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Integration of Geological, Petrographic and Abrasion Resistance Data of the Gneisses from Santa Catarina Granulithic Complex: An Application in the Road Paving Sector

Integração de Dados Geológicos, Petrográficos e de Resistência à Abrasão dos Gnaisses do Complexo Granulítico de Santa Catarina: Uma Aplicação no Setor de Pavimentação Rodoviária

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Abstract

Among the factors that contribute to the adequate performance of the aggregates, the abrasion resistance of these materials stands out, a parameter strongly related to the mineral composition of the rock. Therefore, this work aims to analyze and integrate data from Los Angeles abrasion tests to the petrographic analysis of gneisses of the Santa Catarina Granulithic Complex in order to understand the petrographic characteristics that can interfere or control the resistance results, such as: composition, texture, mineralogical alterations, granulometry and microfractures. The work was developed in four stages: (1) field activities, where descriptions of the outcrops of the four quarries studied were performed, focusing on the characterization of the compositional, textural and structural aspects of the rocks, in addition to sample collection and photographic survey; (2) petrography via conventional optical microscope and BSE images and semi quantitative analysis by electron microscope; (3) analysis of Los Angeles abrasion test data samples from the studied quarries and (4) their integration with petrographic data. Two main lithologies, enderbitic and tonalitic gneiss were identified. The results of the Los Angeles abrasion tests showed that the crushed aggregates (gneiss) of Gaspar Quarry presented the lowest abrasion values, followed by the Vale Selke, Rio Branco and 1001 quarries. Regarding composition, the enderbitic gneiss presented an average loss of 17.2%, while in the tonalitic gneiss the loss was 17.7%. The composition (high content of mafic minerals), texture and the presence of localized microfractures were the main factors that contributed to the higher values found in quarry 1001. However, both lithologies present acceptable abrasion results, in view of the specifications of the regulatory services, DNIT (031/2006) and DNIT (141/2010). The present study shows a good correlation between the result of the Los Angeles abrasion and the petrographic data, showing that composition is the main determining factor of Los Angeles abrasion results.

Keywords: Asphalts aggregates; Alterations; Microfractures

Resumo

Dentre os fatores que contribuem para o desempenho adequado dos agregados, destaca-se a resistência à abrasão desses materiais, parâmetro fortemente relacionado com a composição mineral da rocha. Diante disso, este trabalho tem como objetivo analisar e integrar dados de ensaios de abrasão Los Angeles à análise petrográfica de gnaisses do Complexo Granulítico de Santa Catarina, a fim de compreender as características petrográficas que possam interferir ou controlar os resultados de resistência, tais como: composição, textura, alterações mineralógicas, granulometria e microfraturamentos. O trabalho foi desenvolvido em quatro etapas: (1) atividades de campo, onde foram realizadas descrições dos afloramentos rochosos das quatro pedreiras estudadas, com foco na caracterização dos aspectos composicionais, texturais e estruturais das rochas, além da coleta de amostras e levantamento fotográfico; (2) petrografia via microscópio óptico e microscópio eletrônico de varredura (MEV); (3) análise dos dados de ensaios de abrasão Los Angeles das

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amostras das pedreiras estudadas e (4) integração destes com os dados petrográficos. Foram identificadas duas litologias principais, gnaisses enderbíticos e tonalíticos. Os resultados dos ensaios de abrasão Los Angeles mostraram que os agregados britados (gnaisses) da Pedreira Gaspar apresentaram o menor desgaste por abrasão, seguida pelas pedreiras Vale Selke, Rio Branco e 1001. Quanto à composição, os gnaisses enderbíticos apresentaram perda média de 17,2%, enquanto que nos gnaisses tonalíticos essa perda foi de 17,7%. A composição (alto teor de minerais máficos), textura e a presença de microfraturas localizadas, foram os principais fatores que contribuíram para a maior taxa de desgaste encontrada na pedreira 1001. Entretanto, ambas litologias apresentam resultados de abrasão aceitáveis, tendo em vista as especificações dos serviços regulamentadores, DNIT (031/2006) e DNIT (141/2010). O presente estudo mostrou uma boa correlação entre o resultado do ensaio de abrasão Los Angeles e os dados petrográficos, mostrando que a composição é o principal fator determinante dos resultados de abrasão Los Angeles.

Keywords: Agregados asfálticos; Alterações; Microfraturas

1 Introduction

Asphalt mass pavements, also called flexible pavements, are those in which their coating is composed of a mixture of aggregates of various sizes and proportions, joined by an asphalt ligant (Bernucci et al. 2006, 2008 and 2010), and bitumen is used as the main ligant in Brazil (Roberts et al. 1996; Teixeira & Araújo 2018). This asphalt coating is the top layer that directly resists the loads caused by traffic actions and environmental weather (Bernucci et al. 2010).

Crushed stone is the term that refers to the fragments of hard rocks extracted by the process of disaggregation of quartz rocks, such as the gneiss (Petrakis et al. 2010; Old 2005), and is widely used as aggregate in asphalt coatings on highways throughout Brazil, and which presents a good performance and applicability.

A type of aggregate that has been constantly explored in the northeast of the state of Santa Catarina, and applied in the road sector, comes from rocks of the granulites, which corresponds mostly to the gneiss of the Santa Catarina Granulitic Complex (SCGC). In such context, given the growth of the road network in the country, it is essential to know the properties of natural aggregates to consider possible applications for different uses of road construction.

According to Bernucci et al. (2007), Ge et al. (2018) and Li et al. (2020), understanding how the constituents of a coating react, directly influences the good performance of the work. Among the factors that contribute to produce adequate performance, the abrasion resistance of these materials stands out a parameter strongly related to the mineral composition of the rock (Alves 2014; Fick et al. 2012; Taylor, Kosmatka & Voigt 2007), and the most used in determining the quality of the aggregate (Tunc & Alyamac 2019).

However, laboratory abrasion tests, such as the Los Angeles abrasion test, do not fully represent the mechanical strength characteristics of rocks (Ge et al. 2018). There are studies that support the use of certain natural aggregates in road engineering (Al-Khateeb et al. 2013; Alves 2014; Behiry & Ebrahim 2016; García-González, Yepes & Franesqui 2020; Remedy, Ribeiro & Curtis Neto 2018; Vonto et al. 2020). Some studies also analyze the use of metamorphic aggregates (Alves 2014), granitic (Vonto et al. 2020) and volcanic (García-González, Yepes & Franesqui 2020) in asphalt mixtures. However, the characterization of the aggregate based on petrographic analysis of electron microscopy is not usual.

Thus, this work aims to analyze data from Los Angeles abrasion tests required by the DNIT standard, and integrate them into the petrographic analysis of SCGC gneiss, in order to understand the petrographic characteristics of these rocks that can interfere or control resistance results, such as composition, texture, structure, mineralogical alterations and microfractures. Given the specificity of the study, the use of electron microscope images is very useful for qualitative characterization of altering mineralogy, as well as in the detailed identification of some microfractures and microstructures, not seen in conventional petrographic analysis.

The determination of the quality of crushed aggregates from CGSC through the characterization of its geomechanical and petrographic characteristics are of great importance for paving. Therefore, the study in question is fundamental, since the life of the flooring depends on the properties of such components.

2 Methodology and Data

To perform this work, samples of rocks collected in the field, thin slides and data of Los Angeles abrasion tests performed in different lithological samples of the quarries studied (Table 1), were used.

Samples were collected in quarries from where most of the paving material were extracted. Given the lithological and structural homogeneity of the quarries, a sample per quarry was collected, seeking the collection of representative samples of lithologies with dimensions of approximately 40 x 40 cm.

The work was developed in three stages: (1) field work; (2) petrographic analysis (conventional microscopy and electron microscope) and (3) analysis and integration of Los Angeles abrasion data with petrographic data. Table 1 shows the list of materials and data used to carry out the study.

Table 1 List of materials and some tools used to perform this work. Hand samples refer to rocks collected in the field in the respective quarries. Each sample has a corresponding thin blade, described by means of an Electron Microscope (ME) and Scanning Electron Microscope (SEM).

Quarry	Hand sample (rock)		Slender blade	
	Number of samples	Description	Number of samples	Description
Rio Branco	1	Pocket magnifying loupe	1	ME and MEV
1001	1	Pocket magnifying loupe	1	ME and MEV
Vale Selke	1	Pocket magnifying loupe	1	ME and MEV
Gaspar	1	Pocket magnifying loupe	1	ME and MEV

The field work consisted on visits to the outcrops of four quarries that explore the rock for gravel production in the NE region of the state of Santa Catarina: Rio Branco, 1001, Vale Selke, and Gaspar (location of the quarries on Figure 1). The field activities consisted of the macroscopic description of the rocks sampled in the quarries, considering the following attributes: mineralogical composition, color, crystal size and textures (Figure 2). Structural features and contact relationships on the outcrop scale were also observed. The petrographic classification adopted was Streckeisen (1976).

In the second stage, the petrographic descriptions of the thin sections from the hand samples collected in the field were performed. For this, we used a conventional optical microscope in order to identify and characterize the mineralogical composition and quantification of these minerals (point counting), the granulometry and contacts among crystals, microstructures, textures, degree of alteration of the primary minerals and the presence of microfractures. The thin sections were made at the Laboratório de Laminação (LabLam) and the petrographic descriptions in the Optical Microscopy Laboratory (Labemo), both in the Federal University of Santa Catarina (UFSC).

In order to improve the conventional petrographic analysis, BSE images and EDS semi quantitative analysis were performed in the Electron Microscope from the Central Laboratory of Electron Microscopy (LCME-UFSC) in order to better characterize and detail petrography and microstructures.

Finally, in the third stage, the analysis and integration of the data from the Los Angeles abrasion tests was performed together with the petrographic data, in order to identify the main geological factors that potentially controls the results of abrasion loss values obtained in the laboratory tests.

According to DNER-ME 035/1998, the abrasion test “Los Angeles” is used to measure the wear of the large aggregates, when these are placed in a steel drum (“Los Angeles machine”) along with an abrasive, silk load subjected to a certain number of rotations at a speed of 30 to 33 rpm. At the end of this test the percentage of worn material is measured.

The accepted limits for Los Angeles abrasion depend on the kind of application of the aggregate and the requirements from the road system. In asphalt coatings, the DNIT 031/2006 – ES standard establishes that the wear values in large aggregates composed of crushed stone must be equal to or less than 50%.

The Los Angeles abrasion tests were performed on rock samples from the studied quarries and these data were provided by PROSUL to perform this study.

3 Geological Context

The Mantiqueira Province is a geotectonic unit located along the east parts of the São Francisco and Rio de La Plata Cratons, at the end of the Neoproterozoic and early Paleozoic (Bizzi et al. 2003). It extends for about 3000 km with NNE-SSW orientation along the Atlantic coast, from Montevideo (Uruguay) to the south of Bahia (Bizzi et al. 2003). It consists of a mobile belt, most of which corresponding to collisional orogens (Sengör 1990) that were aggregated during the amalgamation of the Western Gondwana Supercontinent (Almeida et al. 1977, 1981; Bizzi et al. 2003).

The study area is part of the South American Platform, consisting in one of the oldest units in the Mantiqueira Province, the Luís Alves Craton, bordering the southern and central segments of the orogenic system (Heilbron et al. 2004).

The Paleoproterozoic Luís Alves Craton encloses a set of lithologies of the basement of the oldest lands of the South American Platform, which are limited to the east by the Paraná Basin (Fornari 1998; Hartmann 1976; Kaul 1979). However, this region is quite dubious in the literature, and have different denominations, such as: Luís Alves Complex (Kaul & Teixeira 1982); Luís Alves Microplate (Basei et al. 1992; Heilbron et al. 2004); Luís Alves Domain (Siga Jr 1995); Gneissic Anfibolitic Granulitic Terrain - GAGT (Harara 2001) and Luís Alves Terrain (Heilbron et al. 2004).

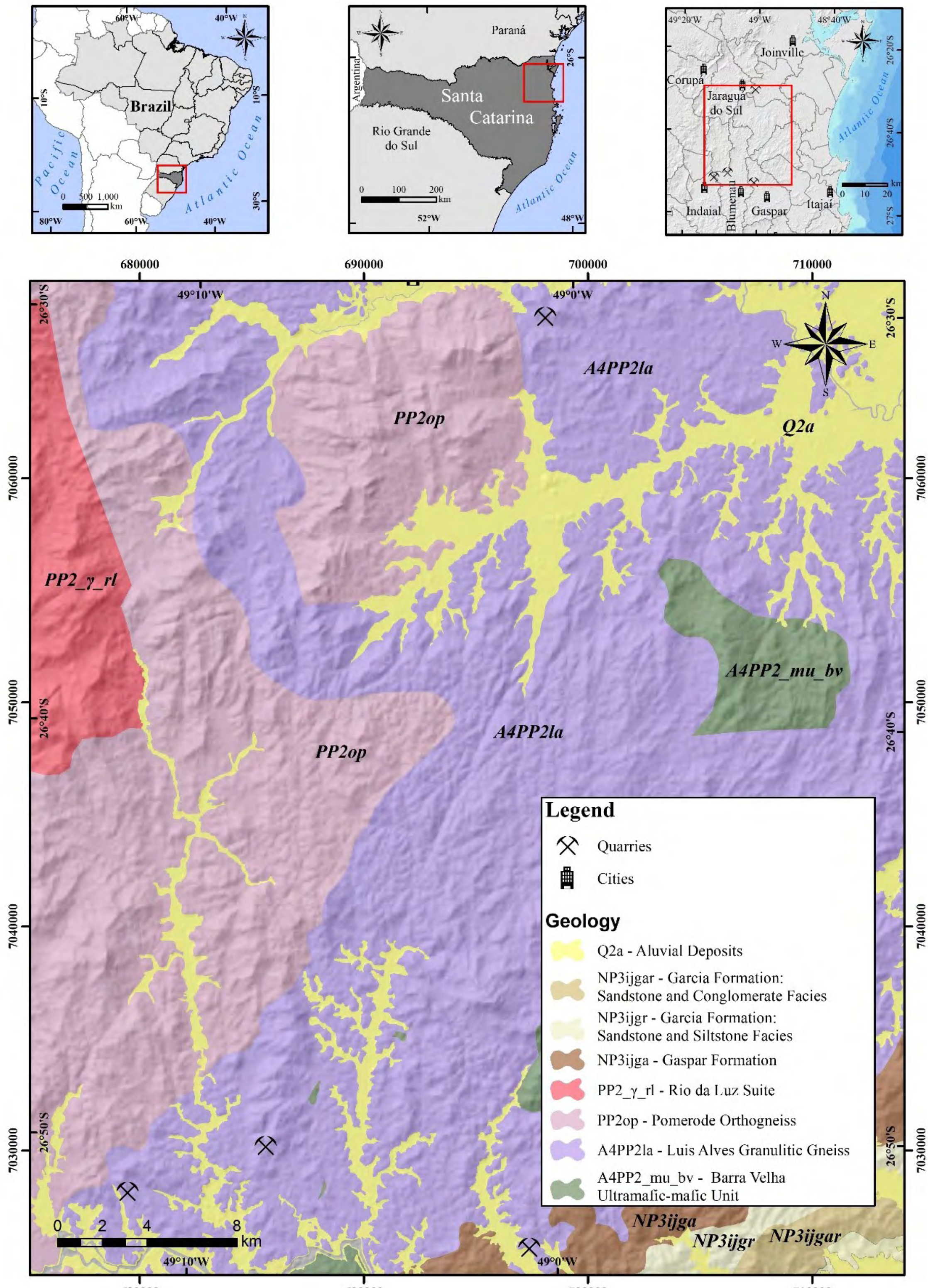

Figure 1 Location and geological maps of the four quarries studied in this work (Source: Sheet SG.22-Z-B - Joinville, Scale: 1:250,000 – CPRM 2011).

Figure 2 Studied quarries, highlighting the difference of the exploration fronts: A. Rio Branco Quarry, in the region of Guaramirim; B. Quarry 1001, in Indaial; C. Vale Selke in Blumenau; D. Gaspar, in the city of the same name.

In Luís Alves Craton there are rocks of high metamorphic grade, from upper amphibolite and granulite facies, known as Santa Catarina Granulitic Complex - SCGC (Hartmann, Nardi & Cupertino 1979; Hartmann, Silva & Orlandi 1979).

The most updated geological map for the SCGC is from CPRM (2011), where the Complex is individualizes into several lithological units (as show in Figure 1). However, associations of enderbitic, charnoenderbites and trondhjemites gneiss, from the Gneiss Granulitic Unit were previously suggested and were confirmed in the new mapping surveys (Biondi et al. 1992; CPRM 2011; Fornari 1998; Moreira & Marimon 1980).

All studied quarries belong to the Enderbitic Unit (Luís Alves Granulitic Gneiss), as shown in Figure 1. These rocks have a mineral paragenesis composed of plagioclase, quartz, hypersten, augite and rare alkali feldspar; with retrograde and/or secondary minerals as hornblende, biotite and chlorite. The main accessory minerals are zircon, apatite and opaque minerals (Fornari 1998).

4 Results

4.1 Field Geology

The geological features and macroscopic descriptions of the collected samples, integrated to preexisting studies of the region (cf. Basei et al. 2000; CPRM 2011; Fornari 1998; Harara 2001; Hartmann 1976, 1988; Hartmann, Nardi & Cupertino 1979; Hartmann, Silva & Orlandi 1979; Kaul 1979, 1980; Kaul & Teixeira 1982; Sirga Jr. 1995), allowed the identification of enderbitic (2 samples) and tonalitic (2 samples) gneiss, as shown in Table 2.

According to the classification of Le Maitre (2002), the studied gneiss are predominantly mesocratic (35 to 65% of mafic minerals), with medium gray color. The only exception is the Vale Selke Quarry, which has locally melanocratic portions (65 to 90% of mafic minerals), thus dark gray colored (Table 2).

The rocks of 1001 and Gaspar quarries are composed mainly of plagioclase (Pl), quartz (Qtz), amphibole

(Anf) and pyroxenes (Px), corresponding to enderbitic gneiss; while the rocks of the Rio Branco and Vale Selke quarries have plagioclase, quartz and biotite (Bt) as main constituents, predominantly tonalitic gneiss (Figure 3 and Table 2).

In the enderbitic gneiss, the average grain size ranges from 1.5 to 2 mm (Table 2), with predominant granoblastic and nematoblastic textures, and locally lepidoblastic, evidenced by the orientation of biotite lamellae. The crystals are oriented in the main foliation that is a well-marked millimeter to centimeter sized discrete gneissic banding. Locally the gneissic banding is even hard to observe (Figures 3B and 3D).

In tonalitic gneiss, the average grain size is 2 mm, moderately deformed with incipient development of foliation, which is marked by the orientation of biotite and elongated quartz crystals, with rare domains where gneissic banding can be observed (Figures 3A and 3C).

Table 2 Petrographic characteristics and composition of rocks found in the studied quarries.

Quarry	Colouring	Main minerals	Average grain size	Classification
Rio Branco	Medium grey	Pl + Qtz + Bt	2.0 mm	Tonalitic gneiss
Vale Selke	Dark gray	Pl + Qtz + Bt	2.0 mm	Tonalitic gneiss
1001	Medium grey	Pl + Qtz + Anf + Px	1.5 mm	Enderbitic gneiss
Gaspar	Medium grey	Pl + Qtz + Anf + Px	2.0 mm	Enderbitic gneiss

Figure 3 Mesoscopic features of the studied enderbitic and tonalitic gneiss: A. Rio Branco Quarry, mesocratic of medium gray color and average grain size of 2 mm; B. Quarry 1001, mesocratic of medium gray color and average grain size of 1.5 mm; C. Vale Selke Quarry, melanocratic, dark gray color and average grain size of 2 mm; D. Gaspar Quarry, medium gray mesocratic rock and average grain size of 2 mm.

4.2 Petrography

4.2.1. Electron Microscope (ME)

The petrographic analyses performed on the thin sections confirm the field classification. The enderbitic gneiss differ from the tonalitic by the orthopyroxene content only identified in the first (Le Maitre 2002; Streckeisen 1974, 1976) (Table 3).

From the compositional (quantitative) analysis, it was possible to verify that tonalitic gneiss (Figures 4A and 4B) can be divided into hornblende-biotite gneiss and biotite-gneiss (Table 3). Both have an average composition containing main minerals such as: quartz (35.8%), plagioclase (43.8%) and biotite (16.3%); in addition to accessory minerals (apatite, zircon and opaque). Only Hb-Bt gneiss present amphibole (5.45%) (Table 3).

The composition of the enderbitic gneiss (Figures 4C and 4D) stands out for the occurrence of ortho and clinopyroxenes (Table 3). The mean values of the constituents of their samples are defined by: quartz (29.6%), amphibole (28.4%), plagioclase (19.9%), clinopyroxene (12.9%), orthopyroxene (3.5%) and biotite (3.02%). Accessory minerals such as zircon, apatite and opaques were also identified.

In both lithologies, quartz and plagioclase occur similarly. Quartz occurs as recrystallized aggregates, sometimes with wavy extinction, deformation bands and stretch of crystals. Grain size range from 0.5 to 2 mm, commonly the crystals are granoblastic. Plagioclase is usually subhedral to granoblastic crystals (1.0 to 2.0 mm) and have regular to interlobated contours.

The amphibole occurs only in enderbitic gneiss, commonly in significant amounts (Table 3). Usually, their size range from 0.1 to 0.2 mm (Figures 5A and 5B). They contacts with pyroxenes are predominantly concave-lobate; and is also common to find amphiboles along fractures, cleavage planes and at the edges of clinopyroxenes, suggesting retrograde and/or alteration processes (Figures 5C and 5D). When in contact with biotite, it is always diffuse.

Clinopyroxenes and orthopyroxenes, only identified in the enderbitic gneiss, constitute individual prismatic and granular crystals, of sparse distribution or in small aggregates, with sizes ranging from 0.2 mm to 1 mm, and oriented along the foliation, with nematoblastic texture (Figure 6).

Biotites are found in significantly low volumes in the enderbitic gneiss, when compared with tonalitic gneiss (Table 3). However, in both lithologies, a process of alteration for chlorite is identified (Figures 5A, 5B and 7D). Accessory and opaque minerals are the same and in both lithotypes.

The tonalitic gneiss has predominantly polygonal to interlobated granoblastic textures, with local lepidoblastic textures (Figures 6A and 6B). There degree of recrystallizationis large and can be observed along the grain boundaries of quartz and feldspars.

In the enderbitic gneiss, the main texture is also the granoblastic (Figures 4C, 4D, 6C and 6D), with equidimensional and polygonal arrangement of quartz and plagioclase crystals. Nematoblastic and lepidoblastic textures are also frequently observed, marked by the alignment of pyroxene+amphibole crystals; (Figure 6B), and biotite, repesctively.

Table 3 Modal compositions (%) of the minerals that make up the described tonalitic and enderbitic gneiss. Tr = dash; ∑ = sum of mafic minerals.

Unit	**Gneiss Granulithic Luís Alves (CPRM, 2011)**			
Lithology	**Enderbitic gneiss**		**Tonalitic Hb-Bt-gneiss**	**Tonalitic bt-gneiss**
Quarry	**1001**	**Gaspar**	**Rio Branco**	**Vale Selke**
Plagioclase	14,41	25,42	39,09	48,47
Quartz	26,13	33,05	35,45	36,12
Biotite	1,80	4,24	18,18	14,41
Amphibole	28,83	27,97	5,45	-
Clinopyroxene	19,82	5,93	-	-
Orthopyroxene	5,40	1,69	-	-
Zircon	Tr	Tr	Tr	Tr
Apatite	Tr	Tr	Tr	Tr
Opaque	3,60	1,69	0,91	1,00
∑Mafic	55,85	38,83	23,63	14,41

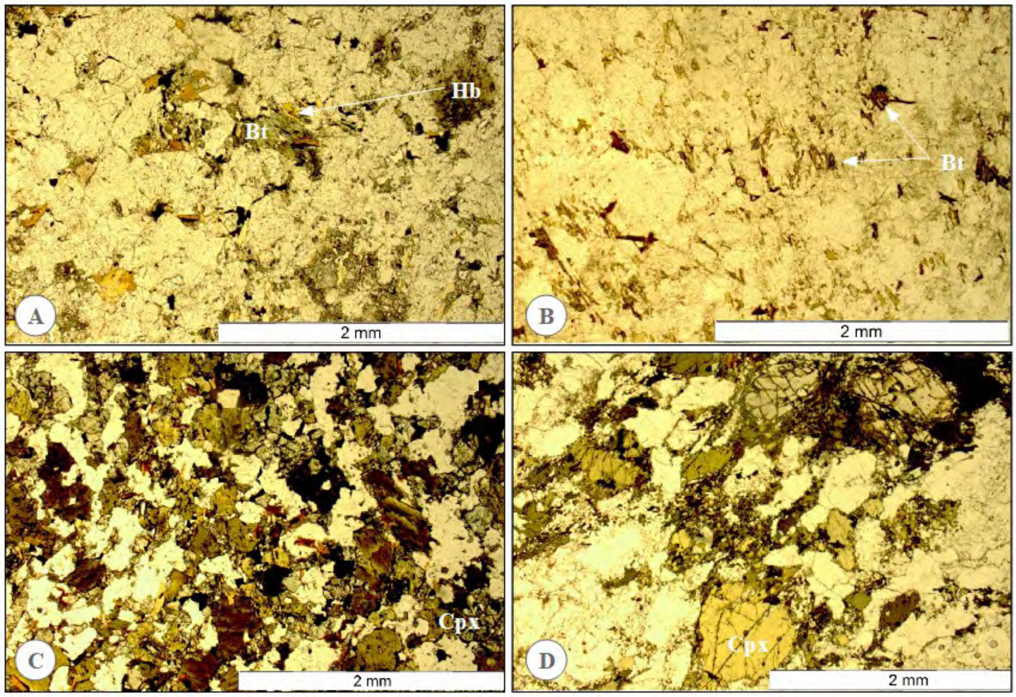

Figure 4 Petrographic aspects of the enderbitic and tonalitic gneiss. All photos were taken with plan polarized light: A. Mesocratic aspect of enderbitic Hb-Bt-gneiss; B. Mesocratic aspect of tonalic Bt-gneiss, with low mafic minerals contents and predominance of quartz and plagioclase; C-D. Leucocratic character of the enderbitic gneiss, with higher content of mafic minerals, clinopyroxene (Cpx) and orthopyroxene (Opx), in addition of the granoblastic and nematoblastic texture (quartz and plagioclase).

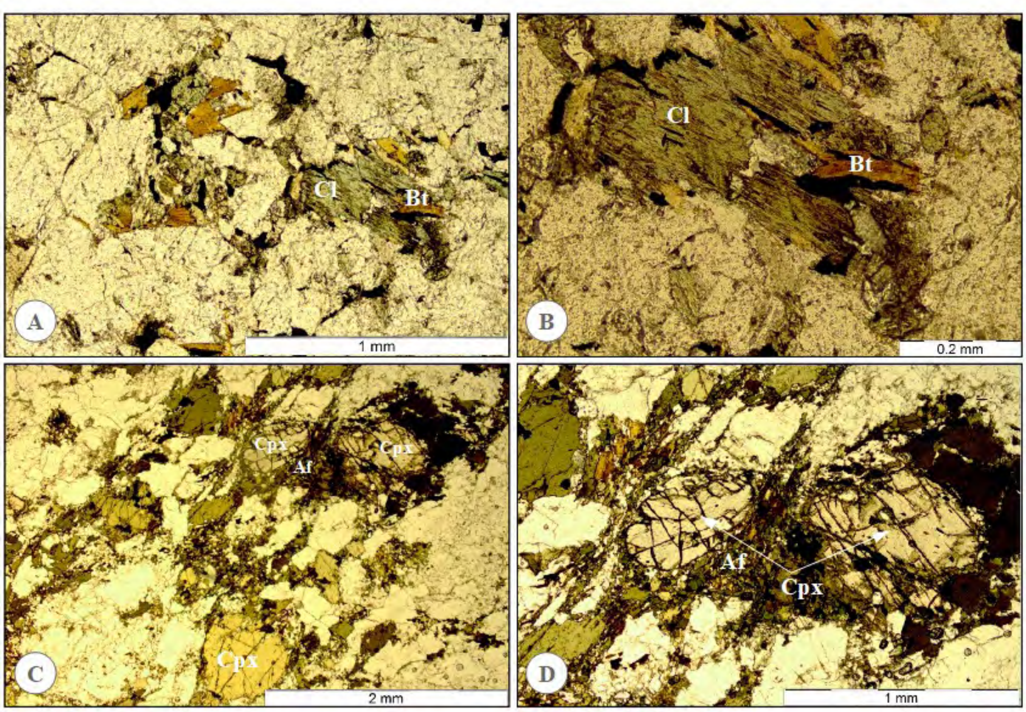

Figure 5 Petrographic and microstructural aspects of tonalitic and enderbitic gneiss. All photos taken in plan polarized light: A. Transformation of biotite crystal (Bt) into chlorite (Clo) in tonalitic gneiss; B. Detail of the previous photo showing the chlorite pseudomorphs on biotite of tonalitic gneiss; C. Amphibole (Af) along the edges of pyroxene crystals, enderbitic gneiss; D. Detail of the previous photo showing the partial replacement of pyroxene by amphibole in the central part of the photo.

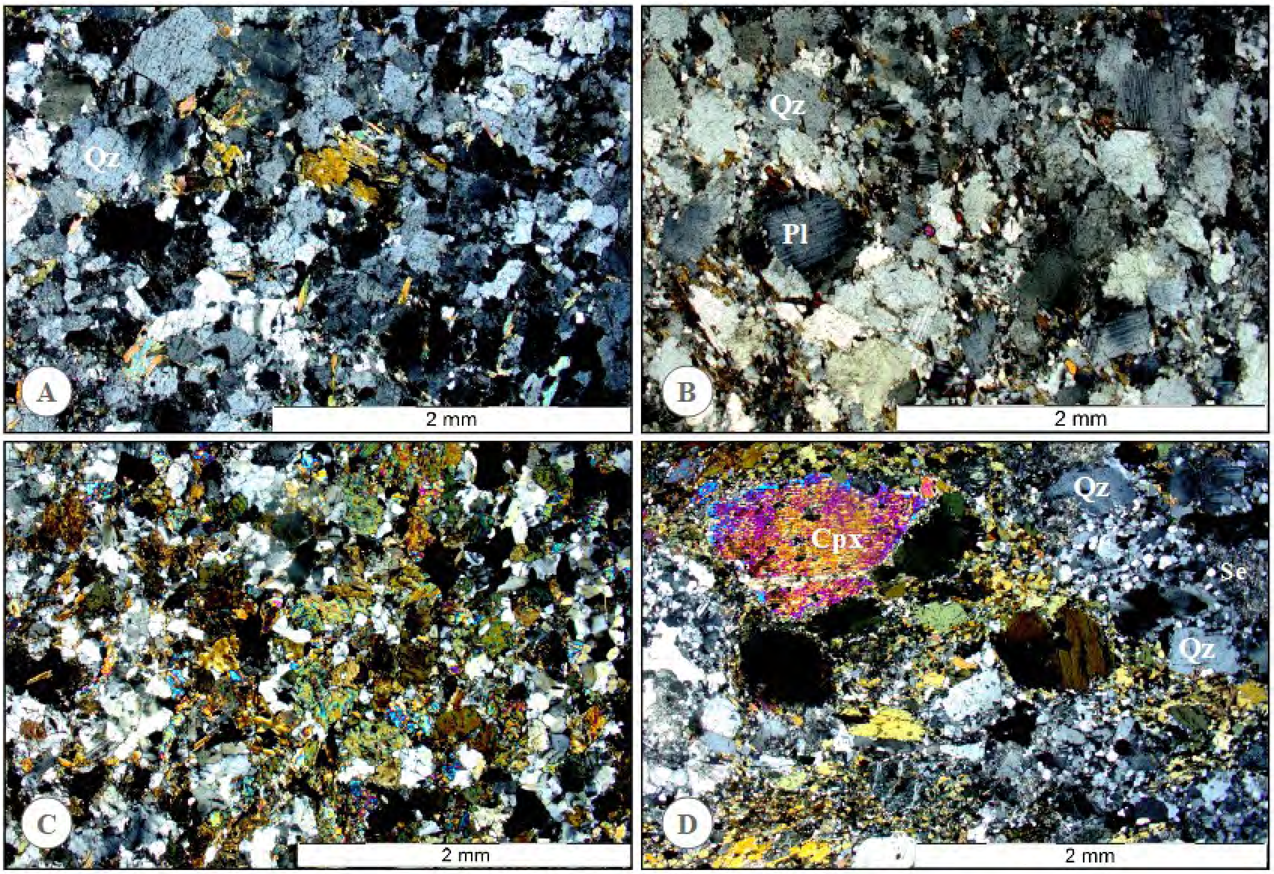

Figure 6 Petrographic and microstructural aspects of the enderbitic and tonalitic gneiss, all photos taken with crossed polarized light: A. Interlobated to polygonal granoblastic texture with strong recrystallization along the contacts of quartz and feldspar in tonalitic gneiss; B. Lepidoblastic texture marked her orientation of biotite crystals in tonalitic gneiss; C. Predominantly granoblastic texture of the enderbitic gneiss; D. Detail of the recrystallized clinopyroxene crystal in the enderbitic gneiss and secondary white mica grow over plagioclase.

In general, the studied gneissic rocks, both tonalitic and enderbitic, have low alteration degree (<1%). The main alteration processes identified are: (1) very localized sericitization, when plagioclase changes to sericite (Figure 6D); (2) biotite altered to chlorite in tonalitic gneiss (Figures 5A and 5B); (3) uralitization, grow of amphibole over pyroxene (Figures 5C and 5D); and (4) rarely the amphibole is converted to biotite.

Micro-cracks or micro-fractures are features that are not abundant, but when identified, they are usually filled with fine material (white mica ±chlorite) that are secondary alteration products.

The type of micro-fracture found was intragrain type, which occurs mainly in larger pyroxene crystals of the enderbitic gneiss (Figures 7A, 7B and 7C). The micro-cracks are commonly welded by sericitic material in plagioclases.

4.2.2. Scanning Electron Microscope (BSE - EDS)

Petrographic analyses made by electron microscope were fundamental to observe in greater detail features of microstructures and alteration of minerals. These observations were made in BSE (Back scattering electron) images and semi-quantitative analyses via EDS (Dispersive Energy System).

In the thin sections of the Rio Branco and Vale Selke quarries, where tonalitic gneiss outcrops, the main features identified were micro-fractures filled by secondary material in plagioclase crystals (Figures 8A and 8B); and some mineralogical alterations. In general, alterations is heterogeneously distributed and with variable proportions (Figures 8C and 8D). Intergranular micro-fractures present in plagioclase porphyroblasts were observed, which may be locally filled by fine chlorite and white mica (Figure 8E) and partial alteration of biotite to chlorite along the cleavages (Figure 8F).

Semi-quantitative chemical data obtained via EDS obtained at specific points of the thin sections (Figure 9), confirm the alteration (transformation) of biotite crystals in tonalitic gneiss, where the main products of this alteration are chlorite and iron oxides (Figures 9A, 9B and 9C). However, these changes are very local and do not spread all over the samples (Figure 9D).

In the thin sections of quarries 1001 and Gaspar, represented by the enderbitic gneiss, the main alterations are intragranular micro-fractures, which occur associated with plagioclase crystals (Figure 10A), amphibole (Figure 10B) and pyroxene (Figures 10C and 10D). However, contrary to what was verified in tonalitic gneiss, plagioclase crystals, although micro-fractured, are not filled with secondary minerals (Figure 10A). The same is true for pyroxene crystals (Figure 10D), although they are not identified in tonalitic samples (Table 3).

In all the gneiss samples studied, the semi-quantitative chemical data obtained by EDS (Figure 11) confirm the mineralogy identified by conventional microscopy analysis, and the BSE images collected highlight that the fractures observed are unfilled in plagioclase crystals (Figure 11A), amphibole (Figure 11B) and pyroxene (Figure 11C). However, the alteration of biotite crystals in the enderbitic gneiss also present as main products the white mica (Figure 11C), as well as chlorite and iron oxide (Figure 11D).

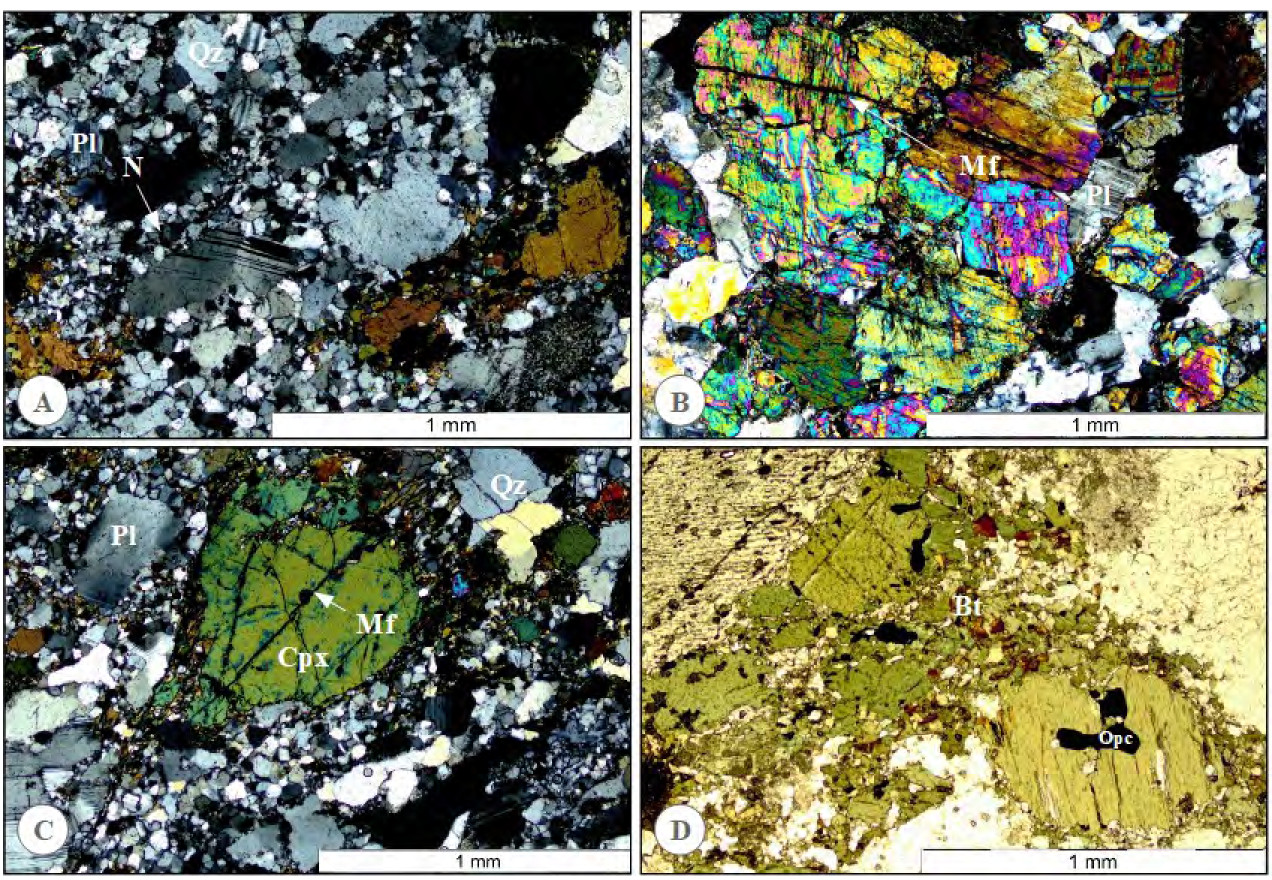

Figure 7 Petrographic and micro-structural aspects of enderbitic gneiss: A. Pyroxene porphyroblast (Px) with micro-cracks; B. Local occurrence of intracrystalline micro fractures (Mf) in pyroxene crystal (Px); C. Micro-fractures in Cpx and along the contact of those crystals with no evidence of alteration; D. Uralitization and biotites (Bt) partially chloritized and generation of secondary opaque minerals (Opc). All photomicrographs taken with cross polarized light, except 18-d, taken with plane polarized light.

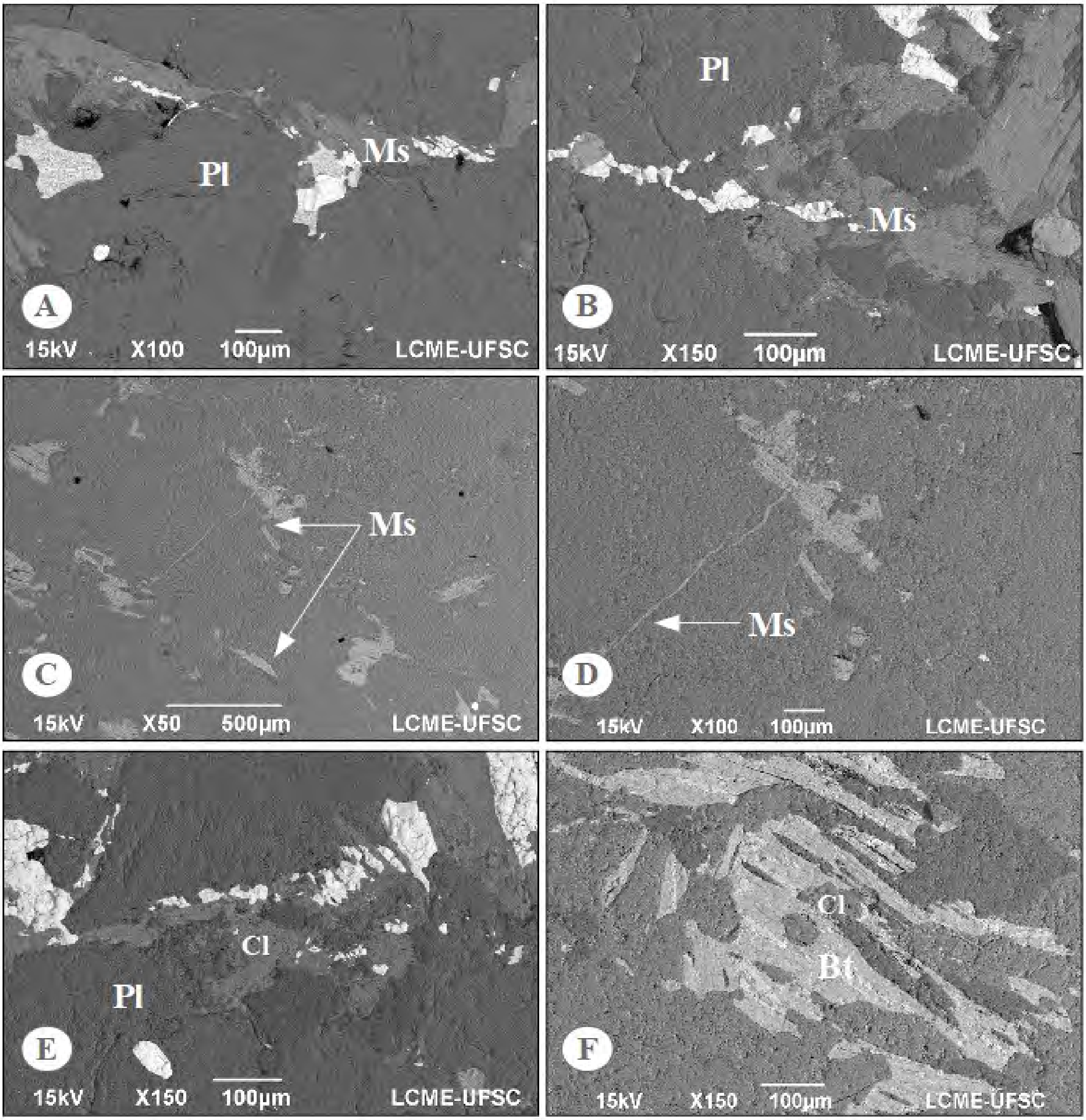

Figure 8 BSE images of tonalitic gneiss: A-B. Fractures in plagioclase crystals (Pl) in filled with white mica (Ms); C. Small fractures filled with secondary material; D. Detail of small fractures with filling of secondary material; E. Chlorite (Cl) filling cracks in plagioclase; F. Partial alteration from biotite (Bt) to chlorite (Cl) along the cleavages.

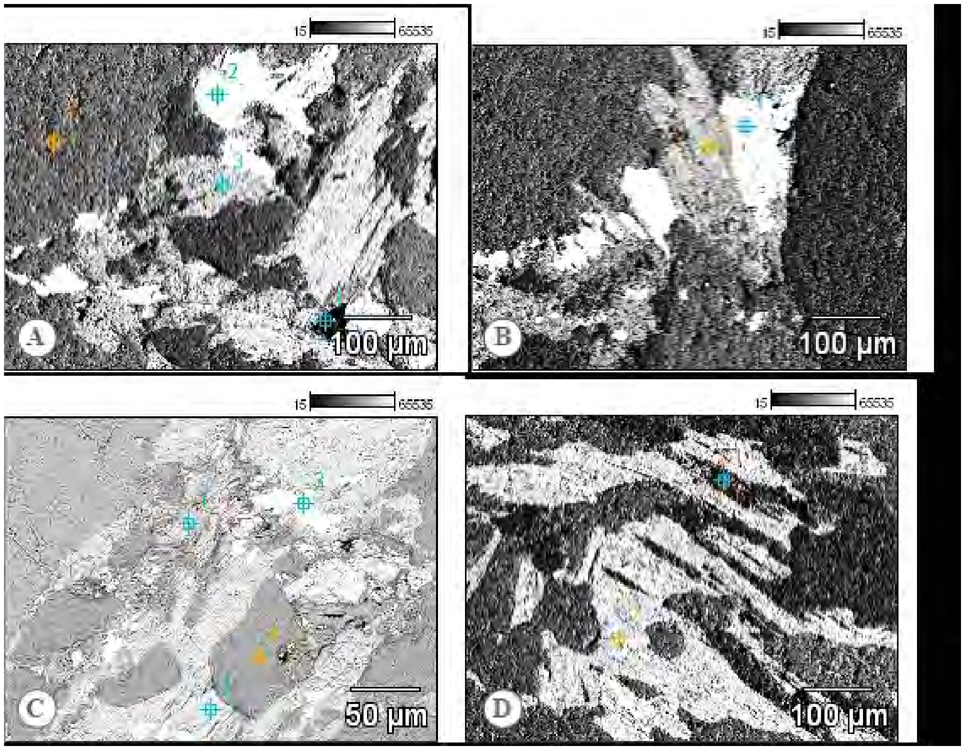

Figure 9 BSE images of tonalitic gneiss: A. Biotite altered to chlorite (1) chlorite (2) iron oxide (3) biotite (4) plagioclase; B. Biotite altered to chlorite (1) hematite (2) biotite altered to chlorite; C. Process of alteration from biotite to chlorite (1) chlorite (2) biotite altered to chlorite; D. Localized occurrence of chlorite and white mica along biotite cleavages (1) chlorite (2) white mica (3) iron oxide (4) quartz.

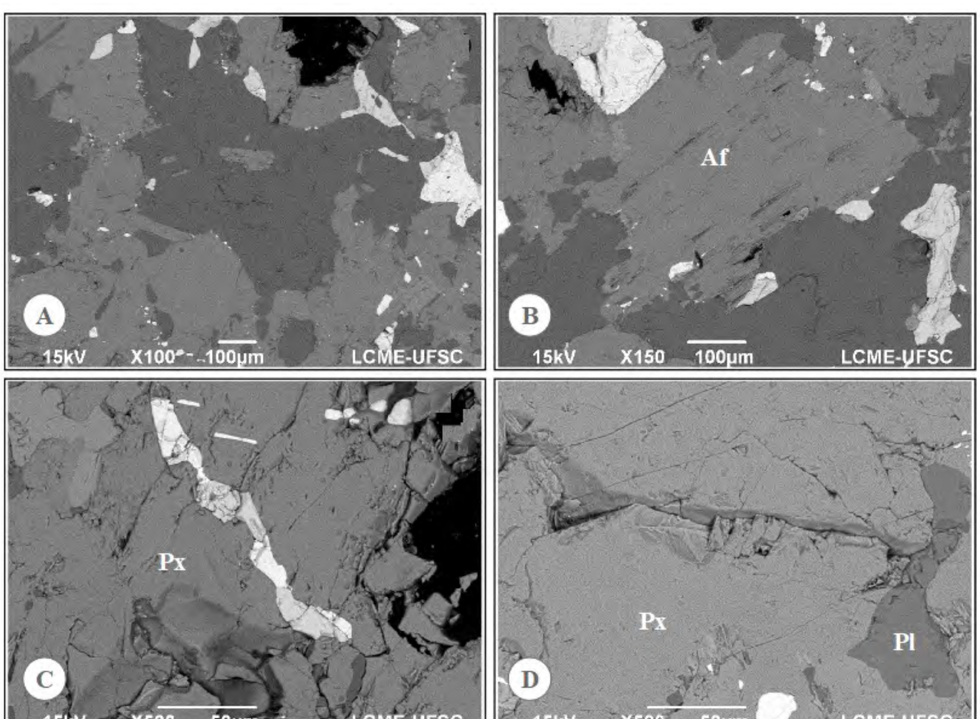

Figure 10 BSE images of the enderbitic gneiss: A. Thin fractures in plagioclase crystals with no filling by alteration material; B. Amphibole crystals without fractures; C. Transgranular fractures in pyroxene crystals without secondary filling; D. Grooves and fractures in pyroxene crystals without secondary filling, as well as the occurrence of pyroxene and plagioclase.

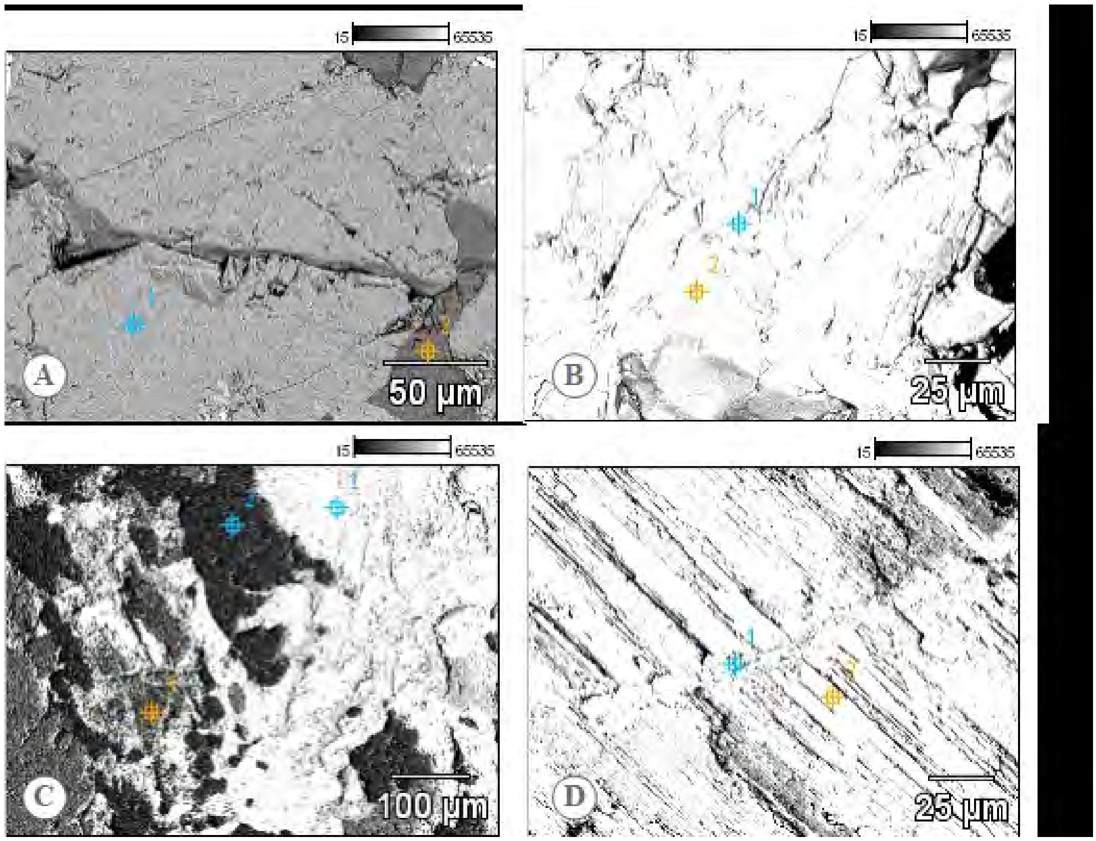

Figure 11 BSE image of the enderbitic gneiss: A. Pyroxene crystal with transgranular fractures and without secondary filling (1) pyroxene (2) plagioclase; B. Biotite partially replaced by Fe-Ti oxides (1) and chlorite (2); C. Alteration zone filled with white mica+quartz near the contact between quartz crystal and chlorite (1) biotite (2) quartz (3) white mica; D. Chlorite filling (1) in biotite fracture (2).

4.3 Los Angeles Abrasion and Petrography

The results of the Los Angeles Abrasion tests show that the average loss of wear of the aggregates produced in the quarries visited was 17.5%. The Gaspar Quarry presented the lowest abrasion wear, followed by the Vale Selke, Rio Branco and 1001 quarries, as can be seen in Tables 3 and 4.

Both lithologies present acceptable results, in view of the current service specifications of DNIT (031/2006) and DNIT (141/2010), which determine as 50% and 55% the maximum acceptable values, for asphalt concrete and granulometrically stabilized base, respectively.

Regarding the general composition of the two lithotypes studied, the enderbitic gneiss presented mean loss due to wear of 17.2%; and in the tonalitic gneiss this value was 17.75% (Table 4). However, the sample number of each lithotype is considered low, so that the wear values by the abrasion tests in these rock groups can be accepted.

Table 4 Average values (%) of abrasion wear (Los Angeles Abrasion test) of the rocks from the studied quarries. Source: PROSUL (2015).

Quarry	Latitude	Longitude	Average wear values (Los Angeles abrasion)
1001	679306,80	7027922,82	20,7%
Vale Selke	697995,75	7067242,46	17,1%
Gaspar	697311,38	7025758,77	13,7%
Rio Branco	697995,75	7067242,46	18,4%
Total average			17,5%

5 Discussion

Although a geological and structural homogeneity is verified on macroscopic scale on the quarries chosen for this study, the detailed petrographic analysis with characterization of the mineralogy and microstructures and semi-quantitative determinations of the alteration mineralogy allows evaluating important factors when considering the results of Los Angeles Abrasion tests in the rocks of the Santa Catarina Granulitic Complex. The integrated approach of geological data on varied scales with the results of these tests allows a more careful evaluation of the materials to be used on coating, as well as to understand the reasons for the heterogeneity results identified in the Los Angeles Abrasion tests.

Thus, the main goal is to discuss and evaluate the petrographic data of each sample in order to investigate the possible geological factors that control the results of the Los Angeles abrasion tests. Table 5 presents summarized compositional, textural and structural features related to each rock sample analyzed, which could be established by petrographic analysis.

The highest abrasion wear rate was verified in the sample of Quarry 1001 (Table 5). It is an enderbitic gneissic with well-defined foliation. This foliation is marked by the preferential orientation (nematoblastic and lepidoblastic textures) of mafic minerals such as pyroxene, amphibole and biotite, minerals that occur in greater volumes in this quarry. In addition, this sample has the highest content of mafic minerals (∑mafics, Tab. 5), which are minerals that have a high coefficient of disaggregation and alteration to secondary minerals. In addition, the foliation and the cleavage planes of biotite and amphibole crystals results in planes of weakness, enhancing the disaggregation capacity of the rock (Trotta, Barroso & Motta 2021). These mineralogical and textural characteristics explain the highest rates of Los Angeles Abrasion identified in these rocks (Table 5).

Another factor that may have contributed to the increase of these indices is the hardness of the minerals that make up this sample. As already mentioned, it presents the highest sum of mafic minerals among all the samples studied (Table 5). According to (Klein & Dutrow 2012), these minerals have low hardness (2.5 to 3.5), in the case of biotite; moderate (5 to 6) in amphibole; and moderate to high (6 to 7) in the case of pyroxenes. Different from plagioclase (6 to 6.5) and quartz (7), which present typically higher hardness. Minerals with lower hardness, attribute to the rock less wear resistance, so the quantification and characterization of rock mineralogy is an immediate response to Los Angeles abrasion results.

Table 5 Composition, textures and structures observed in the petrography of the studied enderbitic and tonalitic gneiss, related to the Los Angeles abrasion wear values of each sample.

Factors (composition, texture and structure)	Lithology			
	Enderbitic gnaissis		Tonalitic gnaissis	
	1001	Gaspar	Rio Branco	Vale Selke
Plagioclase	14,41	25,42	39,09	48,47
Quartz	26,13	33,05	35,45	36,12
Biotite	1,80	4,24	18,18	14,41
Amphibole	28,83	27,97	5,45	-
Clinopyroxene	19,82	5,93	-	-
Orthopyroxene	5,40	1,69	-	-
∑Mafic	55,85	38,83	23,63	14,41
Macrostructures	Foliation	Foliation	Banding	Banding
Average grain size	1.5 mm	2 mm	2 mm	2 mm
Microtextures	Granoblastic and nematoblastic	Granoblastic (main), nematoblastic and lepidoblastic (secondary)	Polygonal granular	Polygonal granular
Microfractures	Not filled	Not filled	Filled	Filled
Alteration	Incipient	Incipient	Incipient	Incipient
Los Angeles Abrasion Wear	20,7%	13,7%	18,4%	17,1%
Average wear (%)	17,2%		17,75%	

On the other hand, in the other sample of enderbitic gneiss from the Gaspar Quarry, the opposite in the wear value is observed, with the lowest rate of all samples. Although belonging to the same geological unit, when we observe the data on Table 5 we can notice that the sum of mafic minerals is significantly lower and that the felsic minerals (quartz + plagioclase) make up more than 50% of the rock, which confers greater resistance to abrasion and wear.

The detailed petrographic data obtained by electron microscopy indicate that these rocks have transgranular fractures without high filling index by secondary minerals (chlorite + white mica + felsic minerals) showing that these should not be the determining factors of the discrepancies observed in the Los Angeles Abrasion values obtained in the two samples from the same geological unit.

Instead, tonalitic gneiss has abrasion wear values considered representatively lower when compared to the enderbitic sample of Quarry 1001 (Table 5). The samples of tonalitic composition present predominantly preserved igneous textures, which attest that the metamorphism was incipient, prevailing massive textures, only with dynamic recrystallization observed by the polygonal granular arrangement of the grains. The absence of weakness planes marked by the orientation of mafic minerals, observed in both conventional and electronic microscopy, and the composition rich in quartz and plagioclase, make these rocks less susceptible to abrasion wear.

The result of the local presence of mineralogical alterations and micro-fractures normally not filled by secondary minerals, verified in both geological units, reflect in the mean values of wear by low abrasion 17.2% (enderbitic gneiss) and 17.75% (tonalitic gneiss). However, the higher content of mafic minerals from the enderbitic gneiss from Quarry 1001 points out that this is a decisive factor for abrasion values.

6 Conclusions

The present study showed a good correlation between the result of the Los Angeles abrasion test and petrography data. When treated isolated, both the Los Angeles abrasion assay and the petrographic analysis do not qualify for the abrasion resistance of the rocks.

As for the technological characteristics of wear of the Los Angeles abrasion aggregate, these rocks are in accordance with the parameters suggested by the Service Specification of DNIT (031/2006), which determines the values as acceptable. Thus, the crushed aggregates of the studied rocks can be used as part of the pavement structure (sub-base and base) or as a component of the asphalt concrete of the highways.

The quarry with the best mechanical resistance behavior (Los Angeles abrasion) was the Gaspar Quarry, represented by the enderbitic gneiss. One of the reasons is the fine to medium granulation they present, responsible for the resistance gain. Another important factor is high content of felsic minerals resistant to abrasion and low content of mafic, in addition to the rare occurrence of alterations and/or fractures filled with secondary minerals. On the other hand, the enderbitic gneiss represented by Quarry 1001 presented the highest values of mass loss among the other quarries studied. In this sample are found the highest contents of mafic minerals, little resistant to abrasion, the existence of penetrative foliation, which generates planes of weakness and breakdown of minerals and the higher occurrence of micro-granular fractures, as well as the lower modal amount of plagioclase (mineral less abrasive in relation to quartz). These data point to an important factor to be considered when it is to implement quarries for extraction of paving material in geological units.

Although belonging to the same unit, there are textural, structural and compositional variations within the same unit, especially in complexes, with structural and compositional heterogeneities, such as the Santa Catarina Granulitic Complex. Although quarries are installed in lithologically more homogeneous domains and without many geological variations, one cannot take a Los Angeles abrasion analysis of a geological unit as unequivocal for this entire unit, as faciological, structural and compositional variations are common intra units. This study demonstrates with data of easy and fast obtaining and low cost, the importance of careful petrographic investigation to understand the geological factors that control the resistance of different lithologies to mechanical wear.

On the other hand, the samples of tonalitic gneiss were shown to be a more coherent geological unit from the lithological and compositional point of view. Still considering factors such as modal mineralogical composition, textures, microstructures and secondary mineralogy, the samples from both quarries analyzed show a coherent pattern, which is reflected in the Los Angeles abrasion results.

Although this is not a systematic study of the rocks of the Santa Catarina Granulitic Complex for definitive discussion of the geological factors that control the results of Los Angeles abrasion, it demonstrates that simple analyses, such as petrographic analysis, eventually supported by images and semi-quatitative analysis by electron microscopy, in representative samples of quarries from which the paving material was extracted can help in the definition of which sites are the best for material extraction. Similarly, it shows that an analysis with adequate Los Angeles abrasion results in a part of a geological unit cannot be seen as something systematic and homogeneous, and suggests attention to these results and the search for geological evaluation criteria, such as those performed in this study, for better understanding of the results and definition of the areas to be explored.

The correlations established between the petrographic characteristics and the data from the Los Angeles abrasion tests demonstrate that the behavior of the studied rocks is directly controlled by the compositional, textural and structural characteristics. It is also concluded that, for the studied rocks, it is necessary to consider, in the performance of the tests, the structural state of the quarries attack fronts and composition of the rocks, particularly in the observation of the types of structures found, modal composition and heterogeneity of the quarries.

Therefore, the success of paving works using quarries that explore the enderbitic or tonalitic gneiss of the Santa Catarina Granulitic Complex is strongly related to the compositional, structural and textural factor of the rocks, as well as factors such as granulometry and alteration process. When the rocks present good compositional homogeneity, fine to medium textures and localized and moderate degree of alterations, the works do not present problems during execution, and technological tests as well as petrography corroborate for this result. Thus, petrography, as well as detailed geological mapping, are efficient techniques for identifying the factors that control the abrasion resistance of the aggregates employed as part of the pavement structure.

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João André Martins: conceptualization; formal analysis, methodology; validation; writing – original draft; writing review and editing; visualization. **Lucas da Rocha Pinto:** validation; writing review and editing; visualization. **Luana Moreira Florisbal:** methodology; supervision; visualization.

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