Geochemical characteristics and tectonic setting of metamorphosed rocks in the Tugela terrane, Natal belt, South Africa

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Abstract: The isotopically juvenile Tugela terrane, part of the Grenvillian Natal belt, southeastern Africa consists of a heterogeneous assemblage of regionally metamorphosed (upper amphibolite facies) mafic and felsic rocks. The Tugela terrane is divisible on the basis of lithology and structural style, from east to west, into four major thrust sheets referred to as the Nkomo, Madidima, Mandleni and Tugela sheets, respectively. The Tugela sheet includes the Kotongweni tonalite, a 15 km long body of coarsely crystalline garnetiferous hornblende meta-tonalite. Although strongly lineated and foliated, the intrusive contact of the tonalite with its amphibolite wall rocks remains recognizable, as are wallrock xenoliths within the intrusion. Geochemically, the tonalite is extremely depleted with very low abundance of Ta, Nb, rare earth elements (REE) and LIL elements, features considered diagnostic of arc-related igneous rocks. The lithological and geochemical characteristics of the tonalite and its amphibolite wallrocks suggest their formation in an intra-oceanic arc setting comparable to the present day Izu-Bonin arc. In contrast, amphibolites of the underlying Mandleni sheet are characterized by relatively high abundance of Nb, Ti, LIL and HFS elements more similar to the present day oceanic island basalt. The lithologically and geochemically distinct thrust sheets that comprise the oceanic Tugela terrane were each derived from distinct tectonic settings. The Kotongweni tonalite and its wall rocks, preserved in the Tugela sheet, provide a record of middle Proterozoic magmatic arc development prior to the obduction of the Natal belt onto the Kaapvaal craton at about 1.1 Ga.

key words: Natal, Tugela, Grenvillian, intra-oceanic arc, South Africa

1. Introduction

The Grenvillian-age Natal belt is located in the eastern part of South Africa. It is a part of the Proterozoic Namaqua-Natal mobile belt surrounding the southern margin of the Kaapvaal craton. The Natal belt has been thought as one of the juvenile continental fragments of the first super continent “Rodinia”. The belt is divided into three terranes, each of them having distinct structural, lithologic, and tectonic characteristics (Thomas, 1989). They are from north to south, the Tugela, Mzumbe, and Margate terranes. The
Tugela terrane has long been interpreted as an ophiolite complex (accreted oceanic crust: Matthews, 1972; Matthew and Charlesworth, 1981) obducted onto the Kaapvaal craton, while the Mzumbe and Margate terranes have been thought of as deeply eroded magmatic arcs (Thomas, 1989; Thomas et al., 1999).

During March 1998 and March and August 1999, field surveys were conducted in the Tugela terrane as parts of the Japan-South Africa Joint Research Program. The aims of this joint study were to map various lithologic units, to collect representative rock samples for geochemical and petrographic analyses, and finally to make protolith interpretation of the metamorphic rocks based on the integration of these field, geochemical and petrographic data. Detailed description of the modes of field occurrence and petrographic characteristics of various lithologic units in the Tugela terrane are to be published elsewhere. This paper reports geochemical data of various lithologic units that provide valuable constraints for estimation of their protoliths.

2. Geological setting

The Tugela terrane is composed of four separated tectonostratigraphic packages from east to west respectively referred to as the Nkomo, Madidima, Mandleni, and Tugela sheets (Matthews, 1972; Matthew and Charlesworth, 1981) (Fig. 1). In the Nkomo and Madidima sheets, thick successions of quartzo-feldspathic gneiss is the predominant lithologic units with subordinate amounts of metamorphosed sedimentary rocks and amphibolite, while the Mandleni and Tugela sheets consist of bimodal meta-igneous rocks (mafic-ultramafic meta-volcanic rock and felsic gneiss). Numbers of small bodies of ultramafic schists (serpentine- and talc-chlorite schist) are recognized in the Tugela terrane, thought to define imbricate thrust faults (Matthews, 1959; Harmer, 1979). The Madidima sheet consists of leucocratic biotite feldspathic gneiss with lesser amounts of amphibolite and metasedimentary gneiss. Details of lithology, structure and metamorphism of the Madidima and Mandleni sheets are given by Johnston et al. (2001b). New U-Pb geochronological data (SHRIMP and TIMS) along with details of stratigraphy and structural geology of the Tugela terrane are presented in this volume by Johnston et al. (2001a).

The Tugela sheet the highest tectonostratigraphic package within the Tugela terrane consists of two structurally distinct tectonic slices, the Manyane and Tuma slices (Matthew and Charlesworth, 1981) (Fig. 1). The Tuma slice is separated from the former by thrust faults. The Tuma slice is composed of metasedimentary rocks with subordinate amounts of metamorphosed basaltic pillow lavas and volcaniclastic rocks. The Manyane slice consists predominantly of amphibolite referred to as the Manyane amphibolite and subordinate amounts of metamorphosed gabbroic rocks.

The Kotongweni tonalite complex (Harmer, 1979; Johnston et al., 1998), a 15 km long intrusive body of coarsely crystalline garnetiferous hornblende tonalitic gneiss, is exposed along the Tugela River (Fig. 1). Although strongly deformed, the intrusive contact of the tonalite with the Manyane amphibolites remains recognizable. The complex consists mainly of tonalitic rocks with subordinate amounts of gabbroic rock. Hornblende (Mg/(Mg+Fe)=0.40-0.50), plagioclase (An37-58), quartz and garnet
(Alm₆₅Gro₁₆Pyr₁₆Spe₆) are essential mineral constituents of both tonalite and gabbro. The deformation features of the tonalite complex suggest that it was intruded prior to the obduction of the Tugela sheet onto the Kaapvaal craton (Johnston et al., 2001a). Several additional plutonic bodies are exposed in the Tugela sheet, including the mafic-ultramafic Tugela Rand and Macala complexes, the Ntabasongoma gabbroic intrusion, the Mkondene diorite, and the Dimane granite (Fig. 1) (Matthew and Charlesworth, 1981). They are thought to be younger intrusions on the basis of their structural features (Johnston et al., 2001a).

The Mandleni sheet consists predominantly of felsic gneisses with lesser amounts of amphibolite (the Mandleni amphibolite). The Evuleka layered ultramafic intrusion (Wuth and Archer, 1986) and the Mambulu “massif” type anorthosite complex (Reynolds, 1986) intruded into the Mandleni felsic gneiss and amphibolite. Within the Madidima, Mandleni and Tugela sheets, large numbers of granitic sheets and dykes, referred to as the Wosi granitoid suite (Johnston et al., 2001a) are recognized. They are weakly deformed (up to 30 m thick) intrusions consisting of trondhjemite, granite, quartz monzonite or two-mica granite.

3. Geochemistry

Two hundred and forty-seven samples were collected from the Madidima, Mandleni, and Tugela sheets (Appendix 1). Sample localities are given in Fig. 1. We paid special attention to collect rock samples representative of protolith composition. Central portions of thick homogeneous layer were taken for geochemical samples to avoid chemical modification during metamorphism and alteration. Amphibolites with thin felsic veins and heterogeneous migmatitic gneisses were excluded from geochemical analyses. We carried out XRF whole rock analyses for 141 metamorphosed igneous rocks, and made ICP-MS analyses for 43 rock samples. Major and trace element (Ba, Co, Cr, Cu, Nb, Ni, Rb, Sr, V, Y, Zn, Zr) abundance were determined with X-ray fluorescence (XRF) (RIGAKU RIX-3000) at the National Institute of Polar Research, Japan. The glass beads for major and trace element analyses were prepared from powdered samples that were diluted with five times by Lithium Borate (Li₂BO₂). The analytical procedure followed the methods by Motoyoshi and Shiraishi (1995) and Motoyoshi et al. (1996). Detection limits of major and trace elements are 0.01 wt% and 0.1 ppm, respectively. Trace elements (rare earth elements (REE), Li, Be, Rb, Y, Zr, Nb, Mo, Sn, Sb, Cs, Hf, Ta, Ti, Pb, Th, U) were analyzed by the ICP-MS (Inductivity-coupled plasma mass spectrometry) at the Department of Geology, Shimane University. Kimura et al. (1995) and Roser et al. (2000) described the methods used and precision of the analysis. Mineral analyses were carried out with an automated energy-dispersive electron microprobe (LINK QX2000J system) at the Geological Institute, Yokohama National University. Operating conditions were 15-kV and 0.15 × 10⁻⁶ ampere on Cobalt; beam diameter 2 μm. Analyses were reduced using the LINK ZAF-4/FLS correction program.

In this paper we describe whole rock compositions of mainly gabbroic to tonalitic rocks of the Kotongweni tonalite complex and Manyane amphibolites in the Tugela sheet, and amphibolites and Wosi granitic gneisses in the Madidima and Mandleni sheets. The whole rock compositions of various lithologic units are given in Appendices 2–9.
Cover Rocks
(Paleozoic-Tertiary)

Fig. 1.
Fig. 1. Geological map of the Tugela terrane. Modified after Matthews and Charlesworth (1981).
Amphibolites in the Tugela and Madidima sheets are within the sub-alkalic field while amphibolites in the Mandleni sheet occupy the alkalic field (Fig. 2). Bimodal distribution of metamorphosed igneous rocks in each sheet is well depicted in this figure. The Kotongweni tonalites plot in the sub-alkalic field in contrast to the majority of the Wosi granitic gneisses which have relatively high Na₂O and K₂O.

Changes in the abundance of major and trace elements in the Kotongweni tonalitic and gabbroic rocks are shown on the Harker variation diagrams of Figs. 3 and 4, respectively. The rocks belong to the calc-alkaline series and exhibit smooth and monotonous major element variations from 44 to 73 wt% SiO₂. Relatively low K₂O (<0.35 wt%) and K₂O/Na₂O (<0.23) are characteristic of all of the rocks analyzed (Appendix 2). These features are comparable to those reported from plutonic rocks in various oceanic island arcs such as the Izu arc (Kawate and Arima, 1998), Philippine (Wolfe et al., 1978), New Britain (Whalen, 1985), Guadalcanal (Chivas et al., 1982), Aleutian (Kay et al., 1983), and Alaska (Barker, 1994). Most of the gabbroic rocks in the Kotongweni complex contain high MgO (up to 6.6 wt%), Al₂O₃ (up to 18.0 wt%) and CaO (up to 11.4 wt%) reflecting the high abundances of hornblende and plagioclase.

Trace element abundances in the rocks from the Kotongweni complex exhibit systematic trends with SiO₂ (Fig. 4). Nb shows constantly low abundance (<3 ppm). Compared with N-MORB (Pearce 1983), rocks of the Kotongweni complex are enriched in Sr, K, Rb, and Ba, and noticeably depleted in Nb, Zr, Ti and Y (Fig. 5), both of which are diagnostic features of rocks from subduction-related settings (Pearce, 1983). Relatively low REE abundances (1 to 10 times chondrite values), flat chondrite-normalized REE patterns are other characteristics of the Kotongweni rocks (Fig. 5). Relatively SiO₂-rich rocks in the Kotongweni complex exhibit a positive Eu anomaly suggesting plagioclase accumulation.

Three types of mafic enclaves are noted in the Kotongweni tonalitic complex (Appendix 3). They are amphibolite-, gabbroic-, and hornblendite-enclave. Compositions of the amphibolite enclave are broadly comparable to those of the Manyane amphibolite (Figs. 3 and 4), implying the former is captured country rock of the Manyane amphibolite. The gabbroic- and hornblendite-enclave were probably derived from
Fig. 3. Major element variations of tonalitic and gabbroic rocks of the Kotongweni tonalite complex. Amphibolite enclaves are comparable in chemistry to the Manyane amphibolite country rocks.
Fig. 4. Trace element variations of tonalitic and gabbroic rocks of the Kotongweni tonalite complex. Amphibolite enclaves are comparable in chemistry to the Manyane amphibolite country rocks.
Fig. 5. MORB normalized Pearce plots and chondrite normalized REE plots of rocks of the Kotongweni complex. Tonalite and gabbro compositions of the Miocene Tanzawa complex, Izu arc are given for comparison. Values of the normalization constants are from Pearce (1983) for MORB and Nakamura (1974) for chondrite.
Fig. 6. MORB normalized Pearce plots and chondrite normalized REE plots of amphibolites in the Manyane slice of Tugela sheet together with amphibolites in the Mandleni and Madidima sheets. Low K-tholeiitic basalt composition of the Izu arc is given for comparison. Values of the normalization constants are from Pearce (1983) for MORB and Nakamura (1974) for chondrite.
Kotongweni tonalitic magma by crystal accumulation processes.

Whole rock compositions of the Manyane amphibolite (Appendix 4) are characterized by relatively high K, Ba, and Rb and low Ta, Nb, Zr and other HFS elements (Fig. 6). These features are comparable to those of the Kotongweni tonalite complex. These data suggest that the Manyane amphibolites were derived from low-K tholeiitic basaltic rocks that are chemically similar to those distributed in present day intra-oceanic arc systems (cf. Kawate and Arima, 1998). The Kotongweni tonalite and Manyane amphibolite wall rocks, preserved in the Tugela sheet, provide a record of middle Proterozoic intra-oceanic arc development prior to the obduction of the Natal belt onto the Kaapvaal Craton.

Distinct compositional difference exists between amphibolites in the Madidima sheet and those in the Mandleni sheet. Compared to MORB, the Madidima amphibolites are characterized by relatively low Ta, Nb, Ti and Zr and high K, Rb and Ba (Appendix 5), which are diagnostic features of rocks from subduction-related settings (Fig. 6)(Pearce, 1983). The Madidima amphibolite is interpreted as metamorphosed low-K arc tholeiitic basalts. In contrast, the Mandleni amphibolites exhibit relatively high abundance in both LIL and HSF elements (Fig. 6) and high Nb/Zr and Nb/Y ratios (Appendix 6, Fig. 7) that are indicative of their derivation from basaltic protoliths formed in a tectonic environment similar to present day oceanic islands (Pearce, 1983). Alternatively these “enriched” Mandleni amphibolites represent an anomalous magmatic event within the arc, possibly in response to the subduction of a spreading ridge and resulting development of a slab window. The chemistry of the Mandleni sheet is strikingly similar to the volcanics of southern Costa Rica and northern Panama which have been related to a slab window developed in response to the subduction of a portion of the Cocos-Nazca spreading ridge (see Johnston and Thorkelson, 1997).

The present data indicate that the lithologically and geochemically distinct thrust
The whole rock compositions of the Wosi granitic gneiss are given in Appendix 7. The Wosi granitic gneisses occupy the granite and trondhjemite fields and characterized by relatively high alumina saturation index (A.S.I.) (Fig. 9). Based on the SHRIMP U-Pb data (1155±1 Ma), the Wosi granite is interpreted as the syn-tectonic granite related to
Marked difference exists between the Kotongweni tonalites in the Tugela sheet and Wosi granitic gneiss in the Madidima and Mandleni sheets.

the exhumation and obduction of the Natal belt onto the Kaapvaal craton (Johnston et al., 2001a). Appendices 8 and 9 report whole rock compositions of the ultramafic schists in the Mandleni sheets and late stage mafic intrusions, respectively.

4. Discussion and conclusion

The data presented here clearly indicate that the Tugela terrane consists of thrust sheets, each of which has a distinct tectono-magmatic signature. The Tugela terrane is interpreted to be an accreted terrane consisting of rocks formed at intra-oceanic island arc and oceanic island (plateau) which are accreted to the continental margin of the Kaapvaal continent. It is likely that thrust faulting and metamorphism occurred during initial collision between the oceanic arc and ocean islands, and subsequently between the imbricated oceanic terranes and the continental margin of the Kaapvaal continent. In this
model, the ultramafic schists widely exposed along the thrust sheet boundaries are interpreted as supra-subduction zone ophiolites. The highly deformed Mfongosi and Ntingwe groups, distributed at the most northern margin of the Tugela terrane (Fig. 1), are interpreted as continental self deposits formed on the passive margin of the Kaapvaal craton. The Mfongosi and Ntingwe groups were probably incorporated within this accretionary complex during the Grenvillian continental-arc collision.

Combining the present data with data formerly reported, we speculate that the Natal belt, including the Mzumbe and Margate terranes, originated as a single intra-oceanic arc—the Natal arc. Arc magmatism is inferred to have developed in response to the subduction of oceanic crust of the Tugela ocean that separated the arc from the Kaapvaal craton. The polarity of subduction would be from the Kaapvaal craton toward the Natal arc (Jacobs and Thomas, 1994). The “Mandleni Oceanic Island or Plateau” once built on a foundation of oceanic crust of the Tugela ocean (Jacobs et al., 1996) accreted to the Natal arc during closure of the Tugela (Fig. 10). The modern analogue to this Grenvillian continent-arc collision would be the Banda arc that is nearly colliding to the Australian continent at the Java trench (Hamilton, 1979).

![Fig. 10. Schematic sketch illustrating crust formation of the Tugela terrane during Grenvillian continent-arc collision. The Tugela terrane is interpreted as an accretionary complex composed of intra-oceanic “Natal Arc” and accreted “Mandleni Oceanic Island” during closure of the “Tugela Ocean” that once separated the Natal arc from the Kaapvaal continent.](image-url)
Acknowledgments

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References


Natal. Durban, South Africa, University of Natal.


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### Appendix 1. Sample list.

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### Appendix 1. Sample list (continued).

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## Appendix 1. Sample list (continued).

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### Appendix I. Sample list (continued).

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Appendix 2. Whole rock composition of gabbroic to tonalitic gneisses of the Kotongweni complex.

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<td>0.31</td>
<td>0.31</td>
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| XRF        |       |       |       |       |       |       |       |       |     |
| Ba         | 69.9  | 155.7 | 47.1  | 44.8  | 65.1  | 38.4  | 162.5  | 170.7  | 98.3 |
| Co         | 41.5  | 34.5  | 39    | 31.1  | 32.2  | 27    | 27.9   | 19.5   | 23.6 |
| Cr         | 25.4  | 21.5  | 16.3  | 29.8  | 27.6  | 25    | 18.2   | 19.2   | 16.2 |
| Cu         | 120.4 | 37.2  | 119   | 82    | 108.1 | 59.5  | 21.3   | 15.9   | 20.6 |
| Nb         | 1.4   | 1.1   | 1.8   | 0.8   | 0.8   | 0     | 0.6    | 1.6    | 2.9  |
| Ni         | 13.5  | 1.2   | 12.1  | 9.5   | 8.3   | 7.6   | 8.8    | 3.5    | 5.1  |
| Rb         | 5.4   | 6     | 4.8   | 2.8   | 1.6   | 2.7   | 5.4    | 10.7   | 5.7  |
| Sr         | 211.2 | 278.9 | 289   | 283.7 | 280.2 | 319.8 | 340.3  | 345.3  | 270.7|
| V          | 448.1 | 177.5 | 329.9 | 265.6 | 249.8 | 228.9 | 258.2  | 125.7  | 156.9|
| Y          | 16.6  | 30.2  | 9.3   | 10.2  | 9.8   | 9.2   | 8.6    | 17.7   | 24.6 |
| Zn         | 111.7 | 111.1 | 101.2 | 97.4  | 102.2 | 97    | 77.7   | 79     | 94.1 |
| Zr         | 24.4  | 20.5  | 19.1  | 23.5  | 21.4  | 23.6  | 25.3   | 27.2   | 27.2 |

| ICPM       |       |       |       |       |       |       |       |       |     |
| Li         | 5.91  | 5.46  | 4.63  | 4.03  | 2.74  | 5.60  |       |       |     |
| Be         | 0.24  | 0.26  | 0.29  | 0.22  | 0.22  | 0.58  |       |       |     |
| Rb         | 1.94  | 1.49  | 0.83  | 0.79  | 0.79  | 5.11  |       |       |     |
| Y          | 15.73 | 9.71  | 9.15  | 4.96  | 8.61  |       |       |       |     |
| Zr         | 17.39 | 8.82  | 11.79 | 3.17  | 12.80 |       |       |       |     |
| Nb         | 1.25  | 0.77  | 0.85  | 0.16  | 1.30  |       |       |       |     |
| Mo         | 0.16  |       |       |       | 0.11  |       |       |       |     |
| Sn         | 0.30  |       |       |       | 0.34  |       |       |       |     |
| Sb         | 0.03  |       |       |       | 0.11  |       |       |       |     |
| Cs         | 0.03  |       |       |       | 0.10  |       |       |       |     |
| La         | 1.49  | 4.84  | 1.68  | 1.59  | 1.90  |       |       |       |     |
| Ce         | 5.69  | 4.28  | 4.84  | 4.26  | 4.26  | 4.98  |       |       |     |
| Pr         | 1.06  | 0.71  | 0.77  | 0.63  | 0.75  |       |       |       |     |
| Nd         | 5.99  | 4.07  | 4.15  | 3.41  | 4.00  |       |       |       |     |
| Sm         | 2.00  | 1.40  | 1.27  | 0.96  | 1.35  |       |       |       |     |
| Eu         | 0.69  | 0.53  | 0.49  | 0.47  | 0.67  |       |       |       |     |
| Gd         | 2.31  | 1.55  | 1.46  | 1.04  | 1.53  |       |       |       |     |
| Tb         | 0.43  | 0.29  | 0.27  | 0.18  | 0.29  |       |       |       |     |
| Dy         | 2.85  | 1.91  | 1.76  | 1.05  | 1.73  |       |       |       |     |
| Ho         | 0.61  | 0.40  | 0.36  | 0.21  | 0.34  |       |       |       |     |
| Er         | 1.73  | 1.07  | 1.00  | 0.55  | 0.92  |       |       |       |     |
| Tm         | 0.28  | 0.16  | 0.15  | 0.08  | 0.14  |       |       |       |     |
| Yb         | 1.84  | 1.31  | 1.04  | 0.50  | 0.88  |       |       |       |     |
| Lu         | 0.30  | 0.16  | 0.16  | 0.08  | 0.13  |       |       |       |     |
| Hf         | 0.71  | 0.39  | 0.47  | 0.11  | 0.58  |       |       |       |     |
| Ta         | 0.05  | 0.03  | 0.04  | 0.01  | 0.07  |       |       |       |     |
| Ti         | 0.00  |       |       |       | 0.00  |       |       |       |     |
| Pb         | 3.51  | 1.73  | 1.69  | 2.26  | 6.44  |       |       |       |     |
| Th         | 0.02  | 0.03  | 0.05  | 0.06  | 0.09  |       |       |       |     |
| U          | 0.04  | 0.02  | 0.03  | 0.02  | 0.20  |       |       |       |     |
### Appendix 2. Whole rock composition of gabbroic to tonalitic gneisses of the Kotongweni complex (continued).

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ICP-MS

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Geochemistry and tectonic setting of Tugela terrane

### Appendix 4. Amphibolite and gabbroic rocks in the Tugela sheet (continued).

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Note: The table provides chemical composition data for various rock samples, including SiO₂, TiO₂, Al₂O₃, Fe₂O₃, MnO, MgO, CaO, Na₂O, and K₂O, among others, for the tonalite dyke and pillow lava in the Tuma slice. The data includes additional elements analyzed using ICPMS.
Appendix 5. Whole rock composition of amphibolite in the Madidima sheet.

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**ICP-Mas**

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|------|------|------|-----|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|----|
|      |      |      |     |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |    |
### Appendix 7. Whole rock composition of granitic gneiss.

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**XRF**

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| Co | 4.4 | 14.3 | 0.8 | 11.1 | 0.3 | 0.9 | 9.7 | 5.4 | 4.8 | 10.7 |
| Cr | 2.9 | 17.7 | 19.5 | 4.4 | 6.5 | 9.8 | 20.0 | 10.4 | 14.7 | 46.9 |
| Cu | 15.1 | 38.1 | 4 | 0.1 | 0.5 | 0 | 24.4 | 4.3 | 0 | 68.8 |
| Nb | 4.6 | 4.0 | 2.6 | 8.8 | 4.1 | 3.3 | 2.3 | 4.6 | 10.6 | 1.8 |
| Ni | 3.2 | 7.5 | 7 | 4.4 | 1.7 | 1.8 | 6.6 | 0.5 | 7.7 | 10.6 |
| Rb | 113.7 | 7.1 | 54.3 | 25.1 | 137.9 | 31.5 | 36.6 | 33 | 68.7 | 7.7 |
| Sr | 172.1 | 238.6 | 1081 | 320.5 | 507 | 1100.1 | 862.0 | 615.7 | 1224.4 | 434.7 |
| V | 3.1 | 76.4 | 3.8 | 35.8 | 1.5 | 4.8 | 36.1 | 2.6 | 16.0 | 51.5 |
| Y | 36.3 | 13.9 | 0.7 | 40.2 | 0.7 | 1.8 | 1.4 | 2.3 | 6.2 | 4.7 |
| Zn | 89.6 | 28.5 | 7.1 | 48.9 | 15.4 | 24.9 | 22.6 | 27.1 | 44.3 | 23.7 |
| Zr | 131.1 | 77.0 | 66.9 | 100.4 | 42 | 112.9 | 127.5 | 102.5 | 164.1 | 50.3 |

**ICP-MS**

| Li | 1.46 | 3.30 |
| Be | 0.46 | 1.00 |
| Rb | 131.1 | 2.39 |
| Y | 0.58 | 4.85 |
| Zr | 24.54 | 34.25 |
| Nb | 2.78 | 1.34 |
| La | 1.00 | 3.93 |
| Ce | 1.96 | 6.53 |
| Pr | 0.23 | 0.83 |
| Nd | 1.02 | 3.32 |
| Sm | 0.28 | 0.73 |
| Eu | 0.48 | 0.39 |
| Gd | 0.25 | 0.83 |
| Tb | 0.03 | 0.14 |
| Dy | 0.14 | 0.89 |
| Ho | 0.02 | 0.19 |
| Er | 0.06 | 0.54 |
| Tm | 0.01 | 0.09 |
| Yb | 0.06 | 0.58 |
| Lu | 0.01 | 0.09 |
| Hf | 1.13 | 0.93 |
| Ta | 0.11 | 0.06 |
| Pb | 456.5 | 17.59 |
| Th | 0.74 | 1.10 |
| U | 1.04 | 0.30 |

* ASE: Al₂O₃/(Na₂O+K₂O+CaO)
### Appendix 7. Whole rock composition of granitic gneiss (continued)

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| Rb | 43.00 | 53.64 | | | | | | | | 94.66 |
| Y | 1.07 | 1.33 | | | | | | | | 8.26 |
| Zr | 42.67 | 51.83 | | | | | | | | 46.31 |
| Nb | 2.78 | 2.84 | | | | | | | | 17.21 |
| La | 2.24 | 3.90 | | | | | | | | 20.13 |
| Ce | 3.38 | 6.75 | | | | | | | | 33.76 |
| Pr | 0.43 | 0.78 | | | | | | | | 3.59 |
| Nd | 1.59 | 2.95 | | | | | | | | 12.64 |
| Sm | 0.34 | 0.60 | | | | | | | | 2.44 |
| Eu | 0.42 | 0.73 | | | | | | | | 0.67 |
| Gd | 0.34 | 0.57 | | | | | | | | 2.34 |
| Tb | 0.04 | 0.06 | | | | | | | | 0.29 |
| Dy | 0.25 | 0.29 | | | | | | | | 1.73 |
| Ho | 0.04 | 0.05 | | | | | | | | 0.28 |
| Er | 0.11 | 0.12 | | | | | | | | 0.71 |
| Tm | 0.01 | 0.02 | | | | | | | | 0.10 |
| Yb | 0.12 | 0.11 | | | | | | | | 0.66 |
| Lu | 0.01 | 0.01 | | | | | | | | 0.08 |
| Hf | 1.76 | 1.55 | | | | | | | | 1.53 |
| Ta | 0.10 | 0.16 | | | | | | | | 1.34 |
| Pb | 24.52 | 21.53 | | | | | | | | 21.89 |
| Th | 1.03 | 1.67 | | | | | | | | 8.55 |
| U | 1.55 | 1.09 | | | | | | | | 2.42 |

* ASI: Al₂O₃/(Na₂O+K₂O+CaO)
Appendix 7. Whole rock composition of granitic gneiss (continued).

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ASI: Al₂O₃/(Na₂O+K₂O+CaO)
### Appendix 8. Whole rock composition of ultramafic rocks in the Mandleni sheet.

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Appendix 9. Whole rock composition of several late stage intrusions in the Tugela terrane.

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