that they are derived from separate mantle sources. Edgar (1996) hints that there may be more to this, and that some sources for lamproites and kamafugites are similar. Stoppa and Cundari (1998) take this argument further, proposing that the common association of kamafugites and carbonatites at San Venanzo-Pian di Celle (Umbria, Italy)

resulted from a carbonate-rich melt separating from a mantle source. As the melt ascended rapidly to the surface carbonatite detachment from the silicate melt occurred at less than 20 kbar, and subsequent shallow level CaCO_3 dissociation and decarbonation reactions produced the kamafugites. A similar carbonatite-kamafugite association is present within the Mata da Corda (Fig. 2), but far from being as strong as the kamafugite-lamproite association. In Chapter 5 this association for Mata da Corda rocks is explored in more detail, and evidence presented in favour of a common mantle source for lamproites and kamafugites.

CHAPTER 5

**TRACE ELEMENT COMPOSITION OF PEROVSKITE
FROM THE MATA DA CORDA FORMATION, BRAZIL:
IMPLICATIONS FOR IGNEOUS PETROGENESIS AND
DIAMOND EXPLORATION**

5.1 INTRODUCTION

Perovskite is a common accessory mineral in silica-undersaturated igneous rocks, including ultramafic alkaline rocks (lamproites, kamafugites, kimberlites, nephelinites), carbonatites, and agpaitic nepheline syenites. Perovskite's strong bonding characteristics makes it very resistant to physical and chemical change caused by weathering and erosion. This characteristic, in association with its ability to incorporate a wide-range of high field strength elements (HFSE) and rare earth elements (REE), and abundance in Mata da Corda rocks (xenoliths, intrusions, and flows), makes it worthy of study for possible rock type discrimination and igneous petrogenesis applications. This chapter reports on the results of that study, in which laser ablation microprobe (LAM-ICP-MS) trace element analyses of perovskites were carried out on kamafugite, lamproite, nephelinite, and kimberlite samples from the Mata da Corda Formation.

5.2 PEROVSKITE

Ideal perovskite has the general formula ABX_3 . Metallic cations occupy the A and B atomic sites while the X atoms are non-metallic anions. Two dozen elements are known to fill the A site (Ca^{2+} , K^+ , Ba^{2+} , Na^+ , Sr^{2+} , Pb^{2+} , and the rare earth elements - REE^{3+}), whereas 50 elements are known to enter the B sites (e.g. Ti^{4+} , Nb^{5+} , Fe^{2+} , Ta^{5+} , Th^{4+} and Zr^{4+}). The X position can be filled by oxygen and the halogens. Most naturally occurring perovskites occupy compositional space defined by seven end-member compounds (Mitchell, 1996). In this study, 237 laser ablation ICP-MS analyses were done on Mata da Corda perovskites. The results show that, on average, they contain < 0.4 wt.% Sr, < 0.22 wt.% Nb (Table 7), and < 3.0 wt.% total REE (Table 8). Knopite was the mineralogical name previously used to describe perovskites that are host to such small amounts of REE. However, recently there has been a call to drop this varietal name, thus, Mata da Corda Formation rocks studied herein are described as containing prototypical perovskite ($CaTiO_3$).

Mata da Corda perovskites predominantly occur as single euhedral crystals (Plate 18) of variable size, and to a much lesser extent, as crystal aggregates (Plate 19) and poikilitic anhedral masses (Plate 20). Zoned crystals (mostly oscillatory) are common to all rock types

studied (Plate 21). Atoll-textured perovskites (consisting of subhedral to anhedral crystals mantled by rutile; Plate 22) can be abundant, illustrating the possible decomposition of perovskite in response to changing conditions. Modal contents of perovskite can vary from trace amounts to several percent, approaching the role of a rock forming mineral.

Table 7. Mata da Corda perovskite trace element content (ppm) and basic element statistics (n = 237).

Element	Mean	Median	Minimum	Maximum
Sr	3870	3251	1549	18322
Y	206	183	76	479
Zr	348	272	98	3985
Nb	2167	1814	484	10342
Ba	458	54	8	71478
Hf	14	12	4	142
Ta	237	211	16	1520
Pb	18	12	3	220
Th	893	659	14	10350
U	48	37	9	195

Table 8. Mata da Corda perovskite REE contents (ppm) and basic element statistics (n = 237)

Element	Mean	Median	Minimum	Maximum
La	5565	4815	327	32511
Ce	11991	10211	463	74780
Pr	1420	1234	51	8273
Nd	5035	4445	191	25153
Sm	606	541	35	2103
Eu	138	126	10	419
Tb	27	26	4	71
Gd	248	234	25	696
Dy	99	92	16	220
Ho	12	11	3	32
Er	21	18	7	48
Tm	2.0	1.5	0	28
Yb	7.1	6.0	0	46
Lu	0.8	0.5	0	19

Plate 18. Euhedral perovskites (kamafugite intrusion)

Plate 19. Mass of perovskite crystals (pyroxenite xenolith).
The black circular feature is marking ink.

Plate 20. Anhydrous perovskite (kamafugite xenolith)

Plate 21. Zoned perovskite crystal (pyroxenite xenolith).

Plate 22. Backscatter electron image of atoll textured perovskite (pyroxenite xenolith).

5.2.1 Rare Earth Element Content

Perovskites have a strong, yet unequal, affinity for rare earth elements (REE), preferentially incorporating light REE (LREE) over heavy REE (HREE; Borodion and Barinskii, 1960). This is attributed to the similarities in the ionic radii of Ca and the LREE (Boyton, 1975). Nagasawa *et al.* (1980) first suggested that the concentration of REE in perovskite is directly related to the REE content of the source region.

Enrichment in LREE over HREE in perovskite is clearly illustrated on chondrite normalized REE diagrams as steep (negative) REE distribution patterns (Fig.47). This distinct pattern has been observed in perovskite from various alkaline rocks the world over (Jones and Wyllie, 1984; Mitchell and Reed, 1988; Dawson *et al.*, 1994; Lloyd *et al.*, 1996; Mitchell, 1996; Campbell *et al.*, 1997). Perovskites from Mata da Corda Formation kamafugites and lamproites display the same general REE pattern (Fig 48.).

There are few detailed analyses of REE on perovskites (Mitchell, 1996). Most workers report on LREE and MREE abundances, while few provide HREE determinations; of those that do, most are considered inaccurate (Jones and Wyllie, 1984; Mitchell, 1996), because of poor analytical sensitivities in detecting the less abundant HREE.

Typically, the analytical instrument of

Figure 47. Typical chondrite-normalized REE distribution patterns for perovskite (modified after Mitchell, 1996)

Figure 48. Representative chondrite normalized REE distribution patterns of Mata da Corda Formation perovskites.

choice has been the electron microprobe. Although this method can provide good LREE data, it has serious limitations concerning the HREE (Mitchell and Reed, 1988). With the advent of the ion microprobe, some of the detection limit problems were overcome making it possible to determine some HREE accurately, but not all of them (Mitchell and Reed, 1988).

Previously, the most accurate method of analysing for all the REE involved picking mineral separates and then employing instrumental neutron activation analyses (INAA) or inductively coupled plasma-mass spectrometry (ICP/MS). However, these methods require considerable preparation time and expense, and are not useful for studying chemical zonation. Results may also contain inaccuracies due to contamination by mineral inclusions. Herein lies the advantage of in-situ perovskite laser ablation ICP-MS analyses; of all the previously mentioned analytical methods, laser ablation requires the least sample preparation. It is also very effective for studying mineral zonation, and is the least destructive method (only small amounts of the crystal are ablated, leaving most of it intact) of accurately determining the concentration of all the REE in perovskite, including all the HREE.

In alkaline rocks, perovskite typically occurs as an early crystallizing phase (Dawson *et al.*, 1994; Mitchell, 1996; Lloyd *et al.*, 1996), often forming discrete euhedral to subhedral crystals that act as the dominant host of REE (Nagasawa *et al.*, 1980; Jones and Wyllie, 1984; Mitchell and Reed, 1988; Dawson *et al.*, 1994; Dawson *et al.*, 1995; Lloyd *et al.*, 1996; Mitchell, 1996; Campbell *et al.*, 1997). Rare earth element abundances are commonly used to infer source characteristics of some magmas, and presumed differentiation processes that may have taken place during melt ascent from mantle to lower crustal levels (Sun and Hanson, 1975; Beswick and Carmichael, 1978). For perovskites, the characteristic large La/Yb ratios are not representative of the source (Mitchell, 1988), but instead, they are due to large differences in crystal-liquid partition coefficients between the LREE and HREE (Simon *et al.*, 1994). Such conditions result in REE fractionation as LREE enters the perovskite crystal structure, while HREE are concentrated within the residual melt.

Apatite and diopside can also incorporate rare earth elements into their crystal structure. Mata da Corda accessory apatites typically occur as small (<1mm) anhedral to subhedral

crystals, either within the groundmass or as inclusions within diopside. Diopside, on the other hand, is the major rock forming mineral in most Mata da Corda igneous rocks, comprising upwards of 80% of some of the pyroxenite xenoliths. It occurs both in the groundmass and as larger euhedral and subhedral phenocrysts. LAM-ICP-MS analyses on these three minerals clearly show that perovskite accommodates most of the REE (Figs. 49, 50). This agrees with several other studies on REE partitioning (Jones and Wyllie, 1984; Mitchell and Reed, 1988; Dawson *et al.*, 1994; Dawson *et al.*, 1995; Lloyd *et al.*, 1996; Mitchell, 1996; Campbell *et al.*, 1997). Of particular interest is the study by Lloyd *et al.*, (1996), who dealt with rocks that are similar in composition to those of the Mata da Corda Formation (i.e., kamafugitic affinity). In their study, electron microprobe analyses of LREE were carried out on perovskite, apatite, and titanite. They concluded that for minerals crystallized from mantle melts, LREE contents of perovskite > apatite > titanite. Figure 49 clearly shows that when primary perovskite and apatite occur together in the same Mata da Corda Formation

Figure 49. Representative apatite laser ablation REE distribution profile of Mata da Corda Formation rocks. Apatite and perovskite analyses are from the same ultramafic xenolith sample.

Figure 50. Laser ablation diopside REE distribution profiles. A typical perovskite profile is included for comparison.

rocks, most of the REE are incorporated into perovskite. Furthermore, perovskite's REE contents are 100 to 1000 times that of diopside (Fig. 50).

Figure 51. Mata da Corda Formation perovskite and whole-rock chondrite-normalized REE patterns. Note that the whole rock profiles of the xenolith and host overly one another. The same is true of the perovskite profiles.

Given the ability of perovskite to incorporate REE, slight fluctuations in the modal percent of perovskite might significantly affect the total REE content of a rock (Campbell *et al.*, 1997). Therefore, fractional crystallization of small amounts of perovskite could greatly affect the REE composition of the residual melt. Similarly, Jones and Wyllie (1984) and Mitchell (1986) comment that the concentration and composition of perovskite in

kimberlites control their whole rock REE distribution patterns. However, Mitchell and Reed (1988) have refined this theory further, finding that higher precision ion microprobe data revealed a greater variance in kimberlite REE distribution than previously thought, and that the La/Yb ratios of perovskite are much greater than the whole-rock ratios. They attribute this increase in HREE to crustal contamination.

Mata da Corda Formation rocks show remarkable similarities regarding perovskite and whole-rock chondrite-normalized REE patterns. Figure 51 shows representative perovskite and whole-rock REE distribution profiles for the study area rocks. Profile shapes are very similar except for the convergence of the lines toward the HREE end. La/Yb_n (normalized) ratios clearly illustrate this difference (Fig. 51). In keeping with the above statement, patterns should be identical if perovskite is the only phase hosting significant concentrations of REE. The fact that the whole-rock pattern appears flatter than the perovskite pattern implies this is not so, and that another factor may be present contributing appreciable HREE. Mitchell and Reed (1988) proposed that assimilation of crustal material in kimberlites was a likely explanation. However, igneous rocks of the Mata da Corda Formation show no signs of crustal contamination. They are silica undersaturated rocks (~ 35 wt.% SiO_2) possessing initial $^{87}\text{Sr}/^{86}\text{Sr}$ from 0.7045 to 0.7058 (Gibson *et al.*, 1995), values in line with the present-day mantle value of 0.704 ± 0.002 (Zindler *et al.*, 1982; Allegre *et al.*, 1983; Taylor and McLennan, 1985; DePaolo, 1988). Instead, the presence of HREE in diopside appears to be responsible for the difference between REE patterns. For example, the perovskite La/Yb_n ratio for sample QP37a (in Figure 51) is 393, while a typical Mata da Corda diopside would have a La/Yb_n ratio around 57 (Fig. 50). An average diopside contains about 40 ppm La and 0.5 ppm Yb, while a perovskite may contain 5000 ppm La and 6.5 ppm Yb. In other words, a single crystal of diopside incorporates $\sim 0.8\%$ of the La that a single perovskite can, but a diopside can contain almost 8% of the Yb. Given the dominant rock forming role played by diopside (modal percent ranges from 60-85%), 8% is easily compounded into a significant contribution of Yb (as well as other HREE), whereas its 0.8% La content is dwarfed by perovskite's capacity for LREE.

5.3 ROCK TYPE DISCRIMINATION

In the previous section chondrite normalized diagrams were used to show Mata da Corda perovskite REE distribution profiles relative to a universally recognized datum. However, the chondrite benchmark is not very effective for presenting differences between Mata da Corda rock types, as perovskites are so strongly enriched in REE (particularly the LREE) relative to chondrite. The resulting large scale differences are visually reduced by the use of a log scale (see Figs. 48-51).

To address this problem, a different datum was used for normalizing perovskite compositions. Sample FB46, a relatively unaltered kalsilite pyroxenite xenolith from Fazenda Bananal, was chosen because of its Rb-Sr Mata da Corda age (80 Ma), and quality of perovskite laser ablation data (Fig. 52). The reproducibility of laser ablation analyses (Fig. 53) shows that any significant REE variation (for the purpose of rock type discrimination) is probably not due to technique error or machine drift.

Mineralogy consists of euhedral to subhedral acicular kalsilite, euhedral to subhedral diopside, anhedral Ti-rich andradite garnet, and anhedral perovskite (Plate 20). Average

Figure 52. Typical perovskite signal profile for FB46 illustrating the exceptional quality of laser ablation signal response. Seconds denote laser burn-time and resulting data collection interval analysed by the mass spectrometer.

Figure 53. Laser ablation ICP-MS perovskite REE distribution profile of duplicate analysis.

perovskite REE values from this sample, based on four laser ablation ICP-MS analyses, were used to normalize the laser ablation data base. The resulting perovskite/perovskite^{FB46} data is presented on spider diagrams to show that perovskite REE composition is effective in rock type discrimination.

As illustrated in Plate 21, oscillatory zoned perovskite is very common in Mata da Corda rocks. Therefore, it is important that quantitative assessments of REE

zoning be made before the REE contents of perovskite can be used as a discriminant tool. Numerous rim and core analyses were done on zoned perovskites from study area xenoliths, intrusions and flows. Samples for laser ablation analyses were first identified based on SEM backscattered electron images. Rim and core analyses of suitable crystals were obtained and normalized (Figure 54 contains one core and two rim analyses from a zoned perovskite). The data clearly shows that LREE account for most of the observed zonation, while HREE maintain a fairly uniform concentration. Such a condition attests to the extreme compatibility for LREE compared with HREE in perovskite. In addition, zonation is not always perfectly concentric. For instance, one of the rim analyses in Figure 54 is almost identical to the core analysis, while the other is significantly depleted in LREE.

Care was exercised when choosing a spot on the zoned crystals for analysis. In particular the rim regions were avoided, as these are areas where the greatest fluctuations in REE contents exist. Fortunately, significant zoning in perovskite is optically recognizable in thin section and easily seen in SEM backscattered electron images. Given this kind of control, anomalous analyses associated with zoning were minimized. Furthermore, zoning shown

Figure 54. Laser ablation ICP-MS perovskite REE distribution profile of zoned crystal. REE zonation is mostly a function of the LREE.

in Figure 54 represents an extreme example for Mata da Corda rocks. Most rim-core analyses exhibit a much smaller variation in composition, such that the differences between perovskites from distinctly different rocks types are much greater than that attributed to REE zonation. Consequently, variation between groups is greater than that within groups, a condition necessary for effective discrimination. Also of note is the overall shape of the REE distribution profile, in which perovskites are enriched in LREE and depleted in HREE relative to the average perovskite of sample FB46.

This form is shown by most of the Mata da Corda Formation kamafugites and lamproites.

A xenolith collected from the xenolith-rich breccia pipe phase of the Quintinos polyphase intrusion is shown in Plate 23. It consists of two xenoliths, a rounded kamafugite xenolith core (QP37) surrounded by the kamafugite intrusion host (QP37a). A closeup of the contact region between the two (Plate 24), clearly shows a chill zone separating them. Although the two rocks are touching, their genetic relationship is unclear. Either QP37 is a piece of foreign material simply caught up in the host (accidental xenolith), or it is a cognate xenolith, representative of the source material from which the kamafugite host was derived. To test the two possibilities, perovskites from both samples were analysed and their average normalized REE data presented in Figure 55. The resulting REE distribution profiles are virtually identical, implying that the enclosed xenolith (QP37) is in fact a cognate xenolith. A third sample (AL13a), from the Agua Limpa map area located several kilometres East of

Figure 55. Laser ablation ICP-MS perovskite REE distribution profile of samples QP37 & QP37a. The strong correlation between the profiles suggests QP37 is a cognate xenolith and that QP37a was probably derived from it. AL13a is a kamafugite intrusive sample from Agua Limpa included to show that not all kamafugites possess identical REE patterns.

the Quintinos pipe (Fig. 2), was plotted on the diagram to demonstrate that not all kamafulite intrusions have identical perovskite REE contents.

Detailed mapping of the Quintinos pipe (Appendix 1, Plates 2 to 5) and at Agua Limpa (Appendix 3, Plates 3, 4) revealed the contact relationship between two different kamafulite intrusions. At each location, weakly silicified, locally brecciated, kamafulite blocks are intruded by non-silicified massive kamafulite (Plate 25). Because the second intrusion

erodes more readily than the silicified phase, it is best exposed along slope sections where it is easily identified by its distinctive bluish colouration and interstitial relationship with blocks of kamafulite breccia (Plate 26). At both locations samples were collected within metres on each side of the contact. Their normalized REE profiles are shown in Figure 56. Although the breccia and massive types have similar whole rock major oxide and trace element contents (Appendix 1, Table 3), consistent with their kamafulite classification, the perovskite REE profiles clearly show they are different. In particular, perovskites of the massive kamafulite (later intrusion) are more enriched in REE than those of the brecciated phase, perhaps an indication that the former was derived from a more evolved melt. At Fazenda Andorinha (Chapter 2 and Appendix 11) cyclical differences in rock composition within the kamafulite flow sequence are attributed to a source that has geochemically evolved with time. Perhaps a similar model could explain the REE differences between the brecciated and massive kamafulites. Accordingly, REE would behave as incompatible elements in the early formed perovskites. Thus, the residual melt would become progressively enriched in REE with time. As a result, the latter perovskites would have a

Figure 56. Laser ablation ICP-MS perovskite normalized REE distribution profiles of the two types of kamafulite intrusions.

higher REE content than the perovskites that crystallized earlier. Because perovskite REE data supports the intrusive contact relationships observed at both locations (regarding their relative timings of emplacements), it is proposed that perovskite can be effectively used for rock type discrimination in the Mata da Corda.

Figure 57. Location of samples used to demonstrate perovskite's ability to recognize the genetic association between comagmatic intrusions and flows. Ribeirão da Mata map Area.

Outcrops of kamafugite flows are generally spatially associated with intrusions, yet the two were never observed in direct contact. The implication is that intrusions represent feeders to the flows, but the association remains somewhat tenuous due to the lack of direct physical evidence. Laser ablation analyses were carried out on perovskites from flows and intrusions to find out whether perovskite REE contents are useful in addressing this issue.

Samples of two kamafugite flows and two kamafugite intrusions were analysed from the Ribeirao da Mata volcanic centre. The two flow and intrusion pairs lie about 850 metres apart (Fig. 57). Samples M78 (intrusion) and M128 (flow) lie about 50 metres apart (see Fig. 57). Although they are not in direct contact, strong similarities in their perovskite REE contents (Fig. 58) suggest they are probably derived from the same source, possibly from the same eruptive event. The other

Figure 58. Laser ablation ICP-MS perovskite normalized REE distribution profiles of kamafugite flows and intrusions.

two samples, M145 (intrusion) and M142 (flow) are within 75 metres of one another and show equally strong similarities suggesting they are also genetically related. Also of interest is the marked difference between the two groups of intrusions and flows. Despite the fact their overall perovskite REE distribution patterns are similar, their LREE contents are distinctly different, implying that they could not have been erupted from a melt of the same REE composition. Since not all flows or intrusions within this centre host perovskites with identical REE contents, there must be some process at work causing REE variation. This may be related to temporal differences, such as continuous fractionation which would change the REE composition of the source region, such that each successive event is erupted from a slightly evolved source. Such a process was proposed to explain the differences in perovskite REE contents between the two different kamafugite intrusions at Agua Limpa and the Quintinos pipe, and the cyclical changes in composition observed within the flows at Fazenda Andorinha. Alternatively, variations may be a function of source mixing (crustal contamination has previously been ruled out), or repeated influx of new melt into an open system. Whatever the process, it is apparent that perovskite REE contents reflect the

change, and can be used as a very effective mapping tool.

Plate 25. Typical intrusive contact relationship between older, weakly silicified, kamafugite breccia and younger massive kamafugite. Quintinos Pipe.

Plate 26. Intrusive contact relationship between older, weakly silicified, kamafugite breccia and younger massive kamafugite intrusion. The darker blueish colour is typical of the massive kamafugite. Agua Limpa map area.

Plate 23. Kamafugite xenolith from the ultramafic xenolith-rich breccia pipe phase of the Quintinos polyphase intrusion. The ruler is 15 cm long.

Plate 24. Close-up of the contact region between the xenolith and its host. Note the distinctive contact aureole.

5.4 KAMAFUGITES, LAMPROITES AND KIMBERLITES

Kamafugites, lamproites, and kimberlites occur within this part of the Alto Paranaíba Igneous Province. Kimberlites are believed to be primitive magmas, representing small degrees of partial melting of carbonated asthenospheric mantle (Scott, 1996). On the other hand, kamafugites are thought to be derived by small degrees of partial melting of a metasomatized lithospheric mantle, in an environment of high $\text{CO}_2/\text{H}_2\text{O}$ ratios (Edgar, 1987).

Mitchell and Bergman (1991) proposed that partial melting of ancient metasomatized lithospheric mantle, under H₂O-rich conditions, produced lamproites. They also comment that although kamafugites and lamproites are derived from similar metasomatized mantle, extreme differences in their sources and compositions refute any genetic link between the two. In contrast, based on perovskite REE data obtained in this study, in association with detailed geological mapping, a common source for the generation of kamafugite and lamproite magmas can be inferred for those from the Mata da Corda.

If one accepts the premise that perovskite is the dominant REE sink in alkaline rocks when present in sufficient quantities (Nagasawa *et al.*, 1980; Jones and Wyllie, 1984; Mitchell and Reed, 1988; Dawson *et al.*, 1994; Dawson *et al.*, 1995; Lloyd *et al.*, 1996; Mitchell, 1996; Campbell *et al.*, 1997), and that its REE distribution profile, particularly the LREE, reflects its source region (Sun and Hanson, 1975; Beswick and Carmichael, 1978), then not only should perovskite REE data help discriminate between rock types, but it should also shed light on the REE composition of the source region. In other words, perovskites from different sources should convey those differences through their REE distribution profiles.

Average perovskite REE contents of brecciated kamafugites, massive kamafugites, a Type 1 kimberlite (Tres Ranchos), olivine-phlogopite lamproites, olivine lamproites, and an olivine leucite lamproite were normalized to FB46 and presented on a common diagram to facilitate comparisons (Fig. 59). Although all samples have similar profile shapes, one sample, the Tres Ranchos kimberlite, stands apart from the others, in that its perovskites are considerably enriched in LREE and, to a lesser extent, the HREE. The rest of the samples define a loose cluster, noticeably lacking distinct fields related to lamproite and kamafugite affinities. In addition, there are some noticeable differences in Ce, Pr, and Nd. For the Tres Ranchos kimberlite, the three elements define a negative slope, whereas the kamafugites and lamproites show a clear positive slope. Therefore, it appears that two different sources are represented in Figure 59, a kimberlite source significantly enriched in LREE, and a common source for kamafugite and lamproite generation.

Figure 59 shows that kamafugite and lamproite patterns overlap, suggesting that they are not products of separate, independent, source regions. Instead, it can be argued that they originated from a single source possessing similar REE contents, and that they represent different end member compositions possibly due to crystal fractionation, a

premiss consistent with the geological mapping. For instance, at Fazenda Grotao,

Figure 59. Laser ablation ICP-MS perovskite normalized REE distribution profiles of study area kamafugite intrusion, lamproites, and kimberlites. Note the similarity in profile shape and lack of definition between the kamafugites and lamproites. See text for explanation.

and Ribeirao da Mata (Fig. 2), olivine lamproite intrusions lie within 10 m of kamafugite intrusions. Furthermore, at Quintinos, Fazenda Bananal, and Agua Limpa (Fig. 2) several kamafugite and lamproite xenoliths were collected from outcrops of xenolith-rich breccia pipe. Perhaps the best explanation for these typical spatial associations is that they were derived from a common source. To argue otherwise would be to propose that separate sources for kimberlite, lamproite, kamafugite, carbonatite, melilitite, and clinopyroxenite magmas would have underlain this igneous province; that compositional different intrusions would have been independently emplaced, sometimes within metres of one another; that xenolith-rich breccia pipes commonly containing both lamproite and kamafugite xenoliths have no genetic affiliation; and that this would be best explained by the presence of wholly isolated magma sources. Such a viewpoint implies that an extremely complex, detached, plumbing system was once active beneath the Mata da Corda. Perhaps this order of complexity is not the most realistic explanation for the occurrences of so many different rock types in such a confined area. Instead, it is proposed that the geological mapping and

perovskite REE chemistry evidence points to the more acceptable and realistic portrayal, one of a common source region.

Perovskite REE contents may also help in the identification of certain rock types. Initially, X626 (Fig. 59) was tentatively classified as a kimberlite, based mainly on the presence of a chromite xenocryst (63 wt.% Cr_2O_3 , diamond inclusion field), a lack of groundmass diopside, abundant matrix phlogopite (<2.0 wt.% TiO_2), and olivine xenocrysts altered to serpentine. However, the REE contents of perovskites from it do not reflect a kimberlite affinity. In particular, it lacks the Ce, Pr, Nd negative slope characteristic of the Tres Ranchos kimberlite, and its perovskite LREE pattern falls well below the Tres Ranchos kimberlite pattern, and lies within the kamafugite/lamproite field. This could have significant diamond exploration implications, as only kimberlites and olivine lamproites are known hosts to economic concentrations of diamonds. Perhaps perovskites can be used to discriminate rocks with diamond bearing potential from those that do not, such as the kamafugites. Thus, there exists the possibility that perovskite might be a useful complement to other more traditional diamond indicator minerals.

So far, all Mata da Corda perovskite REE profiles presented (aside from the Tres Ranchos kimberlite) possess roughly similar patterns. To test if all perovskites, regardless of rock type or source, have a similar normalized profile shape, perovskite REE data of two medium-grained kalsilitolite xenoliths (Gr17 & GR23) from Fazenda Grotao (Fig. 2) are presented (Figure 60). Clearly, their REE profiles do not have the typical Mata da Corda shape. It appears that the REE compositions of their perovskite indicate they are

Figure 60. Laser ablation ICP-MS perovskite normalized REE distribution profiles of samples GR17 and GR18.

different, and their unique mineralogy certainly confirms this. The kalsilitolite xenoliths were collected because of their different macroscopic characteristics, but it was not until subsequent microscopic and SEM-EDS analyses that their remarkable, and unique, mineralogy was revealed. GR17 (Plate 27) consists of euhedral kalsilite pseudomorphs (altered to secondary potassic feldspar), anhedral diopside, poikilitic phlogopite, and minor aegirine-augite, perovskite, apatite. GR23 (Plate 28, 29) is different, containing several extraordinary accessory minerals, including wadeite, richterite, shcherbakovite, an unknown K-Ti silicate, and an unknown K-Fe silicate. No other sample like it has been identified from this igneous province. Fortunately, both samples contain perovskite suitable for laser ablation analyses. Since the two samples do not show the typical Mata da Corda perovskite normalized REE profile shape, it is believed they are not compositionally related to the Mata da Corda igneous event. As xenoliths, they may represent exotic material sampled by some of the Mata da Corda magmas. Outcrops of kalsilitolite intrusions were not found, nor is there any mention of this kind of rock existing within the Alto Paranaíba Igneous Province.

The results of the perovskite laser ablation study indicate that most rock types present within the study area appear to be related to a common source region, in particular, the kamafugites and lamproites. They are both so closely related in terms of their mineralogy, mineral chemistry, whole rock major oxide and trace element chemistry, and perovskite REE contents, that it is believed their genesis may be best explained through fractional crystallization of a common magma source. Conversely, the Tres Ranchos kimberlite's LREE enriched perovskites suggests its source was different from all other Mata da Corda rocks. On the other hand, perovskite REE profile shapes of samples GR17 and GR23 are so different from the typical Mata da Corda shape that there can be little doubt their magma source is different from that of the other rocks studied.

Besides normalized plots, many scatter diagrams of perovskite REE contents were produced to study similarities and differences between Mata da Corda flows, intrusions and xenoliths of magmatic origin. Accordingly, trace element contents were examined for possible rock type discrimination applications. Initially, each of six map areas was studied independently, but subsequent studies were broadened, incorporating all map areas and all

rock types.

Plate 27. Kalsilitolite xenolith GR17.

Plate 28. Kalsilitolite xenolith GR23.

Plate 29. Kalsilitolite xenolith GR23.

Although La, Nd and Yb are commonly considered incompatible elements, La and Nd are somewhat compatible within the perovskite crystal structure, while Yb is not. During fractional crystallization compatible trace element concentrations change in a melt (Rollinson, 1993). This is demonstrated for Mata da Corda rocks in Figure 61, showing perovskite La/Yb vs. La/Nd data for kamafugite flows, kamafugite intrusions, and xenoliths from six map areas. The La/Yb ratio reflects the degree of REE fractionation, while La/Nd measures the degree of LREE fractionation. The large data range in La/Yb ratios clearly shows the fractionation of LREE from HREE, while the smaller variation in La/Nd ratios is evidence that LREE fractionation is minimal. The resulting data distribution defines an asymptotic curve, with very few anomalous samples. Such a well-constrained population, made up of four different rock types from six different map areas separated by several tens of kilometres, is perhaps best explained if it is considered that they were all derived from a common source, and that their perovskite REE variation is primarily a function of fractionation. If magma mixing of two or more different components were proposed as a

possible explanation for perovskite REE variability, then it would also have to be explained how such a seemingly haphazard process could lead to the generation of four different rocks types (separated by great distances) all having perovskites with similar REE compositions. Although the system may have been open to new additions of melt, potential additions were not drastically different in terms of their REE content. If they were, a greater scatter of sample points shown on Figure 61 would be expected.

Perovskite composition, as it applies to similarities and differences between kamafugites, lamproites, and kimberlites, was also studied. Normalized perovskite REE diagrams indicate that Mata da Corda lamproites and kamafugites were derived from the same source, and that the Tres Ranchos kimberlite originated from a source very similar to the others, but significantly enriched in LREE. Plotted on a La/Yb vs La/Nd diagram (Fig. 62), these samples show the same trend as

Figure 61. Perovskite La/Yb vs La/Nd plot of igneous rocks from map areas Ribeirao da Mata, Fazenda Bananal, Fazenda Grotao, Fazenda Andorinha, Agua Limpa, and Quintinos pipe map areas (see Fig. 2 for locations)

Figure 62. Perovskite La/Yb vs La/Nd plot of Mata da Corda lamproites and kamafugites.

in Figure 61, suggesting that Mata da Corda lamproites and kamafugites are cogenetic. The only analyses that do not belong to the cluster are those of the Tres Ranchos kimberlite, which is omitted from the diagram in order to more effectively show the kamafugite and lamproite trend, and the lack of distinction between the two.

At the beginning of this chapter it was shown that normalizing the perovskite data to the average perovskite of sample FB46 more effectively illustrates differences in perovskite trace element content than normalizing to chondrite. As shown in Plate 20, the basic mineralogy of FB46 consists of diopside, kalsilite, perovskite, and Ti-rich andradite garnet. Figure 63 shows the perovskite and garnet REE contents normalized to chondrite, thus illustrating the capacity of

Figure 63. Perovskite and Ti-rich andradite garnet from sample FB46 normalized to chondrite.

Figure 64. FB46 Ti-rich andradite garnet normalized to the average perovskite of FB46.

perovskite to accommodate a greater LREE content than garnet, and conversely, garnet's greater affinity for HREE.

However, when the garnet REE data is normalized to the perovskite (FB46) data (Fig. 64), the plotted sample points produce a well-defined asymptotical curve. Thus, ratioing REE data for garnet to perovskite (FB46) illustrates the relationship between the partition coefficients for REE substitution in these two minerals. The diagram also reveals two other important things. First, it appears that garnet and perovskite are in equilibrium and are the only two minerals extracting appreciable REE from the melt. If there were other phases, such a well-defined data curve would not be produced, leading to a more scattered dispersal. Secondly, the LAM-ICP-MS technique is very effective for accurately detecting REE contents. If there were analytical problems in detecting any of the elements, than that would manifest itself as data points lying off the data trend.

5.5 CONCLUSIONS

Results of this study reveal that:

- 1) perovskite REE content is effective for identifying coeval flows and feeder intrusions, thus constituting an effective mapping aid in confirming similarities defined by geological mapping and petrography.
- 2) perovskite REE can discriminate cognate xenoliths from accidental xenoliths.
- 3) differences between two distinctive kamafugite intrusions, and their relative timings of emplacements, are reflected in perovskite REE contents.
- 4) perovskite REE reveal that Mata da Corda kamafugites and lamproites are genetically related, and are best explained as products of fractionation from a common magma source.
- 5) Mata da Corda kimberlites have drastically different perovskite REE contents than associated lithologies of kamafugitic and lamproitic affinities. This last observation may have merit as an exploration tool, as only kimberlites and olivine lamproites are hosts to economic concentrations of diamonds. Perhaps perovskites can be used to discriminate rocks with diamond bearing potential from those that have no potential, such as the kamafugites. Thus, there exists the possibility that perovskite might be a useful complement to other more traditional diamond indicator minerals.

CHAPTER 6

CONCLUSIONS

6.0 CONCLUSIONS

Eighty million years ago a large episode of continental volcanism produced the mafic potassic and mafic ultrapotassic rocks of the Mata da Corda Formation (Gibson et al., 1995; Card, 1996). The dominant eruptive style was passive, fissure fed, eruptions of low viscosity magmas, akin to flood basalt-type eruptions, that lead to the creation of the now largely eroded Mata da Corda lava plain. The onset of volcanism was characterized by hundreds or perhaps thousands of brief phreatomagmatic and/or magmatic eruptions forming maar-type volcanoes. Thus, in this volcanic field's current eroded state, vent systems are marked by maar-type craters.

A typical Mata da Corda volcanic centre was fed by one, or several, polyphase intrusive pipes. Two types of kamafugites may be present, an older, weakly silicified, brecciated intrusion, and a later, massive, non-silicified intrusion. Lamproite intrusions may also be present, and typically occur close to the kamafugites. Ultramafic xenolith-rich breccia pipes can occupy the same pipes as the kamafugites, or, more commonly, lie along the margins of the volcanic edifice. Pyroclastic rocks are not present in the underlying pipe, evidence that a downward propagation of a prototypical maar diatreme did not develop beneath some Mata da Corda volcanoes. Within the central portion of the edifice, lower crater facies rocks are dominated by volcanic intrusions, kamafugite flows, and minor lapilli tuffs. Intrusions are less common within marginal sections of the crater, where flows and fluidized Areado sandstone breccias dominate. At all centres the overlying crater facies materials have been eroded, thus evidence establishing the lateral extensiveness of the flows is lacking.

The sequence of flows at Fazenda Andorinha represents the only known occurrence of flows outside the crater setting, and is considered, in part, representative of the once extensive Mata da Corda lava plain. Preserved in the 110 m stratigraphic section is 22 individual kamafugite flows, with associated flow-top and foot breccias. Flow thicknesses vary from < 2 m to 10 m. Columbia River flood basalts range in thickness from 15-35 m, while less viscous ultramafic komatiites typically range in thickness from <1 m to > 10 m (Cas and Wright, 1993). Thus, the consistency of flow thicknesses at Fazenda Andorinha, and those described herein within the Mata da Corda maar-type craters, is consistent with low

viscosity lavas. Given a conservative estimate that the pre-eroded Mata da Corda once spanned 40,000 km², and that the lava plain was at least 250 m thick (twice the known thickness of the Fazenda Andorinha flow sequence), then a volume of at least 10,000 km³ would have been erupted. In comparison, considerably less than the 195,000 km³ calculated for the Columbia River flood basalts.

The geochemical evolution of the flows documented at Fazenda Andorinha, in accordance with their crystal-rich nature, suggests that the magmas originated from a fractionating source. Presumably, this hypabyssal magma chamber was an open system allowing the influx of compositionally homogeneous magma between eruptions, leading to the distinctive flow cycles preserved at Fazenda Andorinha.

Of the five areas mapped in detail, only the basal sections of the volcanic edifices are left intact, and they lack the deposits and features indicating that prolonged hydrovolcanic eruptions were responsible for their creation. The lack of definitive evidence for sustained phreatomagmatism suggests that brief phreatomagmatic and/or magmatic eruptions were responsible for crater excavation. These were immediately followed by voluminous flood basalt-type eruptions that quickly filled the crater (thus preserving the lower crater facies rocks) and generated laterally extensive alkaline flows. Although sustained interaction between water and ascending magma does not appear to have occurred in the areas studied, there are hundreds of other volcanic centres in this field where suitable conditions may have existed. Thus, the presence of typical maar volcanoes in the Mata da Corda, and their associated underlying well-developed diatremes, cannot be ruled out.

Initial eruptions were centred within the Areado sandstone, excavating maar-type craters below the pre-eruptive surface. However, craters failed to develop further as continued maar forming eruptions were arrested, either because the local aquifer was unable to recharge, thus explosive interaction of magma and water could no longer take place, the aquifer was effectively sealed by the enormous outpouring of lava, or assuming the initial eruptions were magmatic, once the Areado sandstone cap rock was explosively breached, conditions were no longer suitable for violent magmatic eruptions.

On geochemical discrimination diagrams most Mata da Corda samples plot consistently

within the kamafugite field and a few within the lamproite field, showing that they have a strong kamafugitic affinity, and some lamproitic characteristics. However, the most distinguishing compositional feature of the Mata da Corda Formation rocks is their extremely elevated Nb values, making this mafic ultrapotassic volcanic province geochemically unique. It is believed that kamafugite and lamproite intrusions, kamafugite flows, and some ultramafic xenoliths share a similar source composition, and that fractional crystallization is the dominant process leading to magma evolution. The volcanological evidence presented in Chapter 3 is consistent with this interpretation. Although, it is currently accepted that kamafugites and lamproites are derived from distinct mantle sources, Mata da Corda rocks do not exhibit lithogeochemistries consistent with this model. In fact the compositional similarities and common occurrences of Mata da Corda kamafugites and lamproites are best explained if they are viewed as fractionated products derived from a common source.

Mata da Corda Formation rocks are mineralogically similar, yet distinct, when compared to other ultrapotassic volcanic provinces. For instance, they contain a higher percentage of diopside, perovskite, and zeolites. In addition, rare kalsilite was found at Fazenda Bananal (the second known occurrence reported in the Mata da Corda); wadeite at Fazenda Grotao, Ribeirao da Mata, and the Quintinos pipe, representing the first known occurrences in South America; shcherbakovite at Fazenda Grotao (the first known occurrence in the Mata da Corda), and melilite at several other locations throughout the Mata da Corda. Also, two possibly new minerals were identified in a kalsilitite xenolith collected from Fazenda Grotao.

The lamproite mineralogical classification scheme proposed by Woolley et al. (1996) cannot be practically applied to Mata da Corda rocks. In general, Mata da Corda kamafugites have a similar mineralogy to Mata da Corda lamproites except that they lack forsterite. For example, concerning diopside and phlogopite, two minerals cited in their definition, there is no difference in composition between the two rock types. Thus, a forsterite bearing Mata da Corda kamafugite, by virtue of their definition, would be a lamproite. Samples FB27 and FB46 are excellent examples of the failings of this definition when applied to Mata da Corda rocks. Phlogopite and diopside compositions of FB27 fall within the required lamproite thresholds, yet they also host kalsilite, whose presence dictates a kamafugite designation.

In addition, the kalsilitite xenolith FB46 contains Na and Al deficient diopside, typical of lamproitic diopsides. To confuse matters even further, three xenolith samples QP12, M170 and RBD contain phlogopite and diopside in accordance with the lamproite definition, but a third primary phase is lacking (such as forsterite); therefore, they were classified as kamafugites. However, subsequent SEM-EDS analyses revealed the presence of wadeite, thereby changing their classification from kamafugite to lamproite. In essence, the only major mineralogical difference between these rocks is the presence or absence of the typomorphic minerals wadeite and kalsilite, yet according to current thought this is sufficient evidence of two separate magma sources. Sample GR23 is a kalsilitite xenolith collected from Fazenda Grotao that contains more wadeite than any other sample yet known from the Mata da Corda, however other than the presence of two lamproite accessory minerals, wadeite and shcherbakovite, it does not conform to the lamproite definition. Of the seven primary lamproite minerals only Na and Al-depleted diopside is present. In addition, a second pyroxene is present and plots as aegirine-augite on a Ca-Mg-Fe-Na pyroxene classification diagram. The sample also contains kalsilite pseudomorphs, a typomorphic mineral of kamafugites. Thus, this sample contains both lamproite and kamafugite determinant minerals.

Both lamproites and kamafugites occur in almost every map area. In some instances, such as at Fazenda Grotao, the two types of intrusions are almost in contact, while at others, there is an abundance of lamproite xenoliths within volcanic centres dominated by kamafugite intrusions (Ribeirao da Mata and Quintinos). This recurring spatial association raises the question that Mata da Corda lamproites and kamafugites may not have originated from two different, and mutually exclusive, sources. Field relationships point to the possibility that they may share a common genesis, and that their minor chemical and mineralogical differences are a function of magma fractionation. Edgar (1996) hints that some sources for lamproites and kamafugites are similar. Stoppa and Cundari (1998) take this argument further, proposing that the common association of kamafugites and carbonatites at San Venanzo-Pian di Celle (Umbria, Italy) resulted from a carbonate-rich melt separating from a mantle source. A similar carbonatite-kamafugite association is present within the Mata da

Corda, but is far from being as strong as the kamafugite-lamproite association.

In support of this argument, results of the perovskite laser ablation study also suggest that most rock types present within the study area can be related to a common source region, in particular, the kamafugites and lamproites. They are both so closely related in terms of their mineralogy, mineral chemistry, whole rock major oxide and trace element chemistry, and perovskite REE contents, that we believe they are best explained as fractionation products from a common magma source. Conversely, the Tres Ranchos kimberlite's LREE enriched perovskites suggests its source was different from all other Mata da Corda rocks. On the other hand, perovskite REE profile shapes of samples GR17 and GR23 are so different from the typical Mata da Corda shape that there can be little doubt their magma source is different from that of the other rocks studied. In summary, results of this study in conjunction with the detailed mapping of seven volcanic centres, reveal that:

- 1) perovskite REE content is effective for identifying coeval flows and feeder intrusions, thus constituting an effective mapping aid in confirming similarities defined by geological mapping and petrography.
- 2) perovskite REE can be used to help distinguish cognate xenoliths from accidental xenoliths.
- 3) differences between two distinctive kamafugite intrusions, and their relative timings of emplacements, are reflected in perovskite REE contents.
- 4) perovskite REE suggests that Mata da Corda kamafugites and lamproites are genetically related, and are best explained as products of fractionation from a common magma source.
- 5) Mata da Corda kimberlites have drastically different perovskite REE contents than associated lithologies of kamafugitic and lamproitic affinities. This last observation may have merit as an exploration tool, as only kimberlites and olivine lamproites are hosts to economic concentrations of diamonds. Perhaps perovskites can be used to discriminate rocks with diamond bearing potential from those that have no potential, such as the kamafugites. Thus, there exists the possibility that perovskite might be a useful complement to other more traditional diamond indicator minerals.

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CANABRAVA DIAMOND CORPORATION

PATOS DE MINAS PROJECT
MINAS GERAIS STATE, BRAZIL

QUINTINOS PIPE (BLOCK K)
ANOMALY X433

SURFACE GEOLOGY MAP

DATE: MAY, 1997
GEOLOGICAL MAPPING AND AUTOCAD BY: MIKE BYRON

THS
P.H.D.
1999
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5 of 6

THS
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Map 6

Fazenda Andorinha Road Section
(looking southwest)