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SPECIAL ISSUE

Black dimensional stones: geology, technical properties and deposit characterization of the dolerites from Uruguay

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Abstract Dimensional stones with a black color occupy a prominent place on the international market. Uruguayan dolerite dikes of andesitic and andesitic–basaltic composition are mined for commercial blocks of black dimensional stones. A total of 16 dikes of both compositions were studied and samples collected for geochemical and petrographical analysis. Color measurements were performed on different black dimensional stones in order to compare them with the Uruguayan dolerites. Samples of the two commercial varieties (Absolute Black and Moderate Black) were obtained for petrophysical analysis (e.g. density, porosity, uniaxial compressive strength, tensile strength, etc.). Detailed structural analyses were performed in several quarries. Geochemistry and petrography determines the intensity of the black color. The Uruguayan dolerite Absolute Black is the darkest black dimensional stone analyzed in this study. The petrophysical properties of Uruguayan dolerites make them one of the highest quality black dimensional stones. Structural analyses show that five joint sets have been recognized: two sub-vertical joints, one horizontal and two diagonal. These joint sets are one of the most important factors that control the deposits, since they control the block size distribution and the amount of waste material.

Keywords Dolerites · Black dimensional stones · Petrophysical properties · Structural analysis · Block size distribution · Uruguay

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Introduction

Black dimensional stones are known on the international market as “black granites” because their hardness and strength are similar to those shown by granitic rocks. Petrologically, these rocks are classified as gabbros, norites, diorites, dolerites (or its synonym: diabase), basalts and anorthosites. Five of them are considered mafic rocks, except for anorthosite, which is classified as a felsic rock.

The Uruguayan Dolerite Dike Swarm, which intruded the Río de la Plata Craton at 1,790 ± 5 Ma (Halls et al. 2001) is composed of hundreds of parallel dikes with an average width of 30 m and average lengths of around 1,000 m. In Uruguay, they have been quarried since the early 1960s due to their deep black color, which is always en vogue, and their excellent technical properties, such as extremely high uniaxial compressive strength (UCS) and remarkable low porosity and water uptake. These dimensional stones are used as high-quality cladding, worktops, bathroom vanities, tombstones and precision tables.

Due to their physical properties and appearance, these rocks have been quarried since the time of ancient Egypt, where they were used for the construction of sacred monuments (tombs and temples) or magnificent buildings (palaces) (Ashurst and Dimes 1998). They were also utilized for the production of various decorative elements, such as valuable pieces of art (e.g. statues, fountains, etc.). Over the centuries and even today, dolerites and other black dimensional stones are used for representative buildings and other constructions worldwide.

Examples of the use of black dimensional stones in Germany can be found in the Düsseldorf Airport, which uses the Shanxi Black (dolerite) from northern China for the interior flooring tiles. The Office of the Federal President in Berlin uses the Impala Dark (gabbro/norite) for the building façade (Börner and Hill 2010) (Fig. 1a) and in Bad Homburg the footbridge masts are constructed of Nero Assoluto (gabbro) from Zimbabwe (Fig. 2). In the United States of America, the base façade of the Empire State Building utilizes Ebony Black (dolerite) from Sweden (Ashurst and Dimes 1998) (Fig 1b) and in Uruguay the entrance columns of the Antel Tower are made of Uruguayan Black Absolute dolerite.

The prices for black dimensional stones on the international market vary from 900 to 2,400 US\$/m^3, whereas the Uruguayan dolerites are priced at 900 to 1,700 US\$/m^3. Dolerites from China have prices ranging from 1,000 to 2,000 US\$/m^3, the South African gabbro/norite shows prices up to 2,000 US\$/m^3 and the most expensive black stone is the iridescent norite from India with a price of 2,400 US\$/m^3. Prices depend on two aspects: the intensity of the black color (the darker the stone, the more expensive

Fig. 1 **a** Empire State Building (New York, USA) façade made of Ebony Black from Sweden. **b** Office of the Federal President in Berlin (Germany) made of Impala Dark from South Africa

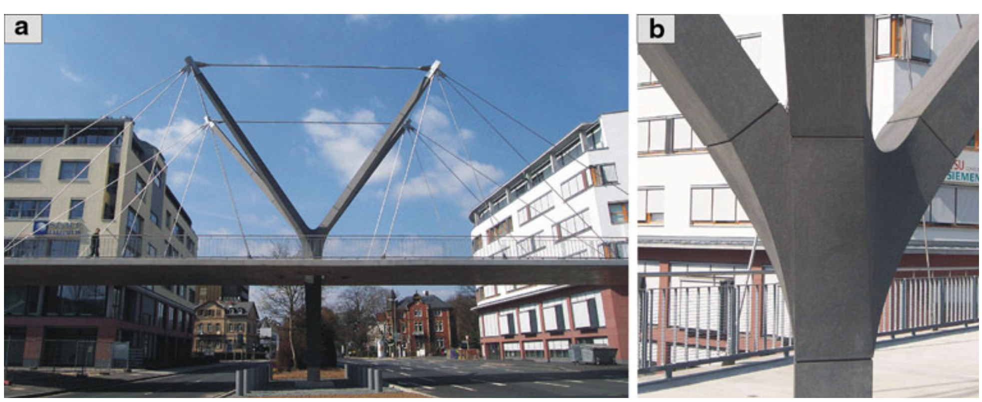


Fig. 2 Footbridge in Bad Homburg (Germany) made of Nero Assoluto from Zimbabwe (*Source* SBP GmbH). **a** General view of the footbridge; **b** detail of support mast

it is) and the block size (the largest blocks are relatively more expensive).

Present mining situation

In Uruguay, the methods of mining dolerites have evolved since the 1960s when quarrying began. Mining was initially done by manual extraction and then evolved by using the modern technique of the diamond wire saw, which has proven to be a highly effective method.

The different periods in the production of dolerite blocks are closely related to specific economic cycles in Uruguay (Fig. 3). Since the beginning of production in 1960 and until the end of the 1970s it was a period of slow growth, with a maximal annual production of around 1,000 tons. This first growth period was probably favored by the initial support that the mining and geological sector received from the military dictatorship during the period from 1973 to 1985. By the end of the 1970s, the government implemented a macroeconomic deflation plan via a pre-announced decrease of the exchange rate. Thus, Uruguayan products became more expensive than they really were and in the long run the exporters lost their competitiveness. This situation lasted until 1982, when the country was in the middle of a deep crisis. The government stopped bolstering the Uruguayan peso to the US dollar, leading to a strong devaluation of the national currency. In these years dolerite production suffered a sharp decline, of almost 90% in the deepest moment of the crisis with respect to that of the year 1978, which had the highest level of production on record.

Later, the production entered into a new phase of growth until the beginning of the 1990s, which was related to regional/national growth cycles and the entry of new investors in the stone sector. A new period of stagnation in dolerite production occured at the beginning of the 1990s, when the national economy entered into a new recession phase. In the years 2001–2002, this period of recession turns into a severe crisis, accompanied with a new devaluation of the national currency. Dolerite production reached the lowest level in the last 10 years, but as the economy recovers so does the production of black dimensional stone.

Today production is in a new growth phase, mostly influenced by the positive market trend for "Absolute Black", which as of 2005 is due to the demand for stones of black color. Despite the facts that in the present only three companies are quarrying the dolerite dikes, the production in the last several years has exceeded the average of the last 45 years (Fig. 3). This can be directly related to the use of the diamond wire saw, which increases the efficiency of the extraction, and the recent trade policy strategy that promotes the export of these products.

Historically, there have been 19 quarries, 4 of which mined only superficial blocks. The quarries now active are distributed in two regions in the Department of Colonia,

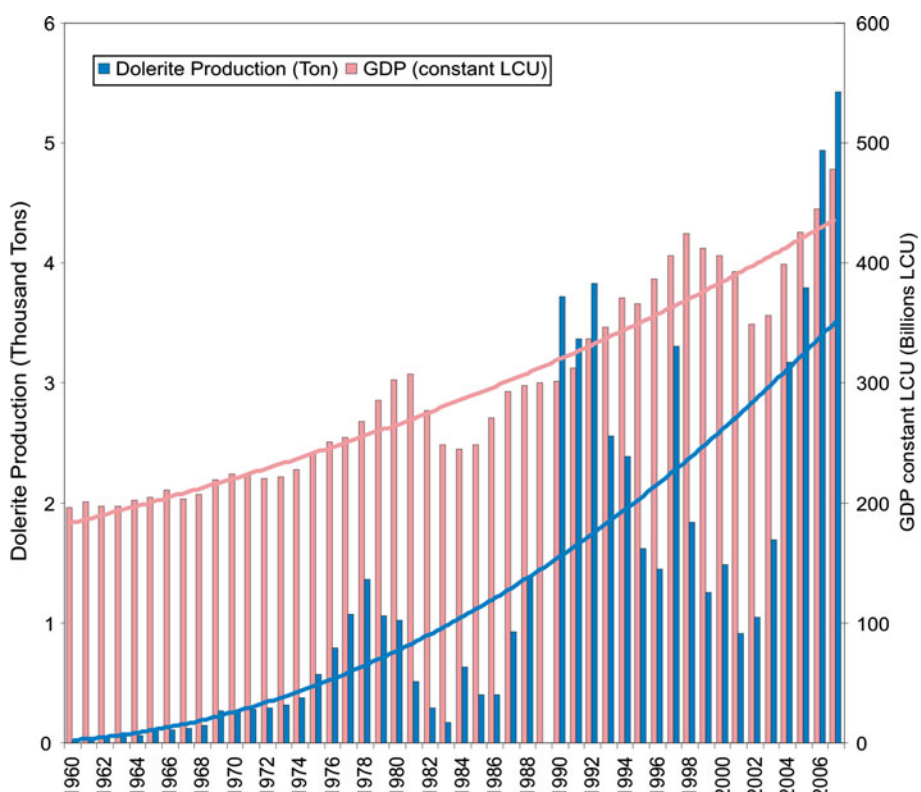


Fig. 3 Evolution of dolerite production in Uruguay (Data after Bossi and Campal 1991; Morales Pérez 2004 and Dirección Nacional de Minería y Geología, DINAMIGE 2010) and GDP (Gross Domestic Product) in constant local currency units (LCU) (Data after World Bank homepage, 2010)

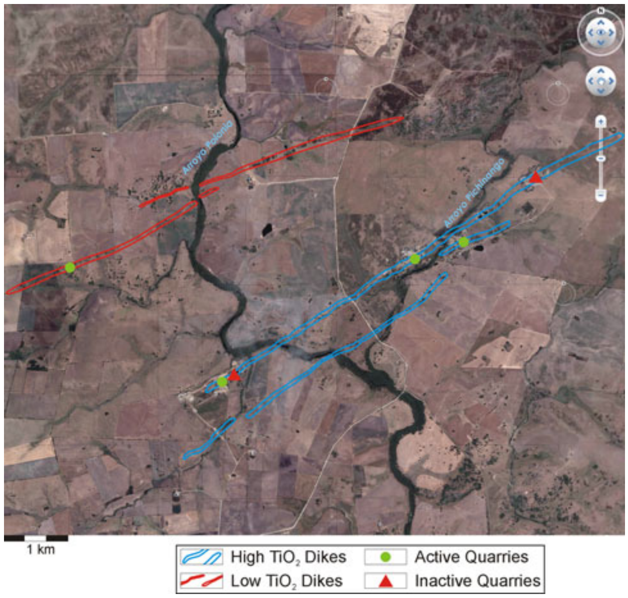


Fig. 4 Satellite image showing different dolerite dikes in the region of Polonia-Pichinango along with active and inactive quarries (*Image Source* Google Earth, 2010)

one in the region of Arroyo de la Quinta, and the other in the region of Polonia-Pichinango (see Fig. 4). Two quarries are located in the same dike. Two large active sawmills are in operation in the region, which cut the blocks extracted from the quarries, produce polished slabs and sell the products on the national and international markets. One sawmill is located in Nueva Palmira with access to a harbor. The other sawmill is located in Las Piedras, 25 km away from the main harbor in Montevideo (Uruguay). Both harbors have the facilities to ship the blocks and other processed materials, such as polished slabs. Numerous small sawmills in the country buy the already polished slabs.

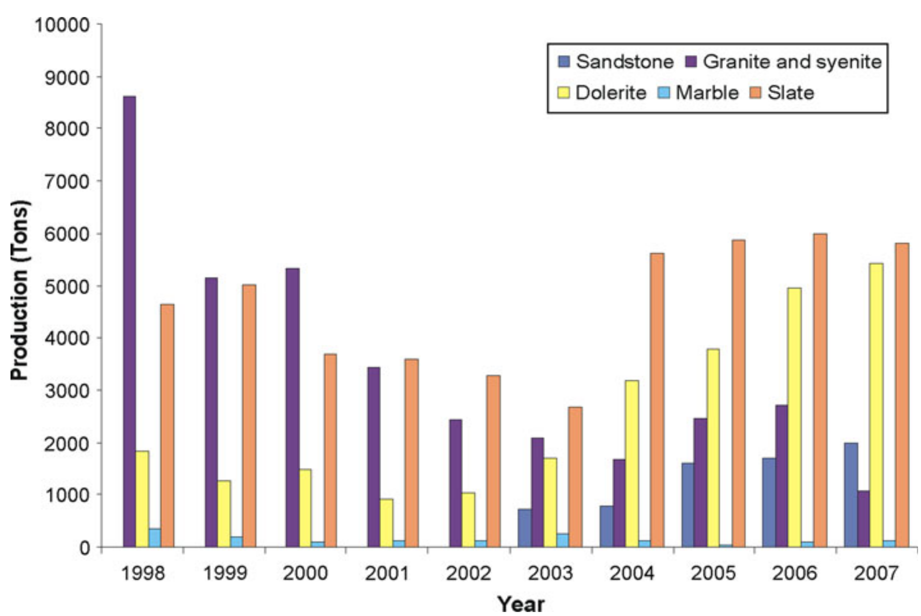
The non-metallic mineral export of Uruguay in the year 2007 was around 4.4% of the total export of the country. No information on the amount of dimensional stone exports is available.

In the last 10 years, the dimensional stone sector in Uruguay has been represented by the production of granite and syenite (red, pink, gray and dark green), slate (black, gray, red and green), dolerite (black and dark gray), marble (white) and recently sandstone (orange and yellow) (Fig. 5). Granite and syenite production (plotted together in Fig. 5) has decreased in the last 10 years as dolerite production has grown. Marble production is marginal and sandstone has entered the market in 2003 with its production continuing to grow. Slate production has remained more or less constant in the last 10 years. The strong decrease in the production of granite and syenite reflects the growing predominance of China as an exporter of these products.

The production of dimensional stones in the year 2004 represents around 0.26% of the non-metallic mineral production (in tons). The dolerite production for the same year is about 22% of the total dimensional stone production (in tons). In US dollars, the dolerite production is almost 40% of the total dimensional stone production (DINAMIGE 2010). This makes dolerite the most important dimensional stone product of Uruguay.

The world demand for black dimensional stones of high quality is not yet totally covered by the other productive countries, such as China, South Africa, Sweden, Zimbabwe, India and Brazil. Uruguay, whose production is not very large at the present time, will probably occupy a more constant position on the world market when more dolerite dikes are developed for production.

Fig. 5 Dimensional stone production in tons (Data after Dirección Nacional de Minería y Geología, DINAMIGE 2010). Data for granites and syenites are combined



Geological setting of the dolerite dike swarm in Uruguay

The geology of Uruguay is characterized by a Precambrian basement that crops out in the south part of the country. This basement was originally divided into two regions by Ferrando and Fernandez (1971), taking into account their ages: the eastern domain belonging to the Brasiliano Cycle (Neoproterozoic) and the western to the Transamazonian Cycle (Paleoproterozoic).

The Río de la Plata Craton was defined by Almeida (1971) including the Transamazonian outcrops of southern Brazil, Uruguay and Argentina. Fragoso-Cesar (1980) defined the Dom Feliciano Mobile Belt of southern Brazil and Uruguay, as a series of petrotectonic associations of Brasiliano age.

Bossi and Ferrando (2001) divided the Uruguayan basement into three tectonostratigraphic terranes: the Piedra Alta and the Nico Pérez Terrane (these two terranes correspond to the Río de la Plata Craton) and the Cuchilla Dionisio (corresponding to the Dom Feliciano Mobile Belt). These terranes are separated from west to east, by two first-order tectonic regional discontinuities: Sarandi del Yí and Sierra Ballena Shear Zones (Fig. 6).

Recently, Oyhantçabal et al. (2010) proposed a redefinition of the Río de la Plata Craton, based on new and previously published geochronological and isotopic data that shows different events of crustal growth and crystallization ages for the Piedra Alta and Nico Pérez Terrane. These differences support the exclusion of the Nico Pérez Terrane from the Río de Plata Craton, which now comprises the Piedra Alta Terrane in Uruguay and the Tandilia Belt in Argentina.

The Piedra Alta Terrane is especially significant for this work because it contains the dolerite dike swarm. According to Oyhantçabal et al. (2007a, b), this terrane is composed of two supracrustal metamorphic belts with an E–W direction. Each one of them is composed of a metamorphic volcanic-sedimentary formation and spatially associated plutonic bodies, and extended granitic–gneissic belts in between (Bossi and Ferrando 2001).

The metamorphic belts are from north to south: the Arroyo Grande Belt and the San José Belt. The first one was defined by Bossi and Ferrando (2001) and corresponds to the Arroyo Grande Formation (a folded volcano-sedimentary succession of greenschist facies, Oyhantçabal et al. 2010) and associated intrusions formerly defined by Ferrando and Fernandez (1971). The San José Belt comprises the Paso Severino Formation and associated intrusions, the San José Formation and the Montevideo Formation (Oyhantçabal et al. 2007b). The Paso Severino Formation, as defined by Oyhantçabal et al. 2010 consists of a greenschist facies folded volcano-sedimentary

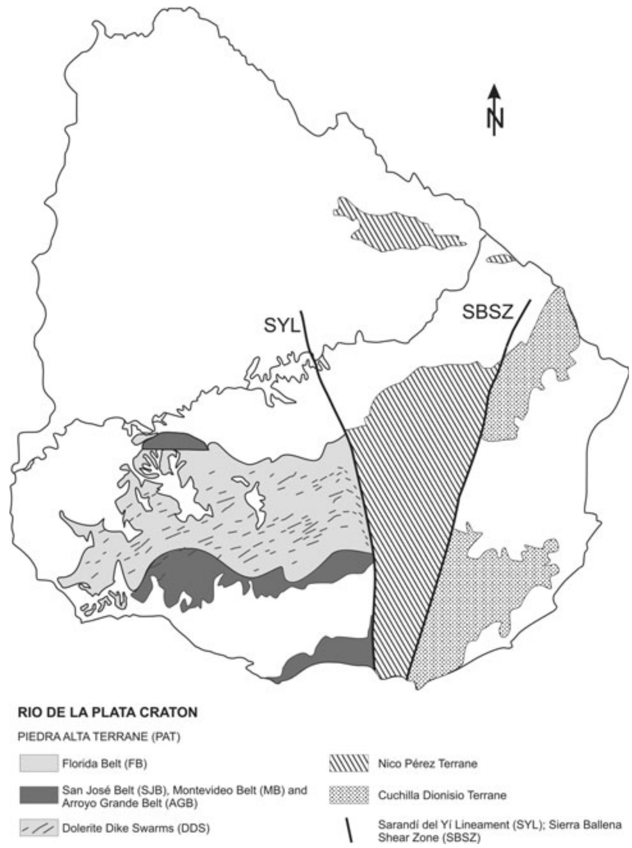


Fig. 6 Schematic geological map of Uruguay (modified from Hartmann et al. 2001)

succession. The San José Formation is composed of paragneisses and garnet and staurolite-bearing micaschists (Oyhantçabal et al. 2003, 2007a, b). The Montevideo Formation comprises amphibolites, paragneisses and garnet and staurolite-bearing micaschists (Bossi 1965; Bossi et al. 1993; Oyhantçabal et al. 2003, 2007a, b).

Between these belts there are elongated granitic–gneissic areas that also include decameter to kilometer-sized blocks of micaschists, paragneisses and amphibolites. These areas are known as the Florida Central Granitic–Gneiss Belt (Bossi and Ferrando 2001; Oyhantçabal et al. 2010).

The tectono-thermal activity of this terrane, and therefore the Río de la Plata Craton, consists of two Transamazonian events at 2.2–2.1 and 2.1–2.05 Ga (Oyhantçabal et al. 2010). An orogenic event occurs with the intrusion of the basic dike swarm in an extensional regime (Bossi and Ferrando 2001) at 1,790 ± 5 Ma (U–Pb on baddeleyite by Halls et al. 2001). This swarm encompasses an area of 25,000 km^2 (100 km width and 250 km length) with a general trend of ca. 060° and intrudes in all the lithologies of the Florida Central Granitic–Gneiss Belt (Bossi and Campal 1991). This mafic dike swarm (Bossi et al. 1993) is also known as the Uruguayan Dike Swarm (Teixeira et al. 1999;

Halls et al. 2001) or the Florida Dyke Swarm (Mazuchelli et al. 1995).

The craton was stable for a long time after the intrusion of the basic dike swarm, until the last event at the end of the Proterozoic, when its edge was reworked by a dextral mega-shear known as the Sarandí del Yí Shear Zone. This event caused the rotation of the eastern extreme of the dike swarm to the south (Bossi and Campal 1991).

Characterization of the dolerite deposits

In Uruguay, a wide spectrum of names are used to describe these rocks. They have been called “black granites” (mostly in the commercial sector; Bossi and Navarro 1982; Bossi et al. 1990; Techera et al. 2004; Comunità Economica Europea-Uruguay, no date), microgabbros (Bossi and Navarro 1982; Bossi et al. 1989; Bossi and Campal 1991; Bossi and Ferrando 2001; Spoturno et al. 2004), andesitic and andesitic–basaltic dikes (Bossi and Campal 1991; Bossi et al. 1993, Bossi and Ferrando 2001), gabbros (Comunità Economica Europea-Uruguay, no date) and in the recent literature dolerites (Oyhantçabal et al. 2006, 2007a, b, 2008).

The term dolerite, synonymous with diabase and microgabbro, is used to describe an igneous hypabyssal rock of dark color composed of plagioclase (labradorite in composition) and clinopyroxene (normally augite or titanoaugite), with opaques as the main accessory minerals (magnetite, titanomagnetite or ilmenite). The grain size is between that of gabbro and basalt (medium-grained, between 1 and 5 mm) and the typical texture is ophitic or subophitic (laths of plagioclase totally or partially surrounded by crystals of augite) (Allaby and Allaby 1990; Jackson 1997).

Bossi and Campal (1991) studied and related the petrographic characteristics to the geochemical features, dividing the dike swarm into two groups. One group comprises rocks of andesitic composition and high titanium content (Group A) and the other one of andesitic–basaltic composition and low titanium content (Group B). In the present work these two groups were also recognized.

In each dike it is possible to recognize three zones when taking into account the grain size (see Figs. 7, 8; Table 1). Figure 9 depicts the distribution of the different zones. Zone 1 is in contact with the country rock; its thickness is not more than 60 cm, is normally very finely fractured and defines the chilled margin of the dike. Zone 2 is 1–1.5 m thick, is less fractured and characterized by a fine grain that increases toward the middle of the dike. Zone 3 is located in the center of the dike, representing ca. 90% of the width. The contact with Zone 2 is gradual. The grain size in this zone is medium-grained, ranging from 1 to 2 mm.

In the three quarries where a grain size profile was taken and analyzed, observations indicate that Zones 1 and 2 on both sides of the dike represent not more than 11% of the dike width (Fig. 7). As shown in Table 1, no strong correlation between the dike width and the maximal grain size exists, although the wider dikes (for example U8 and U59) show the coarser grain and the finer dikes (as the case of U62) show the finer grain. Further investigations are still necessary to clarify this observation.

Geochemistry

Major and minor elements were determined by X-ray fluorescence spectrometry at the GeoForschungsZentrum in Potsdam (Germany). A total of 24 samples from 14 dikes were already investigated by Bossi et al. (1993) and a total of 28 samples from 16 dikes were analyzed in this study. Another five dikes were identified, but they were unreachable for samples collection. In some dikes two samples were analyzed, one from Zone 2 (fine-grained) and the other from Zone 3 (medium-grained), in order to ascertain the

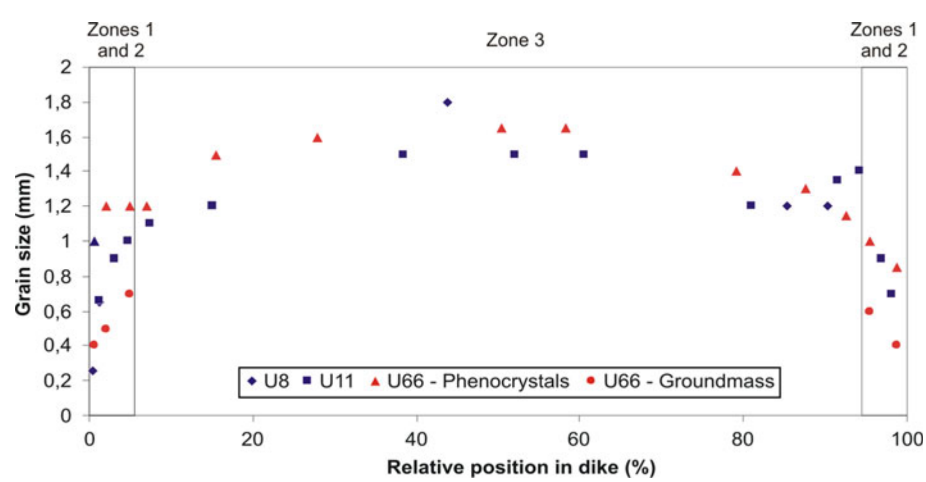


Fig. 7 Grain size distribution in three dolerite quarries. High TiO_2: U8, Rosarito and U11, Blackstone; Low TiO_2: U66, Pimafox (grain size of phenocrysts and groundmass separated)

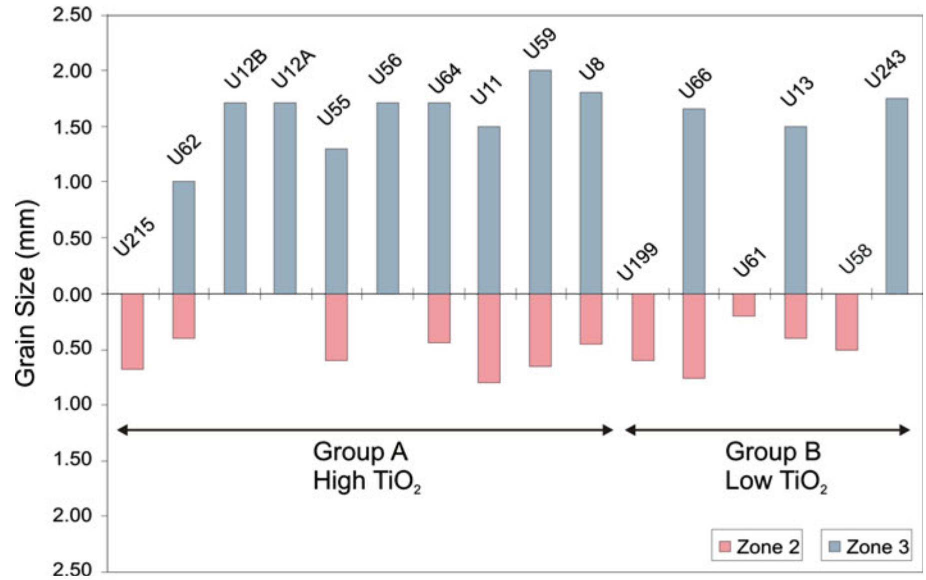


Fig. 8 Grain sizes in Zones 2 and 3 for both dike groups

Table 1 Dike width and grain sizes in Zones 2 and 3

Group	Sample	Quarry/Location	Grain size (mm)		Dike width (m)
			Zone 2	Zone 3	
Group A (high TiO_2)	U215	La Sierra	0.68		16
	U62	Las Acacias	0.40	1.00	19
	U12B	Talita Chica		1.70	20
	U12A	Talita Grande		1.70	25
	U55	Mexico	0.60	1.30	30
	U56	Los Fresnos		1.70	30
	U64	Pintado	0.44	1.70	35
	U11	Blackstone	0.80	1.50	38
	U59	Omar Mendez	0.65	2.00	40
	U8	Rosarito	0.45	1.80	41
Group B (low TiO_2)	U199	Arroyo Polonia	0.60		20
	U66	Pimafox	0.76	1.65	24
	U61	Inex S.A.	0.20		25
	U13	Victor	0.40	1.50	30
	U58	Boria	0.50		30
	U243	Arroyo de la Quinta		1.75	30

geochemical differences that can be correlated to the petrography of these rocks.

The results of these analyses (Tables 2, 3) corroborate the observations made by Bossi and Campal (1991), who divided the dikes into two groups based on their geochemistry that correspond to the two petrographic groups. Group A is characterized by relatively high contents of TiO_2 (between 1.5 and 2.5%) and an andesitic composition, and Group B is defined by relatively low contents of TiO_2 (<1.2%) and an andesitic–basaltic composition. This is shown in the De La Roche diagram in Fig. 10. Group A also shows relatively higher values for the other major elements: FeO_t, MnO, Na_2O, K_2O, P_2O_5, but lower values of Al_2O_3, MgO and CaO (Fig. 11). They also exhibit different mg# values ($MgO/MgO + FeO_t$), where the values for Group A are around 0.17 and 0.25 and those for Group B are between 0.35 and 0.45.

Group B shows higher values of the following trace elements: Rb, Ni, Y, Zn and V and lower values of Cr with respect to Group A. The other trace elements, Nb, Zr, Sr, Ba and Ga, show a similar distribution between both groups.

In both groups, a different geochemical signature in the two dike zones considered can be recognized. Regarding the major elements, Zone 2 represents an enrichment of the following elements in Groups A and B: TiO_2, Na_2O, K_2O

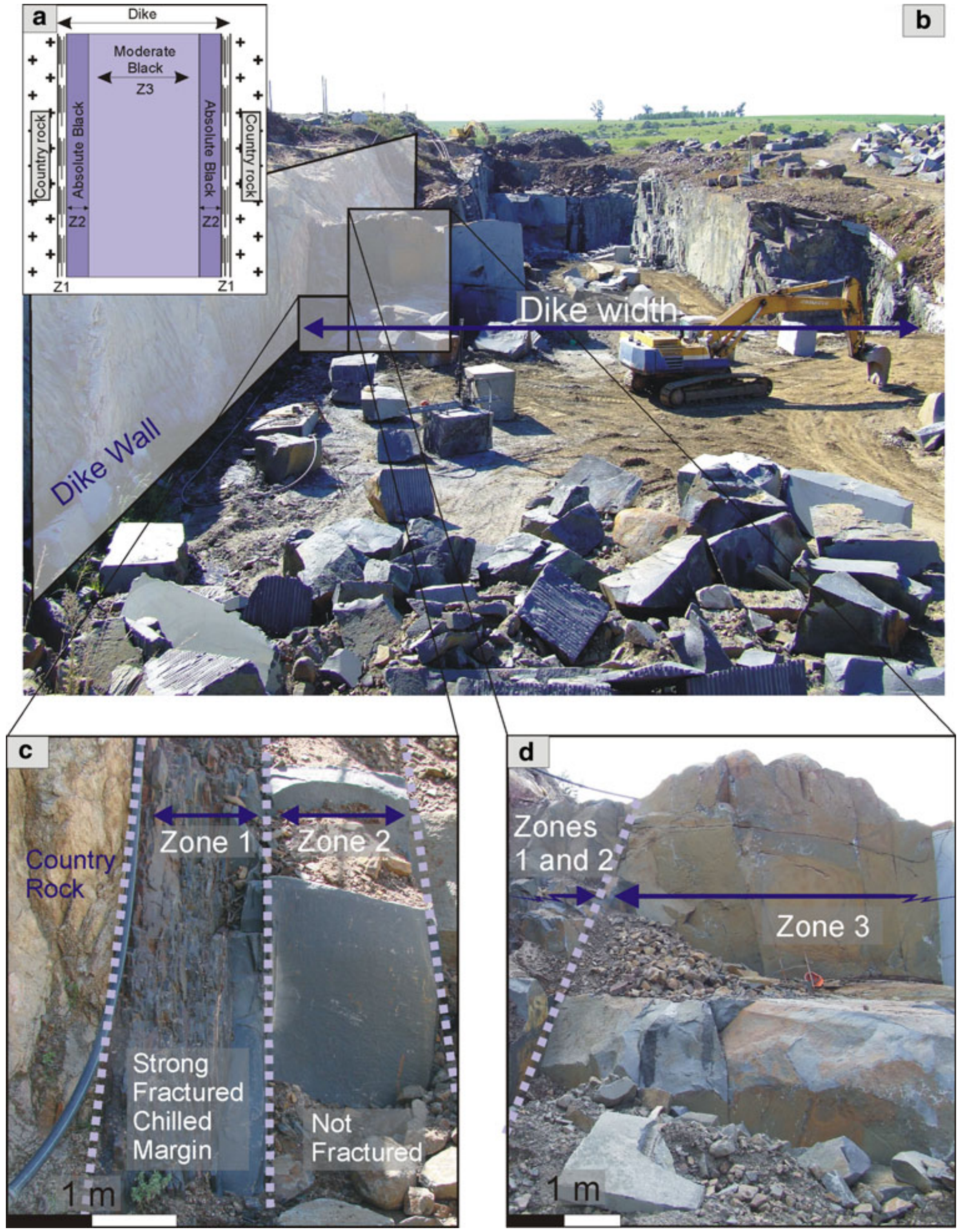


Fig. 9 Black Stone Quarry in dike of Group A. **a** Schematically figure where Zones 1, 2 and 3 (Z1, Z2 and Z3, respectively) are represented; **b** general view of quarry, contact with country rock is shown; **c** contact zone of dike with the country rock. Strongly fractured chill margin (Zone 1), not fractured Zone 2; **d** Zone 3, with few horizontal and vertical joints

and P_2O_5, and a decrease of SiO_2, MgO and CaO. For some other major elements a different behavior can be observed. In Group A, an enrichment of FeO_t and MnO and a decrease in Al_2O_3 is observable, when comparing Zone 2 to Zone 3. In the Group B, the opposite behavior occurs.

Trace elements are distributed as follows: there is an enrichment of Rb, Nb, Zr and Ba in Zone 3 of both dike groups, whereas only Group A presents an enrichment of Sr and Ga in this zone. Cr, Ni and Zn behave differently between both groups, where enrichment occurs in Zone 2 of Group A and a decrease is observable in the same zone of Group B. Y and V also show a different behavior between both groups, with an enrichment of these elements in Zone 2 of Group B, and a decrease in Group A. Different geochemical signatures between both groups can be explained by various stages in the magmatic evolution within a tholeiitic series, with Group A being more evolved than Group B (Fig. 12).

Petrography

Bossi and Campal (1991) described the petrography of the dike swarm based on the differences correlated with the two geochemical groups in the dikes. According to these authors, the main petrographical differences between both groups are mineralogical, where the high TiO_2 rocks

Table 2 Major element compositions of the dolerites (in wt.%)

Sample	SiO_2	TiO_2	Al_2O_3	FeO_t	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Fe_2O_3	FeO	H_2O	CO_2	mg#
Group A															
U8Z2	54.2	2.409	12.3	13.56	0.162	2.73	6.79	2.60	1.86	0.276	1.71	12.02	1.12	0.25	0.17
U8Z3	53.2	2.261	12.0	14.37	0.185	3.18	7.25	2.49	1.59	0.238	1.81	12.73	0.92	0.19	0.18
U11AZ2	55.4	1.733	12.9	12.54	0.173	3.04	6.97	2.58	1.75	0.224	1.58	11.11	0.63	0.13	0.20
U110Z3	53.2	2.332	12.2	14.50	0.184	3.07	7.25	2.56	1.64	0.247	1.82	12.85	0.59	0.09	0.17
U11Z2	54.1	2.269	12.2	13.53	0.171	2.94	6.99	2.58	1.74	0.255	1.70	11.99	1.10	0.19	0.18
U11Z3	53.2	2.243	12.0	14.35	0.184	3.22	7.26	2.50	1.61	0.238	1.80	12.71	0.89	0.19	0.18
U12AZ3	51.1	2.278	12.2	14.90	0.197	3.77	7.83	2.49	1.45	0.291	1.87	13.20	0.95	0.26	0.20
U12BZ3	51.2	2.297	12.3	14.96	0.196	3.77	7.81	2.50	1.46	0.288	1.88	13.25	0.86	0.22	0.20
U55Z2	50.2	2.419	12.9	14.10	0.205	4.26	8.22	2.56	1.51	0.369	1.77	12.50	0.95	0.24	0.23
U55Z3	53.6	2.192	11.7	14.20	0.184	3.11	7.11	2.49	1.62	0.262	1.79	12.58	1.08	0.32	0.18
U56Z3	53.1	2.251	11.9	14.48	0.186	3.19	7.22	2.53	1.63	0.240	1.82	12.83	0.88	0.20	0.18
U59Z3	49.4	2.380	13.0	14.32	0.212	4.81	8.63	2.46	1.37	0.343	1.80	12.69	0.80	0.25	0.25
U62Z2	55.1	1.750	12.7	12.77	0.173	2.99	6.92	2.55	1.76	0.224	1.61	11.31	0.78	0.13	0.19
U62Z3	55.2	1.782	12.7	12.83	0.175	2.98	6.93	2.57	1.78	0.223	1.61	11.36	0.74	0.21	0.19
U64Z2	53.4	2.300	12.1	14.27	0.184	2.99	7.06	2.57	1.69	0.322	1.80	12.65	0.81	0.19	0.17
U64M2	52.4	2.190	12.3	14.37	0.193	3.51	7.64	2.50	1.48	0.254	1.81	12.73	0.76	0.24	0.20
U215Z2	55.4	1.761	12.8	12.40	0.162	2.95	6.69	2.57	1.82	0.226	1.56	10.99	1.13	0.13	0.19
U215Z3	55.6	1.786	12.9	12.36	0.163	2.92	6.70	2.57	1.84	0.226	1.55	10.95	1.12	0.14	0.19
Group B															
U13Z2	52.2	0.844	15.5	8.81	0.151	5.94	8.68	2.18	1.83	0.115	0.97	7.93	2.18	0.17	0.40
U13Z3	53.2	0.812	14.9	9.24	0.149	6.68	9.62	1.94	0.98	0.109	1.02	8.32	0.79	0.34	0.42
U58Z2	53.7	0.912	14.4	10.07	0.157	5.60	9.34	2.08	1.14	0.121	1.11	9.07	0.86	0.20	0.36
U58Z3	53.8	0.873	14.2	10.00	0.158	5.67	9.32	2.04	1.08	0.116	1.10	9.00	1.16	0.33	0.36
U61Z2	53.9	0.929	14.5	9.94	0.150	5.44	9.34	2.09	1.17	0.123	1.09	8.94	0.89	0.17	0.35
U66Z2	53.9	0.789	14.7	9.07	0.146	6.48	9.56	1.94	0.96	0.106	1.00	8.17	0.99	0.17	0.42
U66Z3	53.2	0.737	15.0	8.82	0.145	7.13	9.74	1.87	0.91	0.099	0.97	7.94	0.82	0.29	0.45
U199Z2	53.4	0.826	15.1	9.16	0.150	6.47	9.34	1.94	1.04	0.113	1.01	8.25	1.04	0.17	0.41
U243Z3	53.5	0.808	15.2	9.05	0.141	6.42	9.42	1.94	1.04	0.112	0.99	8.14	1.13	0.09	0.42

(Group A) show lower plagioclase contents. The plagioclase is of andesine composition in Group A and in low TiO_2 rocks (Group B) plagioclase shows labradoritic composition.

The clinopyroxene present in both groups is augite, but in Group B orthopyroxene (broncite) can also occur. Bossi et al. (1993) determined the composition of the clinopyroxenes as augite to subcalcic augite and pigeonite with high Ca contents. In Group A, more opaques occur consisting of magnetite and ilmenite intergrowths, which are normally automorph crystals associated with pyroxene. Only small proportions of pyrite and chalcopyrite are present. In Group B, the most important opaque mineral is skeletal ilmenite, which is associated with quartz–feldspar intergrowths and sometimes with pyroxene. Amphibole is present as a product of uralitization of clinopyroxene and is more common in Group A.

The term "micropegmatite" is used to refer to quartz intergrowths, normally composed of quartz and alkali feldspar, but sometimes also composed of quartz and plagioclase. These intergrowths are much more abundant in Group A, where they are composed of quartz and oligoclase. When apatite occurs, it is always related to these intergrowths. According to Bossi and Campal (1991), the grain size between 0.1 and 0.2 mm of the plagioclase laths characterizes the "Granito Negro Absoluto (Fig. 13a). "Granito Negro Fino" (0.3 and 0.5 mm), "Granito Negro Oriental" (0.6 and 0.8 mm) (Fig. 13b) and "Granito Negro Grueso" (plagioclase laths > 1 mm) all show larger grain sizes.

Spoturno et al. (2004) have also studied these rocks, but did not differentiate them into two groups. They described the rocks as being composed of plagioclase with grain sizes around 0.3 mm, when measured parallel to the long axis (approximate composition: labradorite) and pyroxene, i.e., augite, pigeonite and occasionally orthopyroxene. Occasionally, microphenocrysts of plagioclase and augite have

Table 3 Trace element compositions of the dolerites (in ppm)

Sample	Cr	Ni	Rb	Nb	Zr	Y	Sr	Ba	Zn	Ga	V
Group A											
U8Z2	136	107	24	8	115	20	194	386	76	16	211
U8Z3	22	29	39	10	203	37	198	478	128	22	328
U11AZ2	54	31	52	11	212	37	207	485	115	20	381
U110Z3	25	25	47	10	195	34	211	453	132	21	404
U11Z2	41	44	35	10	180	34	195	403	124	20	437
U11Z3	54	33	50	10	215	36	214	482	118	21	373
U12AZ3	135	103	15	6	112	20	189	270	74	20	206
U12BZ3	175	115	16	6	106	16	187	275	72	16	201
U55Z2	140	109	30	7	115	22	195	355	80	19	208
U55Z3	77	106	21	4	126	22	212	661	84	18	222
U56Z3	49	30	44	13	204	36	214	483	118	19	368
U59Z3	54	32	49	12	224	37	235	817	98	21	398
U62Z2	28	33	45	10	192	32	199	463	125	20	404
U62Z3	82	107	25	6	125	24	196	307	85	18	220
U64Z2	51	30	47	12	209	39	283	1,732	102	21	385
U64M2	100	63	33	11	244	44	146	339	147	21	377
U215Z2	28	31	33	6	194	33	201	447	127	20	440
U215Z3	81	111	33	7	116	21	193	283	84	19	227
Group B											
U13Z2	32	47	30	10	194	40	176	409	130	21	440
U13Z3	25	31	41	10	193	36	200	451	125	22	411
U58Z2	147	110	18	8	111	17	191	282	77	16	203
U58Z3	139	109	66	6	119	18	235	528	52	18	213
U61Z2	81	54	37	13	267	46	155	373	136	20	348
U66Z2	26	27	45	9	187	35	205	451	127	21	414
U66Z3	22	20	52	12	211	39	214	516	121	22	323
U199Z2	30	49	33	8	192	35	174	393	129	20	429
U243Z3	25	25	43	11	206	34	253	1,117	118	19	392

been observed with sizes up to 2 mm giving the rock a microporphiritic texture. Accessories include ilmenite with leucoxene rims and apatite. These authors also described the presence of amphibole of uralitic origin, a product of alteration of pyroxene.

The petrographical observations corroborate the previous research, with new information being added by this study. In Table 4 the main observations are summarized and the petrographic details are shown in Figs. 14, 15, 16, 17 and 18.

Using the Michel–Levy method, the plagioclase laths in Group A were determined to have an An_{34}–An_{44} composition (andesine), whereas Group B shows an An_{47}–An_{60} composition (labradorite). In both groups, plagioclase occurs as fine-grained euhedrally zoned laths (for grain sizes see Table 1; Figs. 7, 8). In Group A, the laths commonly contain inclusions of very fine-grained apatite crystals.

The clinopyroxene is generally augite, but also some pigeonite can be observed. The augite in Group A occurs as small crystals with grain sizes between 0.4 and 0.6 mm. They are euhedral to subhedral, very often exhibit twining and are surrounded by amphibole and to a lesser extent by biotite. In Group B, the augites are coarser grained, with sizes ranging between 0.4 and 2.4 mm. The crystals are euhedral to subhedral and generally show an aspect ratio up to four. Very often they show twining and are sometimes surrounded by amphibole and biotite.

Biotite is present as euhedral to subhedral crystals with sizes up to 0.9 mm (with an aspect ratio of 4.5) in Group A. In Group B, the grain size only reaches 0.2 mm with an aspect ratio of 2. In both groups it occurs as an accessory. The biotite present is always related to magnetite or augite.

All samples exhibit the presence of granophyric intergrowth as described by Shelley (1993), which Bossi and Campal (1991) and Spoturno et al. (2004) refer to as "micropegmatite" or interstitial quartz–feldspar intergrowths. In some cases, microcline can be recognized within the granophyric intergrowth, but in other thin sections it is difficult to determine the nature of the feldspar present. They are normally up to 0.8 mm in size in Group A, but up to 1.6 mm in some cases and smaller in Group B, up to 0.6 mm.

Opaques are also present as accessory minerals and are much more frequent in Group A, where magnetite crystals are euhedral to anhedral and the ilmenite crystals are skeletal. Both crystals always occur with augite and biotite as intergrowths, never surrounded by plagioclase. Their size is between 0.2 and 0.8 mm. In Group B, the opaques are skeletal, long and lath-shaped ilmenite up to 0.7 mm with an aspect ratio up to 14. The very fine-grained magnetite crystals are subhedral to anhedral with a size up to 0.3 mm. Both are often distributed around augite as well as around the plagioclase. The opaques are homogeneously distributed in the grain size zones (1, 2 and 3), and in Zones 1 and 2 their grain size is generally smaller than the plagioclase laths. In Group B, the opaques are sometimes surrounded by red spots of limonite or hematite.

Apatite is found as an accessory, as very small (up to 0.1 mm in length) euhedral crystals with basal hexagonal sections and needle-like longitudinal sections. They are always included in the granophyric intergrowth and can be very often found as inclusions in the plagioclase of Group A.

Hornblende occurs as a product of uralitization of clinopyroxenes, where they appear either with fibrous habit or as euhedral to subhedral crystals with sizes up to 0.4 mm. They are more frequent in Group A.

Calcite occurs only as an accessory in a dike from Group B in Zone 3 (sample U13). It appears as very fine-grained (up to 0.2 mm) anhedral to subhedral crystals normally associated with biotite.

The texture normally observed in both groups is subophitic, but there are some local variations. A porphyritic

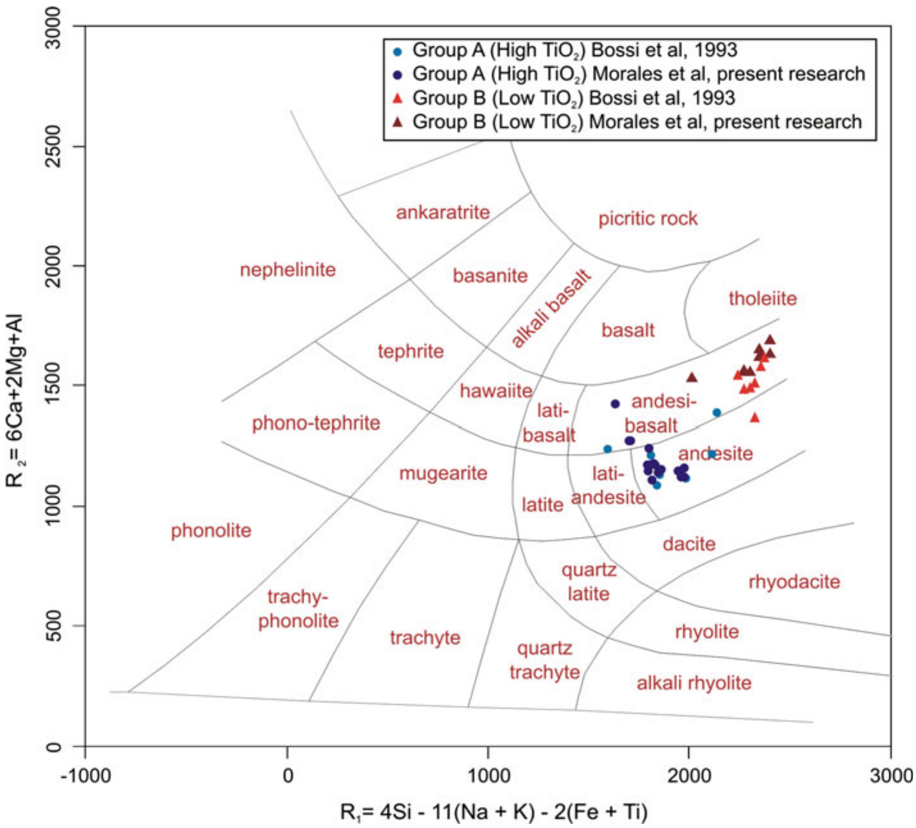


Fig. 10 Distribution of the dikes in a R1–R2 diagram (after De La Roche et al. 1980)

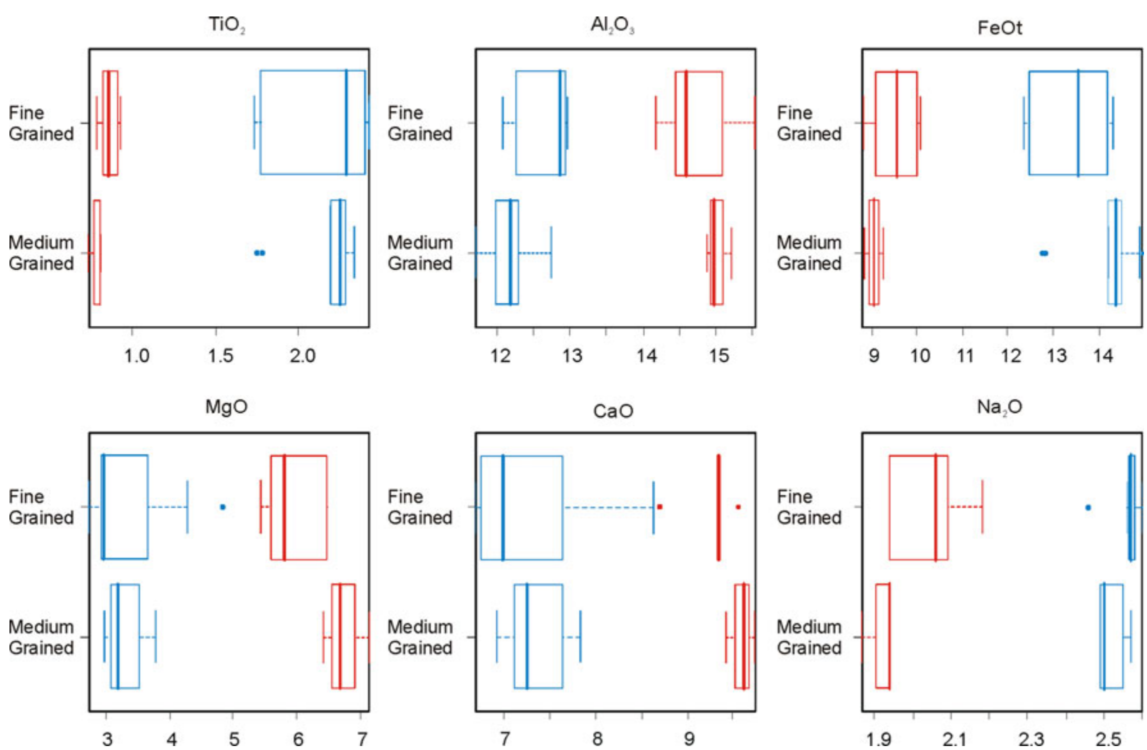


Fig. 11 Box plots of major elements in Groups A (High TiO_2) and B (Low TiO_2) (in wt.%) by taking into account the grain size. Group A is blue and Group B is red. *Bold line* median; *box* Q1–Q3 range; *whiskers* standard deviation above and below the mean of the data; *filled circles* outliers

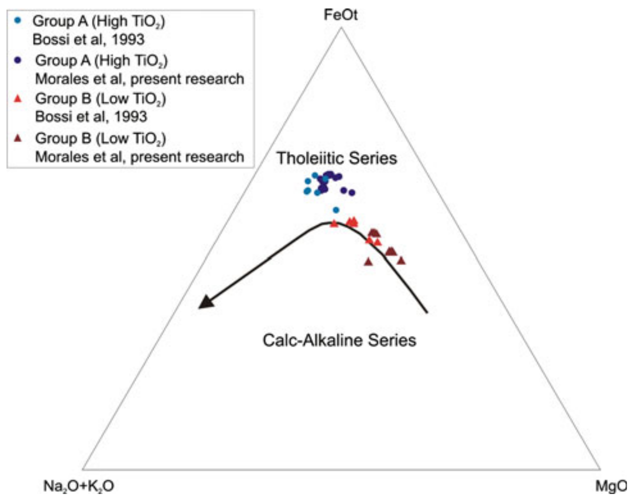


Fig. 12 AFM diagram showing the distribution of the dikes

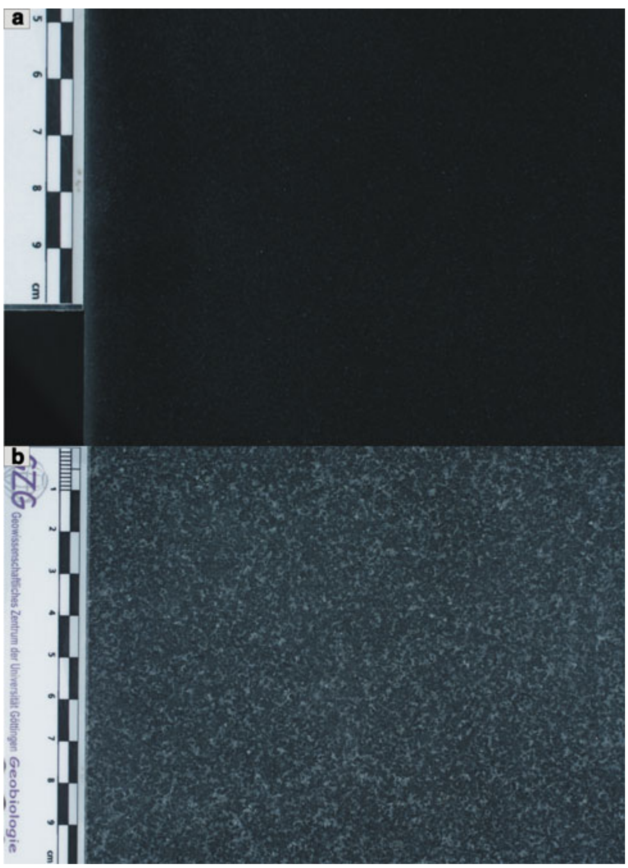


Fig. 13 **a** Absolute Black dolerite; **b** Moderate Black dolerite

texture is observed in the chilled margins of two dikes from Group B and in one from Group A. In the dike from Group A the phenocrysts are plagioclase (sample U55) and in the dikes from Group B they are plagioclase and augite. In one sample (U13) they are altered to calcite and chlorite, respectively.

In both dolerite groups the normative mineral compositions show more or less comparable values (see Table 5). The *M* value (color index: total volume percent of mafic minerals) varies between 29 and 37% in Group A and between 31 and 34% in Group B.

For both groups the normative *M* values are comparable between Zones 2 and 3. For Group A, Zone 2 has a value of 31 and Zone 3 a value of 33%. In Group B, both zones have an *M* value of 33%. Only one sample of Group A shows an important difference: 37% in Zone 2 and 33% in Zone 3 (Quarry U55). Although, *M* values for zones 2 and 3 are comparable, the Absolute Black (Zone 2) appears much darker than the Moderate Black (Zone 3) due to the smaller grain size.

This color index, which is determined by the normative mineral composition, shows some differences compared to the modal mineral composition. In Group A, the modal mineral composition exhibits a *M* value of 49% in Zone 2 and 38% in Zone 3. Group B shows 49% in Zone 2 and 47% in Zone 3. All the samples have an *M* value higher than 30%, and therefore are classified as mesocratic.

Determination of commercial varieties: influence of grain size, fabric, chemical and mineral composition

A first classification based on the color of the rock and grain size of plagioclase was made by Bossi and Campal (1991) and continued by Bossi and Schipilov (2007). They determined that the Absolute Black is aphanitic with a mean grain size between 0.1 and 0.2 mm. Fine Black is a fine-grained variety with a grain size between 0.3 and 0.5 mm. Normal Black (known as Oriental) has a grain size between 0.6 and 0.8 mm and the Coarse Black is coarser than 1 mm.

The results and observations collected in the current investigation broadly agree with the above classification. However, a new one is proposed based on variations in grain size, measured on the *c* axes of the plagioclase laths that are slightly different, and therefore the Uruguayan dolerites can be classified as follows: Absolute Black (Negro Absoluto), with aphanitic texture, grain size <1 mm, Moderate Black (Negro Oriental) with phaneritic texture, 1–2 mm and Special Black, which is similar to moderated black but with some heterogeneity in the color, for example: green or white spots due to the presence of large hornblende and plagioclase crystals, respectively.

The chemical composition influences the mineralogy, and therefore the décor of the rock. For both groups, rocks of Zone 2 are darker than those of Zone 3, caused by higher modal *M* values, but also by their smaller grain size, as the mafic minerals are better distributed in the whole rock.

Table 4 Petrographical data for Groups A and B

Geochemical classification	Group A, high TiO_2 content (between 1.5 and 2.5%) Andesi-basalt	Group B, low TiO_2 content (less than 1.2%) Basalt
Plagioclase	Between An_{34} and An_{44}. Up to 40%, no significant differences between both zones	Between An_{47} and An_{60}. Up to 48% in Zone 2 and 44% in Zone 3
Clinopyroxene	Mostly augite, some pigeonite can be present, up to 25%, no significant differences between both zones	Mostly augite, some pigeonite can occur, up to 40%, no significant differences between both zones
Granophyric intergrowth	Around 10% in Zone 2 and 20% in Zone 3	Around 2% in Zone 2 and 10% in Zone 3
Amphibole	Hornblende as uralitization product of clinopyroxene, up to 13% in Zone 2 and 7% in Zone 3	Hornblende as uralitization product of clinopyroxene, up to 4% in Zone 2 and 6% in Zone 3
Opaques	Magnetite in euhedral to subhedral crystals, ilmenite in skeletal crystals, up to 8%, no significant differences between both zones	Ilmenite in elongated crystals, up to 2%
Apatite	Always present in granophyric intergrowth and as inclusions in PI	Always present in granophyric intergrowth and as inclusions in PI
Biotite	As accessory associated with clinopyroxenes and opaques	As accessory associated with clinopyroxenes and opaques
Texture	Subophitic, occasionally porphyritic in Zone 1 and 2, phenocrystals of PI and Aug	Subophitic, frequently porphyritic in Zone 1 and 2, phenocrystals of PI and Aug
Grain size (Pg)	Between 0.5 and 1 mm in Zone 2, and between 1 and 2 mm in Zone 3	Between 0.5 and 1 mm in Zone 2, and between 1.5 and 2 mm in Zone 4

Mineral abbreviation after Kretz (1983): *An* anorite, *Aug* augite, *PI* plagioclase

Color measurements

Color measurements were performed at the Labor für Baudenkmalpflege in Naumburg (Germany) on 12 different black dimensional stones. In Fig. 19, all results are listed. The L^* values ranged from 25.22 for the Absolute Black dolerite to 42.47 for the Kvemo quartz–phyllite. a^* values are between −0.03 for the Impala gabbro/norite and 1.00 for the Galaxy Brazil. b^* values range between −0.13 for Kvemo and 1.60 for Impala (Fig. 19).

Motoki and Zucco (2005) developed a classification that takes into account the B parameter (brightness) from the HSB color system (see Appendix). The category limits determined by these authors have been converted to the CIE Lab color system as follows: black ($L < 27$), dark gray ($27 < L < 58$), light gray ($58 < L < 87$) and white ($L > 87$). Utilizing this classification, the Absolute Black dolerite can be defined as black and the Moderate Black dolerite as dark gray.

Occurrences and deposits

Regional distribution: length, width, frequency, country rock relations

The two groups investigated from the dike swarm intruded into an area of 20,000 km^2 and in all the lithologies of the Piedra Alta Terrane, which consists of granites, metagranites and metasediments (Fig. 20). Bossi et al. (1993) pointed out that Group A crops out more often in the northern part of the Piedra Alta Terrane and Group B more to the southern part.

The dikes and the quarrying were first mentioned in Bossi (1969). All the mining concessions and 15 locations where the dikes were mined were mentioned in an internal report of the DINAMIGE (National Geological Survey of Uruguay; Medina and Carrión 1986). In 1987, Medina and Carrión presented another report that described just the dikes affected by exploration and the mining permissions obtain from the Florida Department.

Bossi et al. (1989) presented the first photogeological map where the distribution of the dikes is shown. The map depicts thousands of parallel dikes intruding the "ancient orogenic cycle" or what it is now known as the Piedra Alta Terrane (PAT). The dikes follow a NE–E direction, but in the eastern margin of the terrane, near the Sarandí del Yí Shear Zone, they change direction to S–SE, due to the dextral shear activities during the Proterozoic. They were recognized using aerial photographs at 1:20,000 scale and corroborated with field observations (Bossi and Campal 1991). Since this map is based on photographic aerial surveys, it was impossible to verify the presence of all these dikes in the field, and therefore the number of dikes is probably smaller than originally proposed.

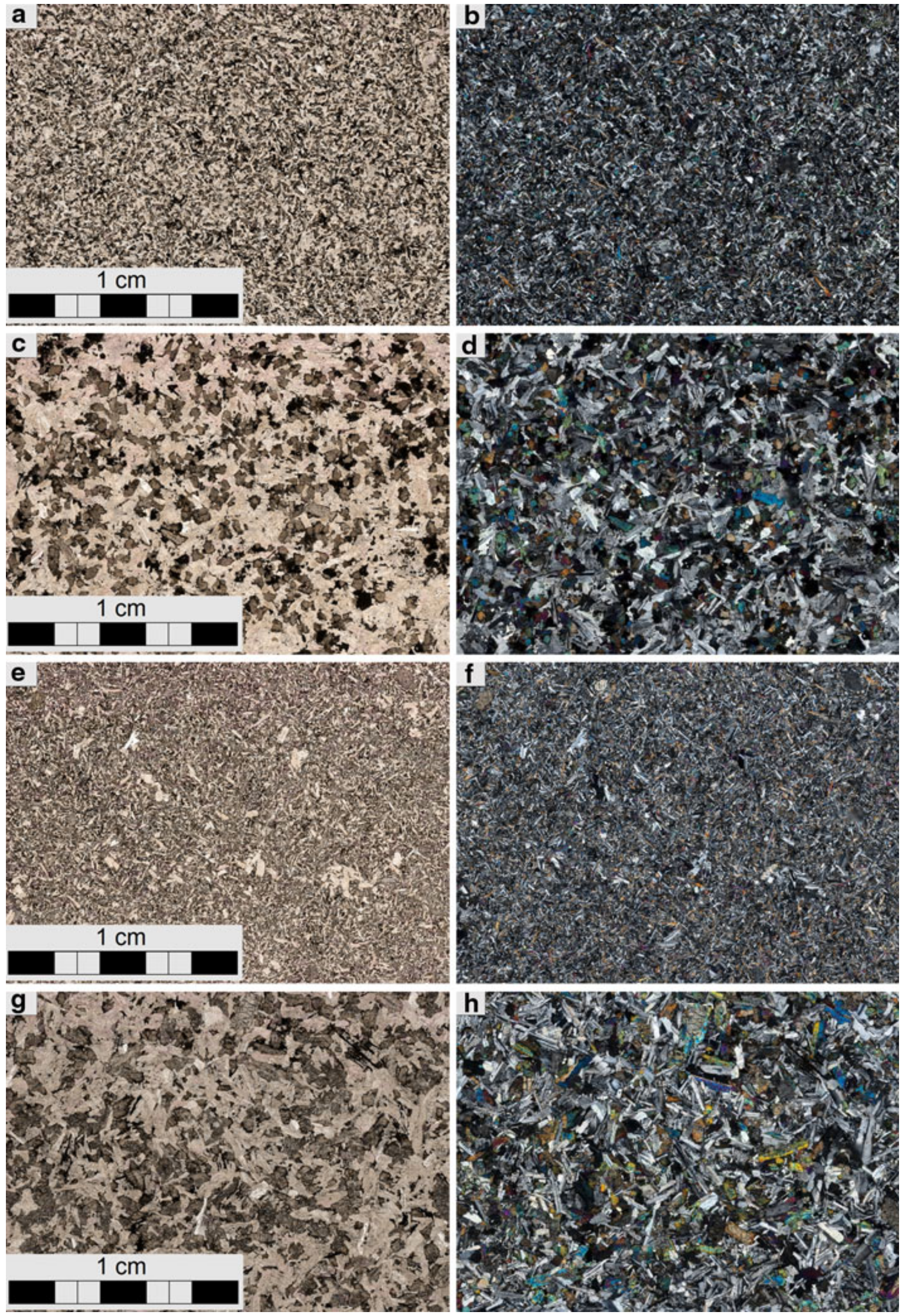


Fig. 14 General overview of the Uruguayan dolerite fabrics. **a** and **b** Zone 2 in dike from Group A. **c** and **d** Zone 3 in dike from Group A. **e** and **f** Zone 2 in dike from Group B. **g** and **h** Zone 3 in dike from Group B (*Left column* plane polarized light; *right column* crossed polarized light)

More recently, Spoturno et al. (2004) published a geological and mineral resources map for the San José Department at a scale of 1:100,000. This represents an area of almost 5,000 km^2, which corresponds to approximately the half of the area to where the Piedra Alta Terrane crops out. They recognized a total of 11 dikes; 6 of them have been mined in the past for the extraction of dolerite blocks for the dimensional stone market. Techera et al. (2004) studied in detail the different quarries present in the San José Department and their observations are in accordance with those of Bossi and Campal (1991) and Bossi and Ferrando (2001).

The field observations made in the current investigation support most of the conclusions of the previously mentioned authors. They are:

1. The dikes are parallel to each other and strike ENE. The length of each dike is usually greater than 1,000 m. In the area of Polonia-Pichinango four quarries are located within the same dike (Fig. 4). Some dikes may have a greater extension as is presently assumed.
2. According to Bossi and Campal (1991), the widths of the dikes range from 0.5 to 80 m, being in average

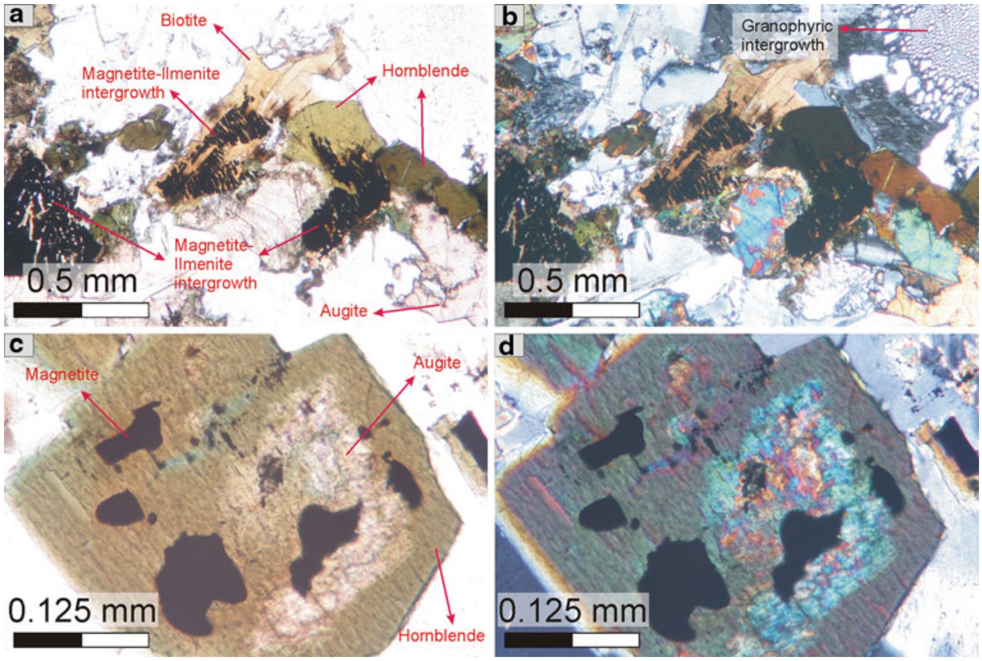


Fig. 15 Texture and mineralogy of Zone 3 in dike from Group A. **a** Biotite crystals surrounding magnetite–ilmenite and hornblende crystals partially surrounding augite and magnetite–ilmenite crystals (plane polarized light, width of view 1.8 mm). **b** Same image as in (**a**), but in crossed polarized light. **c** Augite crystal almost totally replaced by hornblende with inclusions of opaque minerals (plane polarized light, width of view 0.45 mm). **d** Same image as in (**c**), but in crossed polarized light

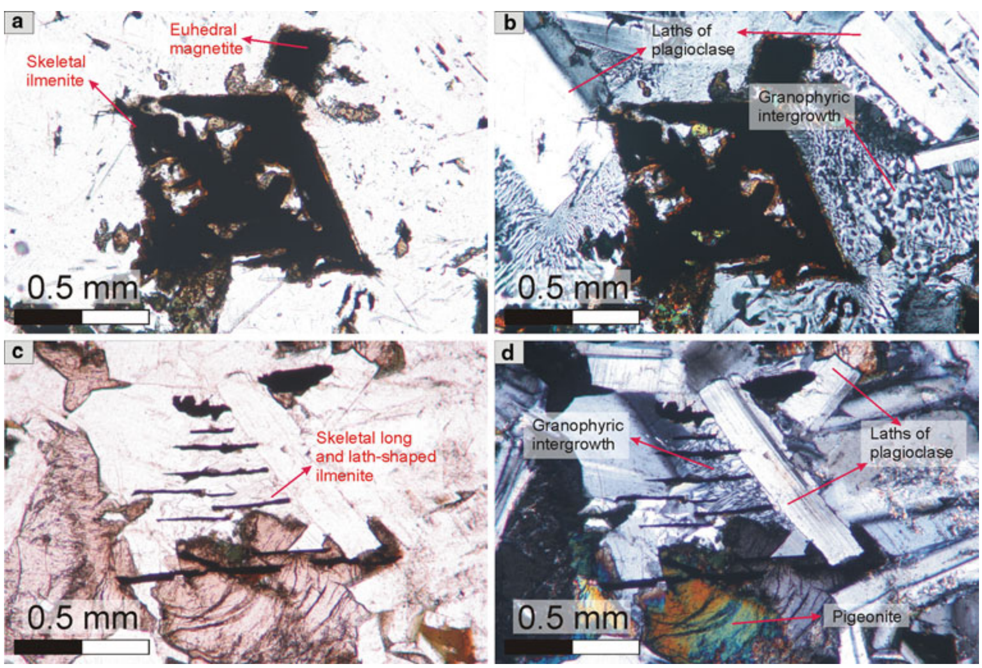


Fig. 16 **a** Skeletal ilmenite and euhedral magnetite, dike of Group A, Zone 3 (plane polarized light, width of view 1.8 mm). **b** Laths of plagioclase and granophyric intergrowth (same image as in (**a**), but in crossed polarized light). **c** Skeletal, long and lath-shaped ilmenite. Group B dike, Zone 3 (plane polarized light, width of view 1.8 mm). **d** Laths of plagioclase and crystals of pigeonite with typically curved fractures (same image as in (**c**), but in crossed polarized light)

20 m. In this investigation the width of the dikes, where a quarry is located, were determined to be between 19 and 41 m.

3. The contacts with the country rock are usually plane and parallel, sub-vertical and dip steeply toward the southeast.

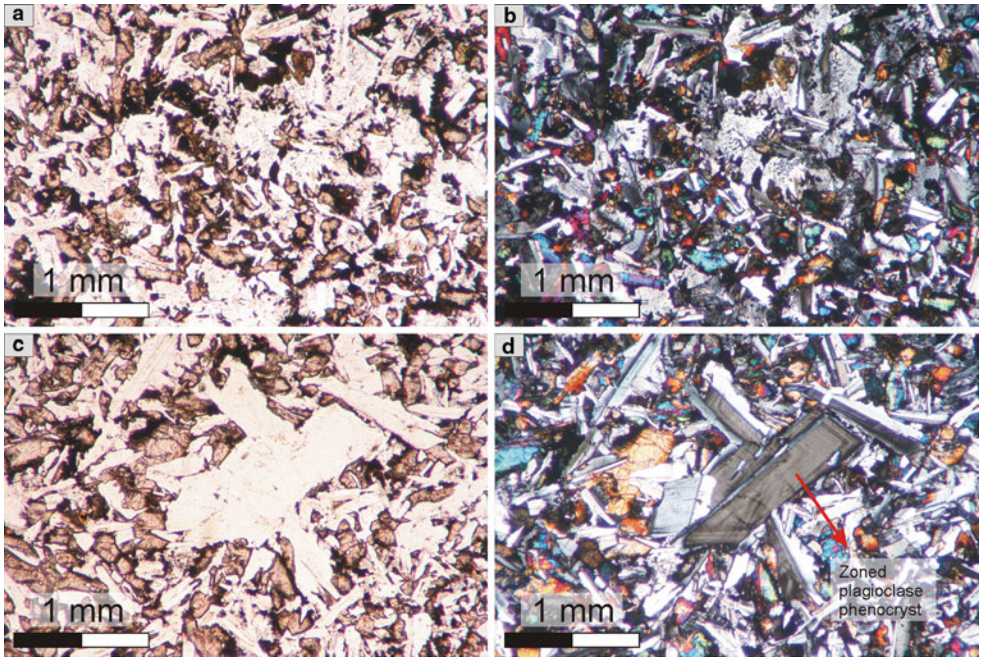


Fig. 17 **a** Subophitic texture in dike of Group A, Zone 3 (plane polarized light, width of view 3.6 mm). **b** Same image as in (**a**), but in crossed polarized light. **c** Subophitic texture in dike of Group B, Zone 3 (plane polarized light, width of view 3.6 mm). **d** Same image as in (**c**), but in crossed polarized light

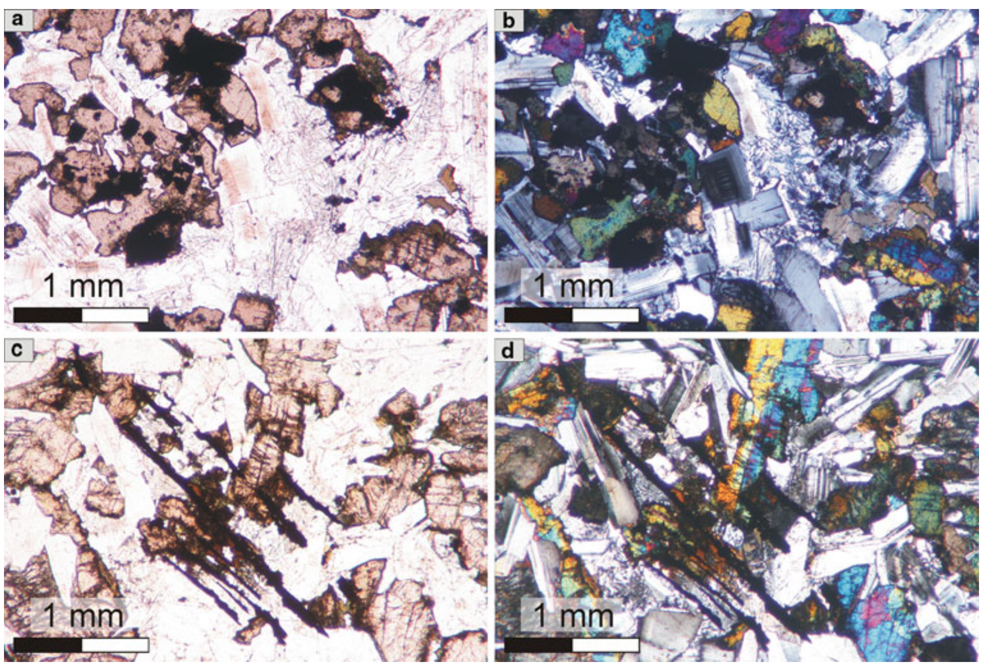


Fig. 18 **a** Equigranular texture in dike of Group A, Zone 2, where a homogenous distribution of the opaques are visible (plane polarized light, width of view 3.6 mm). **b** Same image as in (**a**), but in crossed polarized light. **c** Porphyritic texture in dike of Group B, Zone 2. Several phenocrysts of plagioclase are visible (plane polarized light, width of view 3.6 mm). **d** Same image as in (**c**), but in crossed polarized light

4. The dikes crop out in different ways and not all along their projected paths. Sometimes large boulders crop out; similar to those of granitic rocks (Fig. 21a). In numerous cases the dolerites are poorly exposed and usually very fractured (Fig. 21b).

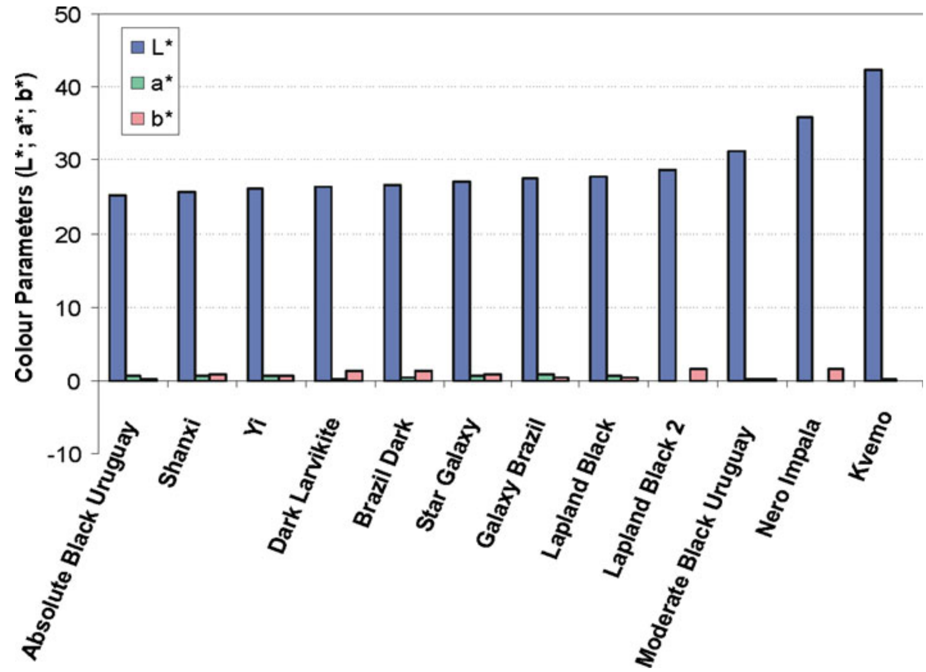


Fig. 19 Color measurements for various black dimensional stones

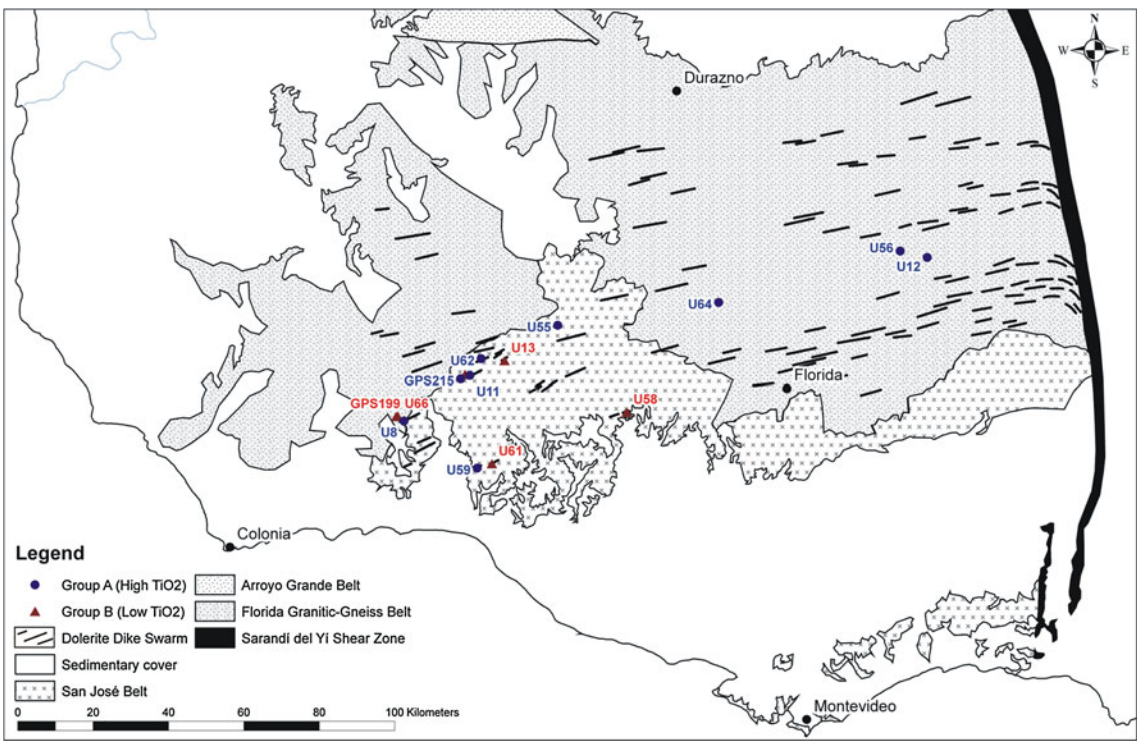


Fig. 20 Geological map with sampled quarries (map redrawn after Bossi and Ferrando 2001)

5. There is no preferred topographical outcrop position. The dikes are found at the top and in the middle of hills but also at the same contour level as streams.

A summary of the dikes sampled are listed in Table 7.

Characterization of dolerite deposits: controlling parameters

The main controlling parameters affecting the deposits of dimensional stones are the volume of the deposit, the

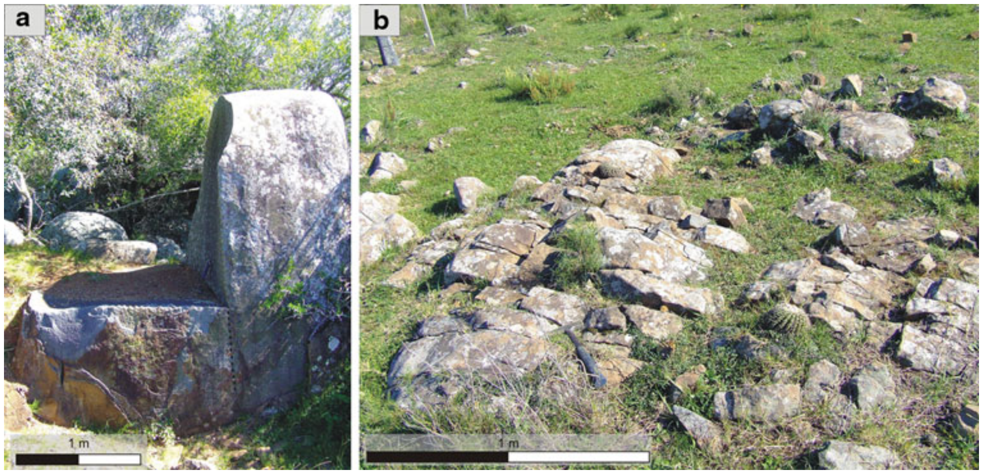


Fig. 21 **a** Large boulder of dolerite weathered in place. **b** Poorly exposed dolerite outcrop

ensemble of lithological aspects (e.g. fabric, mineralogy, geochemistry, etc.) and the tectonic inventory.

The volume is important because enough material has to be present in order to furnish a steady product for regional or international markets, and thus such an occurrence can be considered as a suitable provider. The dolerite deposits are characterized by their tabular shape, being a two-dimensional deposit. The volume of the deposit is limited by the length of the dike and its width, whereas the depth is determined by how deep it is technologically possible to mine.

In Uruguayan deposits, the maximum depth that has been reached in a dolerite quarry is around 10 m. Medina and Carrión (1987) reported that in the quarries U12A and U12B drillings were performed, but any report on the results is lacking. This is also the case of drillings in the quarry U8, where the drill cores are available, but the drilling location and direction is unknown, so it is impossible to know the depth of drilling. The maximum mining depth in this kind of deposit has been attained in the dolerite quarries of Sweden, where the extraction of blocks can reach up to 50 m.

The second controlling parameter is the ensemble of lithological aspects that indicates if the rock is suitable as a dimensional stone, since these influence the décor, e.g. the color and fabric of the rock. For black dimensional stones, the intensity and homogeneity of the black color is very important, so that no other color spots are present. Exceptions to this assumption are the cases where such heterogeneities make an improvement in the quality of the décor, e.g. the Star Galaxy from India or Black Galaxy from Brazil.

Tectonic elements are the third controlling parameter. The main structural elements are joints, which are mainly distributed as orthogonal sets and are probably the result of the cooling and contraction of the rock.

In Fig. 22 the main joint sets are represented, which were observed in all the investigated dikes. Previous authors (e.g. Medina and Carrión 1986, 1987; Bossi and Campal, 1991) have also reported on these joint sets. Three main joint sets occur, two sub-vertical and one horizontal. The two sub-vertical sets are orthogonal: one parallel to the dike walls striking 070–085° and dipping toward the NW or SE (represented as Vt 1 in Fig. 22), and the other one perpendicular to the dike walls striking to 320–360° and dipping toward the NE or SW (represented as Vt 2 in Fig. 22). The sub-horizontal joint set shows dips up to 10° in all directions.

The distribution of the joints in several quarries has been measured in order to calculate the potential block size that can be extracted. The first two joint sets observed are represented in the plots of Fig. 23. A meaningful difference in the orientation of the joints cannot be observed between the dikes of Groups A (High TiO_2) and B (Low TiO_2). However, the dikes of Group A display a higher frequency of joints parallel to the dike wall, whereas the dikes of Group B show a higher frequency of joints perpendicular to the dike wall and of joints that dip to the SW. Since these joint sets are

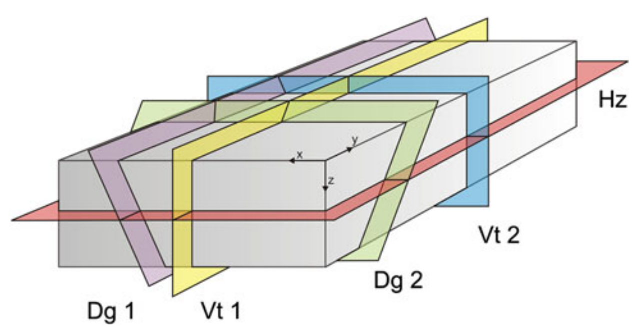


Fig. 22 3D model of joint sets found in dolerite dikes. *X* direction: dike width, *Y* direction: dike length, *Z* direction: depth. *Hz* horizontal, *Vt 1* vertical 1 (parallel to dike length), *Vt 2* vertical 2 (perpendicular to dike length), *Dg 1* diagonal 1 (parallel to dike length) and *Dg 2* diagonal 2 (perpendicular to dike length)

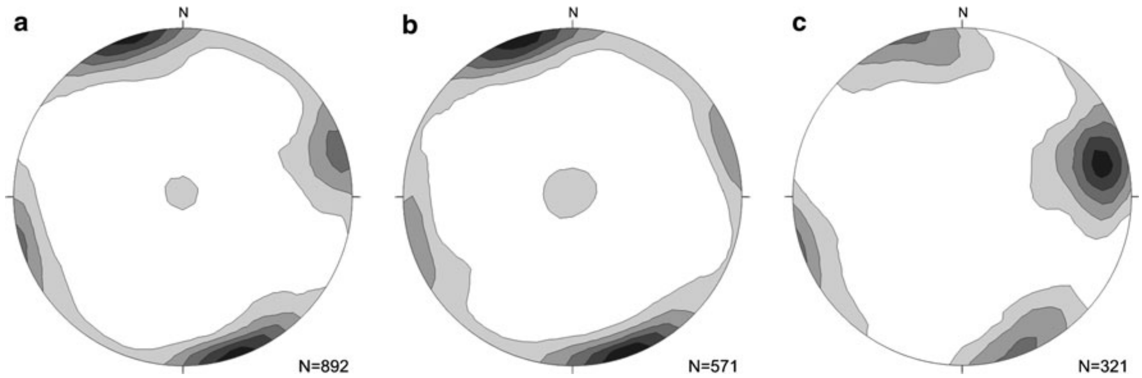


Fig. 23 **a** Total joints measured. **b** Joints measured in Group A dikes. **c** Joints measured in Group B dikes. Stereograms: equal area, lower hemisphere. Contours: 1, 2, 3, 4, 5 times uniform distribution

orthogonal to each other, regular-sized blocks can be quarried. If the spacing between the joints is large enough, the quarry is able to produce blocks on a profitable basis. The problem with this type of deposit is the existence of other joint sets that crosscut the orthogonal ones. Diagonal joints have also been previously described by Bossi and Campal (1991) and Medina and Carrión (1986). Although these joints are not very frequent, their significance for the quarrying operation is very important as they crosscut the regular blocks that could be extracted, increasing the proportion of waste material and minimizing the production of marketable blocks (Fig. 24). In statistical documentations they are often overseen (Fig. 23). Diagonal joints have been isolated in the plots of Fig. 25 in order to better visualize them.

The two diagonal sets are also orthogonal to the dike direction and both have dips between 11 and 75°. One diagonal set strikes N070-085° and dips toward the NW or SE (Dg 1 in Fig. 22), and the other one strikes N320-360 and dips to the NE or SW (Dg 2 in Fig. 22).

Quality assessment of dolerites deposits

All the dikes can be subdivided into three zones by their grain size: Zone 1 (very fine-grained), Zone 2 (fine-grained) and Zone 3 (medium-grained). In quarries located in the dikes of Group A, in which their Zone 2 is unfractured, field observations indicate that the Absolute Black variety can be mined (e.g. Black Stone Quarry, see Fig. 9). The Moderate Black variety (Negro Oriental in Uruguay) is extracted from Zone 3. Since Zones 1 and 2 are not more than 11% of the dike, the ratio between Absolute Black and Moderate Black is at best 0.124.

Several decades ago the scarcity of joints in a dimensional stone deposit was a very negative aspect for the extraction, because they could not be used to facilitate the mining of the blocks (Bossi and Campal 1991). Today the diamond wire saw makes it possible to cut a block of dolerite without any previous discontinuity. However, the problem of a greater proportion of joints in a quarry persists, which is one of the controlling factors in the quarrying of dolerite deposits.

Characterization of the waste material

Before starting the extraction of any dimensional stone, the weathered material (including rounded boulders) and sedimentary deposits that covers the fresh rock must be

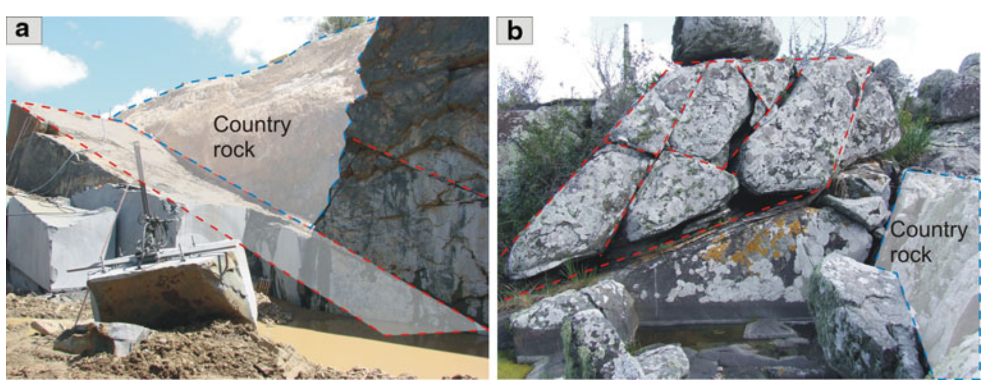


Fig. 24 **a** Diagonal joint dipping parallel to the dike walls and **b** diagonal joints dipping perpendicular to the dike walls

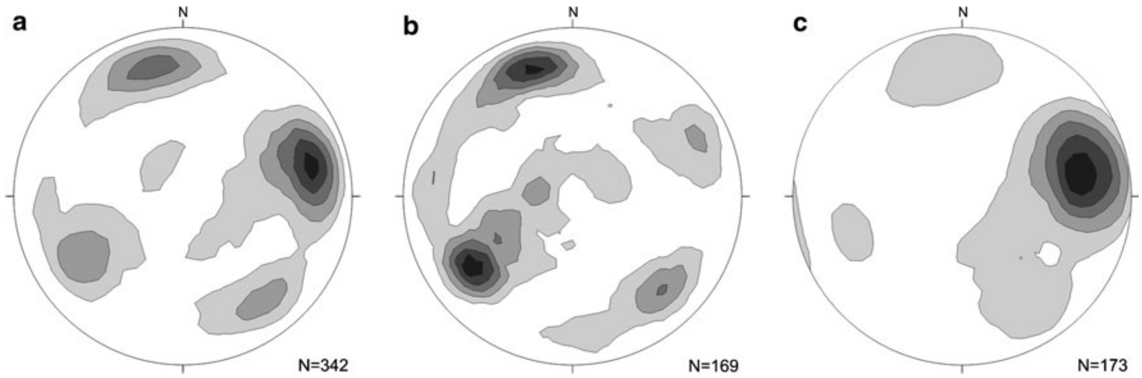


Fig. 25 **a** Total diagonal joints measured. **b** Diagonal joints measured in Group A dikes. **c** Diagonal joints measured in Group B dikes. Stereograms: equal area, lower hemisphere. Contours: 1, 2 3, 4, 5 times uniform distribution

Table 5 Normative mineral distributions in both groups (in wt.%)

Group	Sample	Q	Ort	Ab	An	Hy	Di	Mag	Ilm	Ap	Cc	Percentage of An in PI
Group A (high TiO_2)	U8M1	10.4	11.3	22.6	16.8	18.2	12.2	2.5	4.7	0.7	0.6	42.7
	U8P7	8.9	9.7	21.7	17.3	19.9	14.3	2.7	4.4	0.6	0.5	44.4
	U11A	10.9	10.6	22.3	19.0	18.6	11.9	2.3	3.4	0.5	0.3	45.9
	U110	8.3	9.9	22.2	17.3	19.4	14.8	2.7	4.5	0.6	0.2	43.7
	U11M1	10.0	10.6	22.5	17.2	18.5	13.3	2.5	4.4	0.6	0.4	43.3
	U11M12	8.8	9.8	21.8	17.2	19.9	14.5	2.7	4.4	0.6	0.4	44.2
	U12A	5.4	8.8	21.7	18.4	21.8	15.3	2.8	4.5	0.7	0.6	45.8
	U12B	5.2	8.9	21.8	18.5	21.9	15.2	2.8	4.5	0.7	0.5	46.0
	U55M1	3.0	9.2	22.3	19.9	21.6	15.2	2.7	4.7	0.9	0.6	47.2
	U55M4	10.0	9.9	21.7	16.5	19.9	13.7	2.7	4.3	0.6	0.7	43.2
	U56	8.5	9.9	22.0	16.7	19.9	14.7	2.7	4.4	0.6	0.5	43.1
	U59	1.6	8.3	21.4	20.8	23.0	16.1	2.7	4.6	0.8	0.6	49.3
	U62M3	10.8	10.7	22.2	18.6	18.8	12.2	2.4	3.4	0.5	0.3	45.6
	U62M6	10.8	10.8	22.3	18.4	18.9	11.9	2.4	3.5	0.5	0.5	45.2
	U64M1	9.1	10.3	22.4	16.9	19.6	13.4	2.7	4.5	0.8	0.5	43.0
	U64M2	7.3	9.0	21.8	18.4	20.7	14.7	2.7	4.3	0.6	0.6	45.8
	U215M1	11.4	11.1	22.4	18.6	18.6	11.2	2.3	3.4	0.6	0.3	45.4
	U215M3	11.6	11.2	22.3	18.7	18.4	11.1	2.3	3.5	0.5	0.3	45.6
	Average	8.4	10.0	22.1	18.1	19.9	13.6	2.6	4.2	0.6	0.5	45.0
Group B (low TiO_2)	U13M1	3.3	11.2	19.1	28.2	22.5	12.0	1.5	1.7	0.3	0.4	59.6
	U13M10	6.3	5.9	16.7	29.6	24.1	13.3	1.5	1.6	0.3	0.8	63.9
	U58M1	7.1	6.9	18.0	27.3	21.7	14.9	1.6	1.8	0.3	0.5	60.3
	U58M3	7.9	6.5	17.7	26.9	22.1	14.5	1.6	1.7	0.3	0.8	60.4
	U61	7.4	7.1	18.1	27.3	21.0	15.0	1.6	1.8	0.3	0.4	60.2
	U66P1	7.4	5.8	16.8	29.1	22.8	14.4	1.5	1.5	0.3	0.4	63.4
	U66P12	6.1	5.5	16.1	30.4	24.6	13.4	1.4	1.4	0.2	0.7	65.3
	U199	6.7	6.3	16.8	30.0	23.7	12.7	1.5	1.6	0.3	0.4	64.2
	U243	6.6	6.3	16.8	30.4	23.2	13.2	1.5	1.6	0.3	0.2	64.4
	Average	6.5	6.8	17.3	28.8	22.9	13.7	1.5	1.6	0.3	0.5	62.4

removed. These materials are called overburden or simply waste rock. In addition to these materials, an important amount of country rock (no matter if fresh or weathered) must also be extracted for safety reasons (instabilities, etc.) while quarrying. Considering a mining depth of 50 m, a width of 30 m and a dike dip angle of 89°, the proportion of waste rock to be removed is about 6.5% of the total volume extracted and 26% when the dip is 70°. However, the amount of waste rock will significantly increase by lower depths of exploitation as realize today in Uruguay (maximum depth up to 10 m).

Another kind of waste rock produced comes from the sections of the quarry where a high frequency of fractures occurs. No production of profitable blocks can be performed in these sections (Fig. 26). When the extracted block, which differs from a rectangular cuboid, is squared into one, new waste rock is produced that is highly dependent on the joint systems. Internationally, the waste material produced in dimensional stone quarries is around 30–50% of the extracted volume, however, in Uruguayan dolerite quarries this value can reach up to 90% (Oyhantçabal et al. 2007a, b).

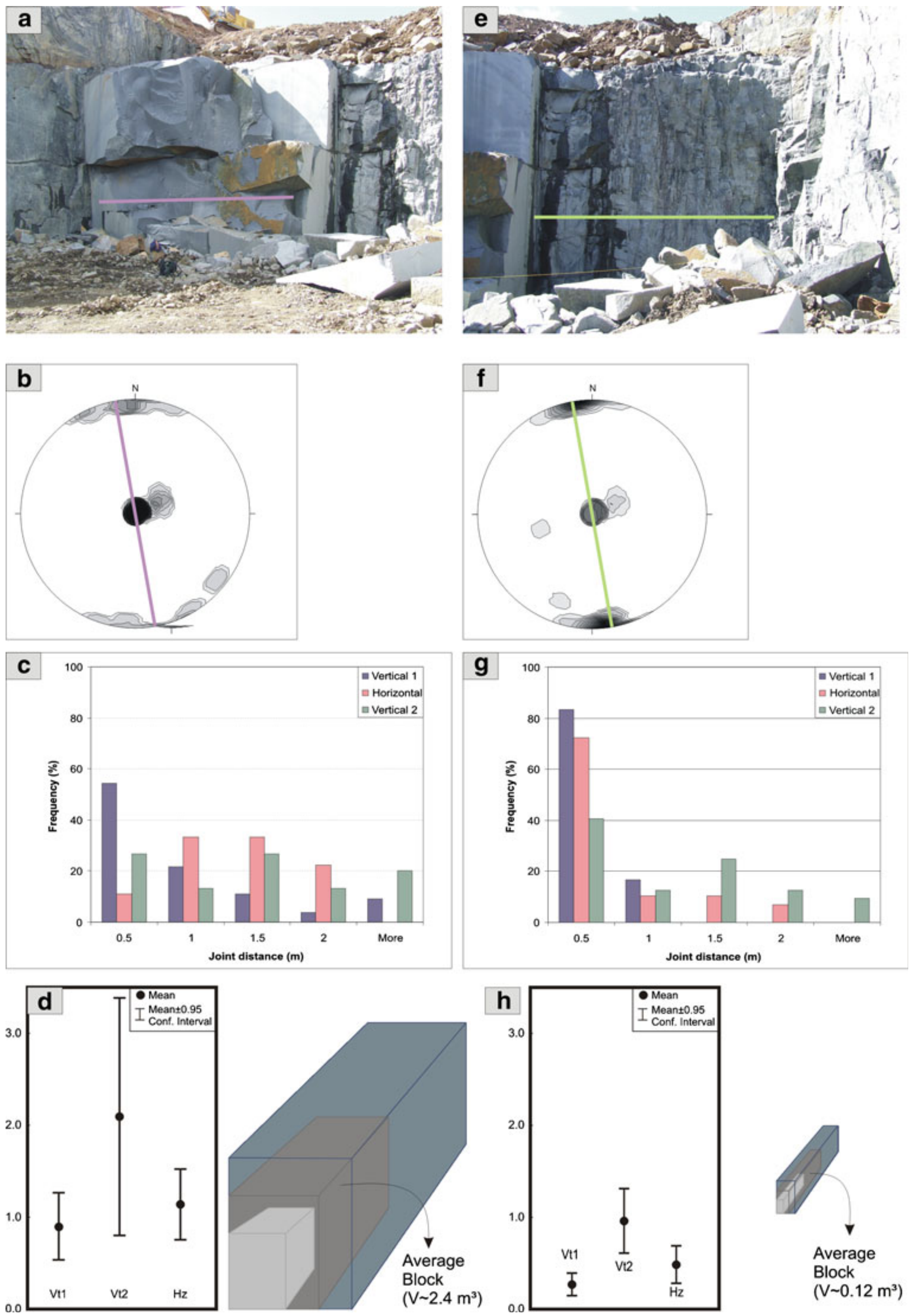


Fig. 26 Comparison of two sections of a dolerite dike: **a** Section suitable for quarrying dolerite blocks; **b** stereogram showing joint distribution; **c** diagram showing distances between joints; **d** box plots showing average distances between joints and the minimal, average and maximal block that can be extracted; **e** section only suitable for quarrying gravel; **f** stereogram showing joint distribution; **g** diagram showing distances between joints and **h** box plots showing average distances between joints and the minimal, average and maximal block that can be extracted

Petrophysical properties

The petrophysical investigations were carried out in the laboratories of the Department of Structural Geology and Geodynamics of the Geoscience Centre of the University of Göttingen, whereas the abrasion strength test (AST) was conducted at the laboratories of AMPA (Amtliche Materialprüfanstalt für das Bauwesen) of the University of Kassel. The materials used for the petrophysical testing are samples from Zone 2 and Zone 3 from the Black Stone Quarry (U11), which is located in a dike from Group A. All the results of the petrophysical properties are listed in Table 6. Table 7 shows the main petrophysical properties of other comparable black dimensional stones, such as

Table 6 Summary of the dikes sampled

Group	Sample	Quarry/Location	Dike width (m)	Present condition	Quarry depth (m)	Quarry/Outcrop length (m)	Dike length (m)	Strike
Group A (high TiO_2)	U8	Rosarito	41	In activity	At least 8	100	3,500	N060°
	U11	Blackstone	38	In activity	8	140	500	N080°
	U12A	Talita grande	25	Flooded	At least 4	135	2,000	N075°
	U12B	Talita chica	20	Flooded	At least 3	150	2,000	N080°
	U55	Mexico	30	Flooded	At least 6	135	1,500	N053°
	U56	Los Fresnos	30	Abandoned	Superficial	170	3,400	N060°
	U59	Omar Mendez	40	Flooded	At least 4	110	1,250	N070°
	U62	Las Acacias	19	Flooded	5	130	2,600	N072°
	U64	Pintado	35	Abandoned	Superficial	430	430	N075°
	U215	La Sierra	16	No quarry	–	220	500	N056°
Group B (low TiO_2)	U13	Victor	30	Abandoned	8.5	110	1,900	N076°
	U58	Boria	30	Flooded	At least 5	120	1,700	N076°
	U61	Inex	25	Flooded	11	225	2,400	N065°
	U66	Pimafox	24	In activity	4	60	2,000	N072°
	U199	Arroyo Polonia	20	No quarry	–	55	560	N065°
	U243	Arroyo de la Quinta	30	No quarry	–	120	800	N050°

Table 7 Petrophysical properties of Group A (high TiO_2)

Commercial name	Negro Absoluto (Zone 2)			Negro Oriental (Zone 3)		
Rock type	Dolerite			Dolerite		
Direction	*X*	*Y*	*Z*	*X*	*Y*	*Z*
UCS (MPa)	399.6 ± 33.6	371.4 ± 37.0	367.00 ± 16.2	266.2 ± 26.8	285.8 ± 29.2	274.7 ± 24.6
Young modulus (GPa)	32.90 ± 7.38	29.60 ± 9.90	30.59 ± 11.93	27.33 ± 15.77	23.47 ± 8.84	17.40 ± 4.54
Tensile strength (MPa)	16.7 ± 4.5	19.5 ± 4.3	17.4 ± 5.8	16.7 ± 3.0	15.9 ± 3.0	14.3 ± 3.4
Flexural strength (MPa)	51.8 ± 2.2	52.8 ± 2.1	46.1 ± 1.5	35.7 ± 2.5	30.8 ± 1.3	32.9 ± 1.3
Abrasion strength (cm^3/50 cm^2)	2.2	2.4	2.2	2.3	2.5	2.4
Breaking load at dowel hole (MPa)		4.7 ± 0.8			4.2 ± 0.7	
Real density (g/cm^3)		2.99			3.02	
Apparent density (g/cm^3)		2.99			3.02	
Porosity (%) (vacuum)		0.03			0.06	
Average pore radii (μm)		0.10			0.06	
Most abundant pore radii class (μm)		0.01			0.02	
Water uptake (%) (atmospheric)		0.01			0.02	
Water uptake (%) (vacuum)		0.01			0.02	
Vapor diffusion resistance factor		6,489			5,010	
Thermal expansion ($\times 10^{-6}$ K^{-1})	6.63	6.60	6.53	6.54	6.56	6.90

basic plutonic rocks or volcanic rocks. Future studies are planned for determining the petrophysical properties in samples from Group B.

Density, porosity and thermal expansion

Density values are similar to gabbro-dioritic rocks, to which they can be compared. For the Absolute Black variety the apparent density value is 2.98 g/cm^3 and for the Moderate Black the value is 3.02 g/cm^3. In both varieties, the real density is quite similar, 2.99 g/cm^3 for Absolute Black and 3.02 g/cm^3 for Moderate Black. The density values of some comparable rocks vary between 2.8 (for Impala and Star Galaxy) and 3.3 g/cm^3 (for Ebony Black) (see Table 7).

The dolerites have very small values of porosity under vacuum, around 0.03% for Absolute Black and 0.06% for Moderate Black. Their pore radii distribution shows that the most abundant pore radii class is 0.01 μm for Absolute Black and 0.02 μm for Moderate Black, whereas the average pore radii is 0.10 μm for Absolute Black and 0.06 for Moderate Black.

The vacuum and atmospheric water uptakes are very low, 0.01 for Absolute Black and 0.02% for Moderate Black due to the low porosity values. The values of the comparable rocks in Table 7 vary between 0.05 and 0.33%, for Preto Absoluto and Shanxi Black, respectively.

The thermal expansion differs between 6.53×10^{-6} K^{-1} for Absolute Black and 6.90×10^{-6} K^{-1} for Moderate Black (Table 8). These values can be compared to those determined by Hoffmann (2006) for a hornblendite (6.64×10^{-6} K^{-1}). There is no permanent change in length after the heating/cooling-cycles.

Mechanical properties of black dimensional stones

The dolerite Absolute Black shows uniaxial compressive strength (UCS) values that vary between 367.00 MPa in the z-direction and 399.56 MPa in the x-direction. Moderate Black shows lower values, with 266.22 MPa in the x-direction and 285.78 MPa in the y-direction (for coordinates references see Appendix). The UCS values for basic plutonic rocks range from around 90 to 400 MPa (Mosch 2008) (Fig. 27a, b). The Young′s modulus for Moderate Black was determined to be 17.40 GPa in the z-direction and 27.33 GPa in the x-direction, whereas for Absolute Black the values are 29.60 GPa in the y-direction and 32.90 GPa in the x-direction.

The tensile strength values determined for the Uruguayan dolerites are between 16.68 MPa in the x-direction and 19.49 MPa in the y-direction for the Absolute Black, and between 14.31 MPa in the z-direction and 16.72 MPa in the x-direction for the Moderate Black. According to Mosch (2008), the tensile strength for basic plutonic rocks is around 28 MPa.

The flexural strength values vary between 46.06 MPa in the z-direction and 52.75 MPa in the y-direction for the Absolute Black dolerite, and between 35.72 MPa in the

Table 8 Technical properties of comparable black dimensional stones (source Börner and Hill 2010)

Sample	Origin	Lithology	Density (kg/dm^3)	UCS (N/mm^2)	Flexural strength (N/mm^2)	Water uptake (vol.%)	Reference object
Shanxi Black (G1401)	China	Dolerite	3.0	350		0.33	Interior stone paving of Düsseldorf Airport
Ebony Black	Sweden	Dolerite	3.1–3.3	294	25	0.10	Facade of Empire State Building in New York
Impala	South Africa	Gabbro/Norit	2.8–3.0	221–260	22–26	0.08–0.32	Haus Sommer, Pariser Platz 1 in Berlin
Impala Dark	South Africa	Gabbro/Norit	3.0	290–300		0.10	Bundespräsidalamt in Berlin
Nero Assoluto	Zimbabwe	Fine-grained Gabbro/Norit	3.0–3.1	240–252	24–29	0.12–0.16	Wallraf-Richartz- Museum in Koln; Gramercy Plaza/Torrance in California
Preto Absoluto	Brazil	Fine to middle-grained basalt (Diabas) with a touch of green	3.1	210	34	0.05	
Star Galaxy	India	Fine to middle-grained Gabbro/Norit with bronzite scales	2.8–2.9	183–203	19–20	0.08–0.12	
Absolute Black	Uruguay	Dolerite	3.0	367–400	46–53	0.01	Antel Tower in Montevideo
Moderate Black	Uruguay	Dolerite	3.0	266–286	31–36	0.02	

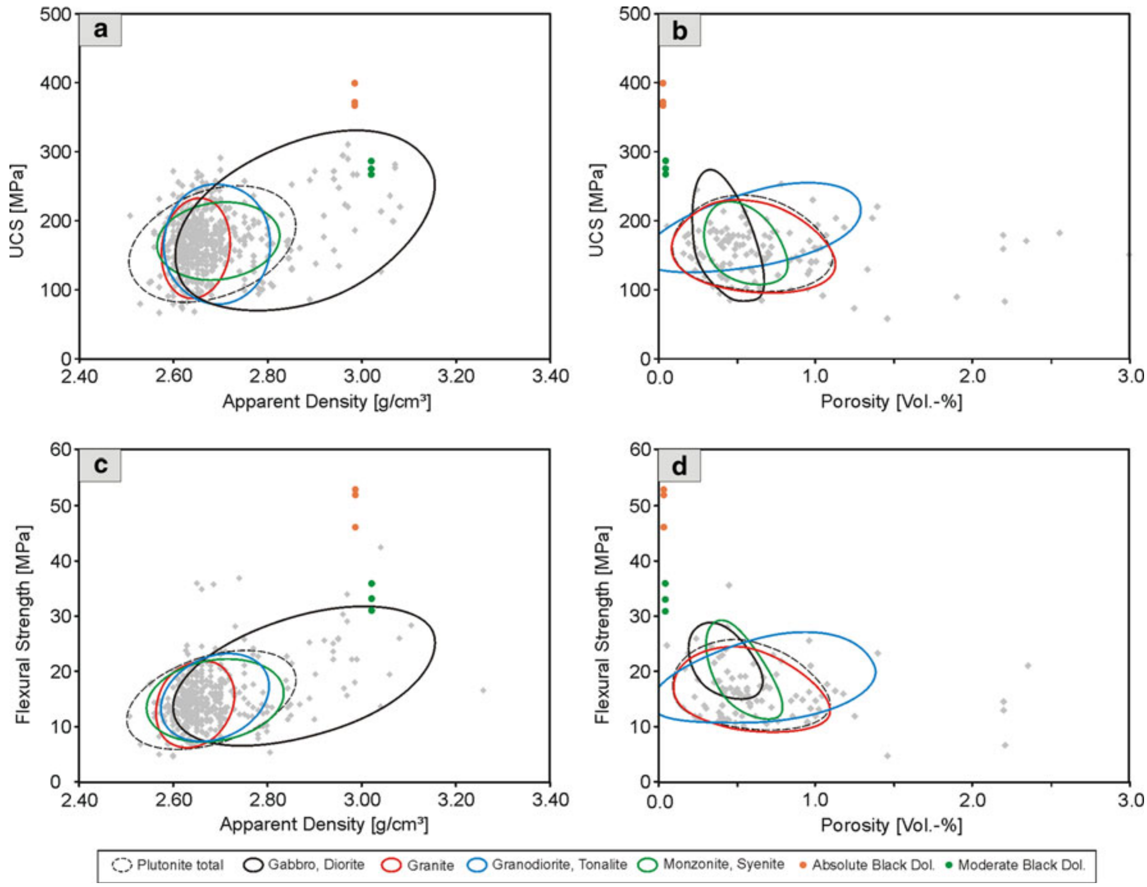


Fig. 27 **a** UCS versus apparent density; **b** flexural strength versus apparent density; **c** UCS versus porosity and **d** flexural strength versus porosity (modified after Mosch 2008)

x-direction and 30.81 MPa in the *y*-direction for the Moderate Black dolerite. The flexural strength values for basic plutonic rocks are around 5–30 MPa (Mosch 2008) (Fig. 27c, d). The breaking load at the dowel hole is 4.68 MPa for Absolute Black and 4.21 MPa for Moderate Black.

The abrasion strength varies between 2.16 $cm^3/50\ cm^2$ in the *z*-direction and 2.36 $cm^3/50\ cm^2$ in the *y*-direction for Absolute Black and 2.26 $cm^3/50\ cm^2$ in the *x*-direction and 2.53 $cm^3/50\ cm^2$ in the *y*-direction for Moderate Black. These are very low values considering the values given by Hoffmann (2006) for diorite, between 7.5 $cm^3/50\ cm^2$ and 15 $cm^3/50\ cm^2$, meaning that the Uruguayan dolerites show a high resistance to material loss due to abrasion.

Summary: evaluation of the "black stone" deposits

Quality assessment with respect to color and décor

Dolerites are valuable dimensional stones, mainly because of two distinct properties: their black color and the possibility of extracting them in larger blocks. The black color is directly related to the décor, and therefore to three properties of the rock: the mineral composition, the texture (which includes grain size, grain shape, and its interlocking flow structures and the observed reaction textures) and the structure (e.g. layering or inclusions). The latter two belong to the rock fabric.

The minerals that determine the black color are melanocratics, such as pyroxene, hornblende, opaques and biotite. Changes in the color can be produced when leucocratic minerals are present or minerals resulting from autohydrothermal reactions. Minerals, such as plagioclase, alkali feldspar and quartz–feldspar intergrowths create white spots in the rock. Green spots are developed when hornblende is present.

The value of black stones increases when the minerals are homogeneously distributed in the rock, exhibit no flow textures, visible intergrowths, nor reaction textures or any visible structure that alters the black color of the rock. If melanocratic minerals are homogeneously distributed, then the rock will have a homogenous color, which can be black or gray depending on their proportion and on the grain size of the rock. Rocks with a finer grain size and the same percentage of melanocratic minerals tend to be darker.

Layering in a black rock affects it negatively, as well as the presence of veins of leucocratic minerals.

For all black dimensional stones three color qualities are defined: absolute black, moderate black and special black. The absolute black color in a dimensional stone can be developed in three different cases. First, when the rock is composed of 100% melanocratic minerals. Second, the rock is composed of melanocratic and leucocratic minerals and the latter contain inclusions of melanocratic minerals, and when the grain size is extremely fine.

The moderate black color can be generated when the melanocratic minerals make up 30–60% of the rock and the grain size is coarse (up to 2 mm) making both mineral colors distinguishable. Three special cases can arise which affects the color of moderate black stones. The first can occur in both varieties when there are minerals present that interrupt the normal color of the stone. Two examples of this are the presence of granophyric intergrowths that produce white spots and the presence of broncite in gabbro that produces golden spots (such as in the Star Galaxy variety of India). Autohydrothermal alteration creates the second special case where whole color changes are produced in the rock. This occurs by the process of uralitization that produces a slightly green coloration. The third situation is given when the rock is cut by veins of different color or layering is present that modifies the whole rock color.

The color index of the Uruguayan dolerites calculated using normative minerals varies between 31 and 33% in Group A and is 33% in Group B. When the color index is calculated using modal analysis, the values are higher. Zone 2 in both groups shows higher modal *M* values than Zone 3. Zone 3 of Group A shows lower *M* values (38%) with respect to Group B (47%), and in both groups Zone 2 can have the same *M* value (49%). The rock is therefore classified as mesocratic using both, the normative and the modal *M* value.

Color variations are related to changes in the grain size, which determines the quality of the main rock varieties. In Uruguayan dolerites, the color of the Absolute Black variety is until now only found in the dikes of Group A. The most important characteristic of Absolute Black is the very small grain size and its homogeneity. The porphyritic texture observed in Zone 2 of some deposits drastically reduces its quality.

The Moderate Black variety develops a dark gray color, in both groups. This is due to the medium grain size of the leucocratic and melanocratic minerals that are distinguishable without any optical aid.

Grain size variations are sometimes visible on the sides of the extracted and squared blocks. A clear layering of melanocratic and leucocratic minerals was not observed; however, in three quarries (two classified as Group A and one as Group B) the presence of leucocratic veins has been observed.

Autohydrothermal alteration can have a negative influence on the color in some parts of a deposit, especially in combination with a porphyritic texture as in Zone 2. When the autohydrothermal alteration is homogenously distributed throughout the entire deposit the quality of the Moderate Black variety is not negatively affected.

Granophyric intergrowths are visible as white spots within a black background, when they are larger than 1 mm. These intergrowths affect the quality of the Absolute Black more negatively than the Moderate Black variety, because the latter one already has coarse white spots (the plagioclase laths) that are homogeneously distributed.

From the color measurement results it can be concluded that Absolute Black dolerite is the darkest of the black dimensional stones considered in this study, followed by Shanxi Black, Yi and Dark Larvikite. The a^* parameter (see Apendix) for the samples analyzed is generally positive (in one sample negative) and very low, indicating that there is a very small proportion of red color in these rocks. The b^* value is also generally positive (in one case negative) and very low, indicating that the rocks studied also have a proportion of yellow in their color. The values a^* and b^* for the samples considered are so small that they have no influence on the color of the sample, which is determined only by the L^* value.

Utilizing the classification scheme of Motoki and Zucco (2005), the rocks analyzed in this study are black and dark gray. Absolute Black dolerite is black, as well as Shanxi, Yi, Dark Larvikite and Brazil Black and Moderate Black dolerite is dark gray, as well as the rest of the rocks analyzed.

Petrophysical aspects

The application and use of dimensional stones are finally controlled by the technical and petrophysical properties. Under normal conditions in a building the technical requirements of a dimensional stone are moderate. Extreme applied loads are seldom. More often the dimensional stones have to show high flexural strength and high resistance to the climatic conditions or the chemical reactants to which they can be exposed to.

In comparison to other black rocks on the international market, the Uruguayan dolerites have similar or even better physical (technical) properties. Particularly the Absolute Black variety shows a maximal compressive strength of 400 MPa and a maximal flexural strength of around 50 MPa. With such high resistance values, these rocks can be used safely in many building parts that require a high compressive and flexural strength. Examples include building façades, free-standing constructions in a building, such as floating stairs, columns and architraves or counter-tops. The footbridge in Bad Homburg (Germany) is a very good example of the use of this type of high strength rock, where individual blocks of Nero Assoluto dolerite from Zimbabwe are used as load-transferring masts.

The low porosity, water uptake, thermal expansion and also the high abrasive resistance of the rock makes it an appropriate material for counter-tops and precision tables for technical/industrial purposes. These types of constructions usually require a high quality, pertaining to their physical, chemical and geometrical properties (e.g. length measures changes, susceptibility to chemical reactions, evenness of the surface, high strength, etc.).

Block sizes distribution and modeling

The dimensions of the preferred blocks are determined by the industrial processes that follows the extraction. The blocks are required to be rectangular cuboids (or right rectangular prisms) without irregularities (such as veins or joints) and with the specified dimensions required for extractable raw blocks. These dimensions determine whether the block is of minimum, optimal, maximal or special size. The minimum block is determined by the smallest piece that can be commercialized, which is a gravestone. The optimal block must have the adequate dimensions to be cut in a diamond gang saw. The available transport condition possibilities determine the maximal weight of a block and therefore the dimensions of the maximal block. The special blocks are determined by the demand. For example, precision tables for technical/industrial purposes may require the blocks to have the dimensions of 3 m long, 1 m wide and half a meter thick.

Uruguayan dolerites have a density of 3 t/m^3 and the maximum block weight cannot exceed 28 tons, because this is the maximum weight that can be transported in containers. The different block dimensions can be distinguished into: small ones (between 0.5 and 1 m^3), medium blocks (between 1 and 3.3 m^3), large blocks (between 3.3 and 6.6 m^3) and very large blocks (larger than 6.6 m^3). The maximum block must be smaller than 9 m^3.

The Black Stone Quarry is a good example for illustrating block production from a dolerite deposit in Uruguay. Between the years 2005 and 2009, this quarry produced a total of 2,536 m^3 as shown in the block size frequency diagram in Fig. 28. Most of the block sizes produced is of the small dimensions with 34% of the total production and the medium dimension making up 44%. Large blocks represent 17%, the maximum blocks and the very large blocks come to 2.8% of the total production. The proportion of Absolute Black in production is very low, being 1.8% for the production time span considered, 0.5% belongs to the small blocks, 0.8% to the medium and 0.5% to the large blocks.

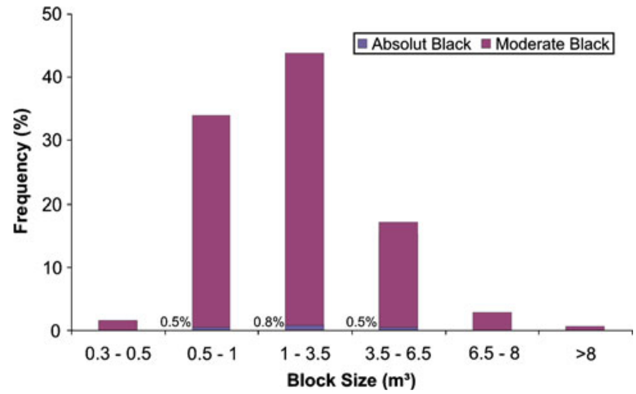


Fig. 28 Production between 2005 and 2009 for the Black Stone Quarry. Block size frequency distribution of the Group A quarry for both color varieties (*Source* Personal communication with Black Stone Quarry owner)

Sections of three quarries were modeled using the program 3D-Block Expert developed at the University of Göttingen (see Siegesmund et al. 2007a, b; Mosch 2008 and Mosch et al. 2010, for details). The raw block size distribution for the models obtained is shown in Fig. 29.

For the Black Stone Quarry a section having the dimensions (8 × 8 × 6 m) has been modeled (Fig. 30a, c, d) and the block size distribution analyzed in order to determine its potential yield. The resulting prism is cut into slabs of 1 m each (Fig. 30b) and then a possible block distribution can be proposed (Fig. 31). From inclined joints it is evident that the block sizes do not match any minimum raw block volume, which corresponds to a higher amount of waste (Fig. 31).

The deposits are characterized by their two-dimensional shape and their limited width, where the extraction can either develop along the length or with depth. The length of one single dike can be up to 3,500 m, such as the dike of the Polonia-Pichinango area, but normally they only attain a length of 1,000 m. The depths of the dikes in the study area are unknown, but in other parts of the world economical mining in such deposits can reach 50 m. Normally, the dikes do not exceed a width of 40 m. The economically more interesting ones are those wider than 15 m, because initial observations show that the thinner dikes have a finer grain size and a greater proportion of Absolute Black. The dip of the quarry walls can present a problem for mining safety, especially when a certain depth is reached. The joint sets determine the efficiency of the quarry, because they control the block size and the amount of waste rock that will be produced.

When planning a mine based on the geometry of the deposit, the efficiency of the mining operation increases, and thus the production yield. Using the program 3D-Block Expert, the volume of blocks extracted in a sector of a quarry taking can be predicted, when taking into account the joint distribution and geometry.

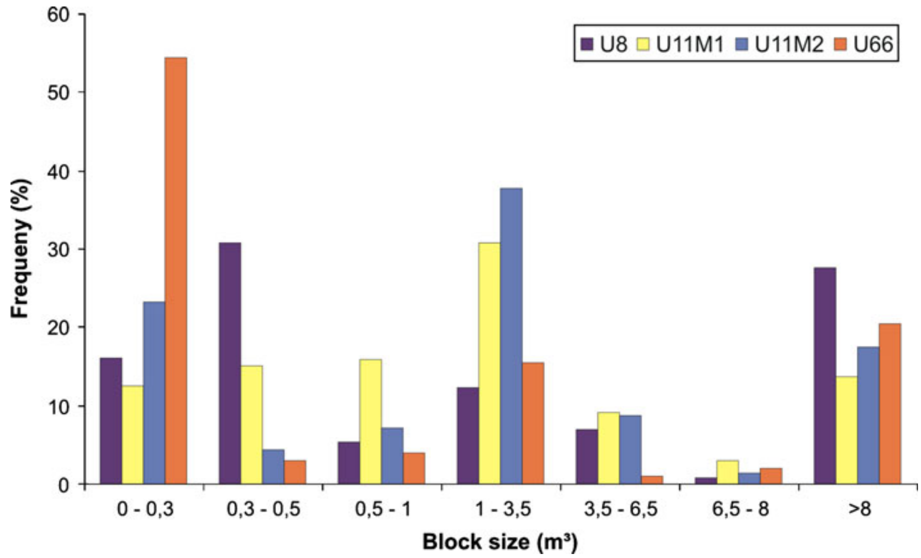


Fig. 29 The raw block size distribution modeled for the three quarries investigated using the 3D-Block Expert program

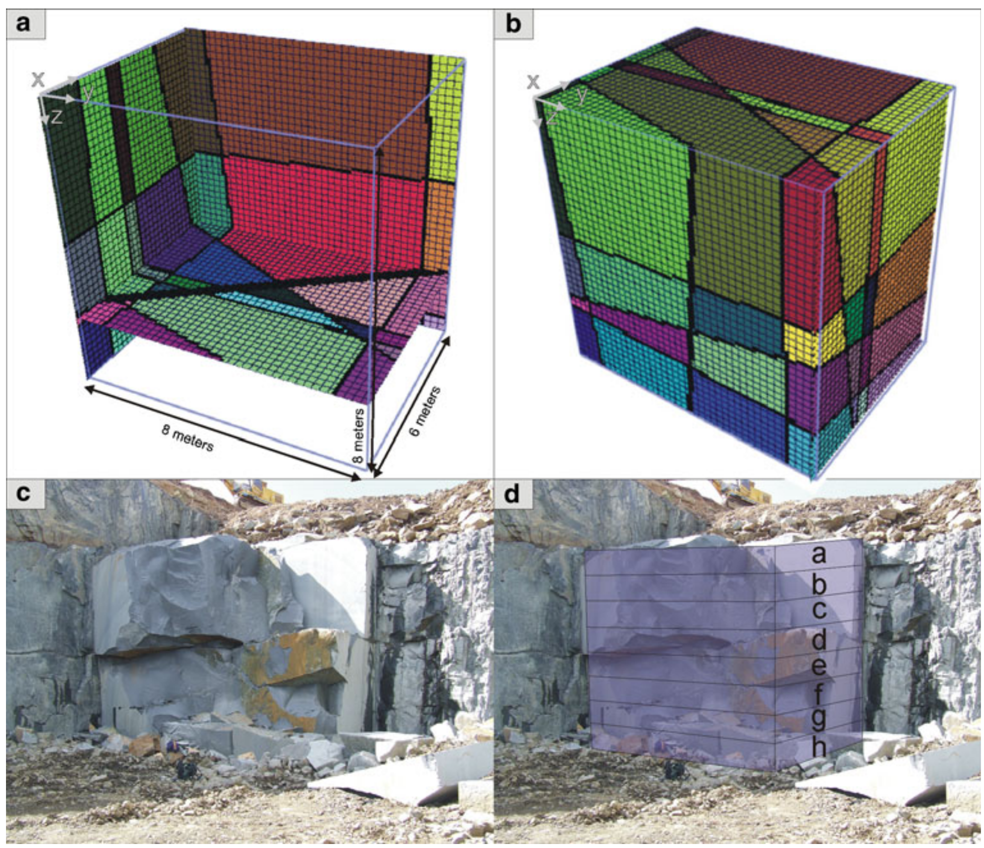


Fig. 30 **a** and **b** Section in the Black Stone Quarry modeled with 3D-Block Expert ($x = 6$, $y = 8$ and $z = 8$ m) and represented with Intel® Array Viewer. The different joint sets can be seen as well as the cross-cutting diagonal joints; **c** image of quarry section modeled; **d** image of quarry section modeled with slabs (one meter each) represented

Estimation of the dolerite resources

The total quantity of dolerite dikes in the Piedra Alta Terrane is difficult to estimate. The available information can be used to estimate a maximum and minimum amount of extractable dolerites.

According to Bossi and Campal (1991), the number of dikes is around 300 and their average length and width is 460 and 20 m, respectively. The minimum value is based on observations published by Spoturno et al. (2004) for the San José Department, where they found a total of 11 dikes in an area of 2,500 km^2. If a similar dike distribution is assumed for the rest of the area where the dikes crop out, a total of 88 dikes may exist. The current investigation indicates that there are about 19 dolerite quarries, where four of them have been superficially mined and five of them are still in operation.

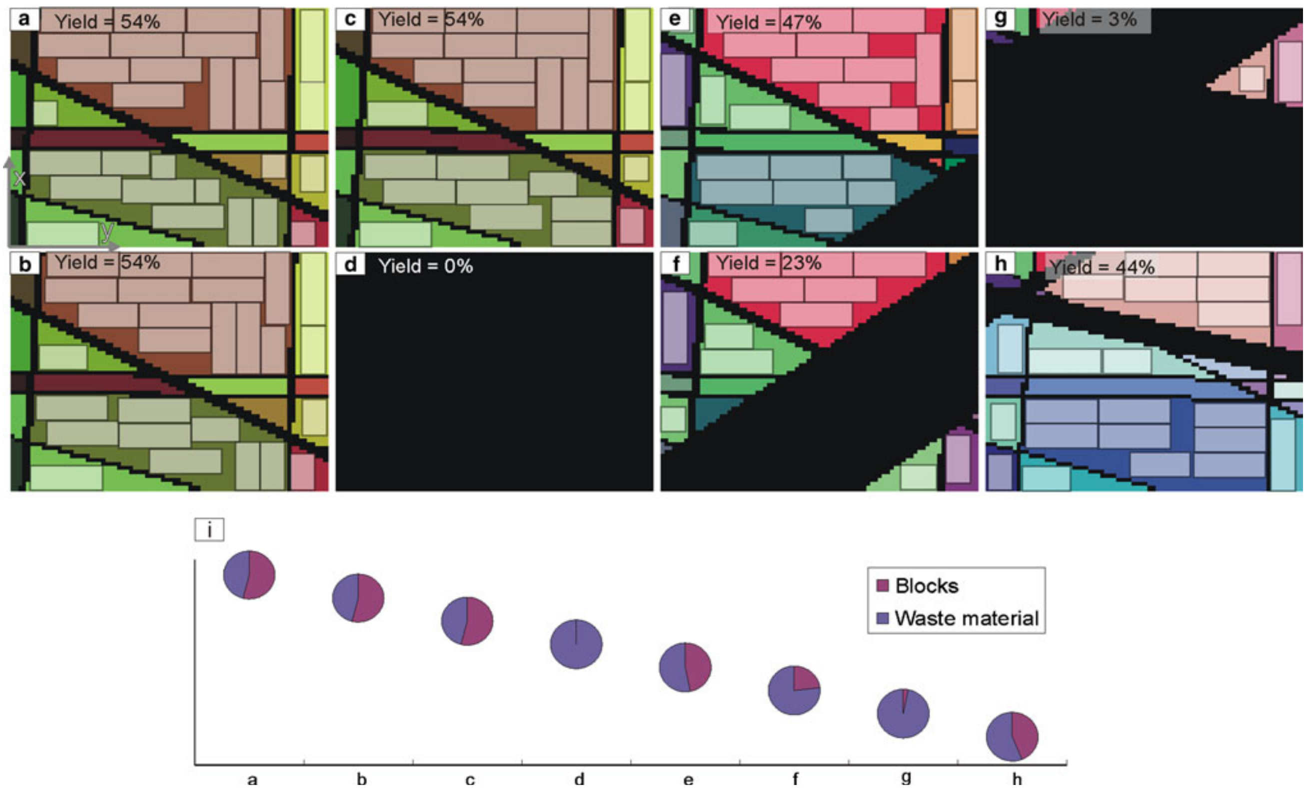


Fig. 31 Possible block size distribution for the Black Stone Quarry section using 3D Block Expert (each slab is one meter thick). **a** First slab from top to bottom of the block. **b** Second slab, etc. The black zones seen in (**d**, **f** and **g**) represent waste material. **i** Pie diagrams showing the yield of each model section

The geometry for this type of deposit is simplified to that of a cuboid or parallelepiped, where the width of the dike is "*a*", the length is "*b*" and the depth of the dike is "*c*". The volume can be calculated by $V = abc$. To calculate the reserves of dolerites in the Piedra Alta Terrane, an average dike is considered to have a width of 30 m, a length of 150 m and a maximum exploitation depth of 50 m. The total volume of this average deposit is 225,000 m^3. Considering that 19 productive dikes at different stages of mining have already been identified in Uruguay, the volume of the reserve base is 4,275,000 m^3. The efficiency of extraction for commercial blocks is not better than 10% (Oyhantçabal et al. 2007a, b) and that 20,310 m^3 were already extracted (Bossi and Campal 1991; Morales Pérez 2004; DINAMIGE 2010), a volume of probable reserves of at least 407,500 m^3 can be suggested. From this volume around 10% of the rock has the quality of Absolute Black.

Comparable dolerite quarries to those in Uruguay can be found in Sweden. At present there are seven quarries in Sweden where each of them produces an average of 8,000 m^3 of stone per year (Swedish Geological Survey 2009). In comparison to Sweden, the production in Uruguay is very low. In the last several years the production ranged from 4,000 to 5,000 m^3/year for the five active quarries in the country. This comparison indicates the production in Uruguay can be increased several times, provided that an adequate exploration strategy is followed.

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Appendix

Petrophysical techniques

Color measurements

Color measurements were performed using a Konica Minolta Chroma Meter CR 300 with a xenon flash-lamp with a measuring spot of 8 mm in diameter. The results are expressed in $L^*a^*b^*$ as required by the International Commission on Illumination (CIE: Commission Internationale de l′Eclairage), where L^* is the brightness (0 is black and 100 is white), a^* is the green/red axis (−60 is green and +60 is red) and b^* is the blue/yellow axis (−60 is blue and +60 is yellow).

Density and porosity, mercury injection porosimetry and water uptake

The standard parameters apparent density (ρ_{ap}), real density (ρ_r) and effective porosity (Φ) were determined as described in Hoffmann (2006) using the Archimedes Principle and relating the masses of a sample in dry (m_d), wet (m_w) and under water (buoyancy) (m_b) conditions in accordance with the following equations:

$$\rho_{ap} = m_d / m_w - m_b \quad (1)$$

$$\rho_r = m_d / m_d - m_b \quad (2)$$

$$\Phi = m_w - m_d / m_w - m_b \quad (3)$$

The pore size distribution was measured by applying the Mercury Intrusion Porosimetry using a "Porosimeter 2000" from the Company Carlo Elba. The samples, cylinders of 10 mm diameter and 40 mm length, are placed in a cell where a vacuum is generated and afterwards filled with mercury. The mercury is then forced into the pores of the sample, by applying pressure in a progressive way. Since the pressure at which the mercury enters the pores is inversely proportional to the pore size, this is easily calculated.

Water uptake was measured following the DIN EN 13755 in 65 mm length cubes under atmospheric pressure and under vacuum pressure. Simplifying the first procedure consists in drying the sample and registering its mass and then placing it under water and waiting 48 h until the sample is completely wet, measuring the mass. The second procedure consists in evacuating the dry sample for 24 h, registering its mass and then placing it in under water for 48 h and afterwards registering the mass again.

Expansion properties: thermal expansion

Thermal expansion was determined in cylindrical samples of 15 mm diameter and 50 mm length in three spatial directions (X, Y, Z) in a special device called dilatometer, as described in Strohmeyer (2003). The samples to be measured were placed in the dilatometer which has six linear displacement transducers with an accuracy of 1 µm and two resistance thermometers (one of which is inside a dummy) with an accuracy of 1°K. The samples were subjected to temperature cycles beginning at 20° up to 90°C with a rate of increase of 1°C/min, which ensures the thermal equilibration of the sample (Weiss et al. 2004). The thermal dilatation coefficient α is a measure of how much the length of a sample varies with a change in temperature. The following formula allows its calculation:

$$\alpha = \Delta l / (l\,\Delta T) \quad (4)$$

where Δl is the length change, l the length of the sample at the beginning of the measurement and ΔT the temperature change in units of $10^{-6}\ K^{-1}$. Residual strain ε is the ratio between the change in the length of a sample Δl and its original length for a defined temperature interval in units of mm/m.

Mechanical properties

The mechanical tests were performed using a Universal Testing Machine Class 1 from the company Walter & Bai. For each test, samples were prepared in order to recognize anisotropies, therefore they were drilled in three orthogonal directions (see Strohmeyer 2003, Figs. 2-3 and 2-4).

The uniaxial compressive strength (UCS) test was performed following the DIN EN 1926 in at least 6 samples, having a diameter and length 50 mm. The method consists in applying perpendicular to the faces (which are plan-parallel polished until ±0.1 mm accuracy) a maximum force up to 1,000 kN with a load increase of 1,000 Ns^{-1}. The UCS (σ_{ucs}) is calculated by using this equation:

$$\sigma_{ucs} = F/A \quad (5)$$

where F is the maximum force at which the sample breaks and A is the area in which this force is applied.

Young's modulus (E) is determined in the UCS test and is a measurement of how much a material resists being deformed when a uniaxial force is applied to it. Therefore, it relates the strength (σ) applied and the strain (ε) of this material, following this equation:

$$E = d\sigma_{ucs}/d\varepsilon \quad (6)$$

For the measurement of the tensile strength the norm DIN 22024 was followed. A maximum force of 50 kN is applied with a load increase of 30 Ns^{-1} onto cylinders of 40 mm diameter and 20 mm length, but in order to develop a tensile strength this force is applied perpendicular to their faces. The tensile strength (σ_T) is calculated by the following equation:

$$\sigma_T = 2F/dl\pi \quad (7)$$

where F is the maximum force at which the sample is crushed, d is the diameter and l the height of the sample.

Breaking load at the dowel hole was determined following the DIN EN 13364. Instead of using samples with a 200 mm edge length and 30 mm thickness, smaller samples were used (150 mm edge lengths and a thickness of 30 mm), which do not have significant difference in the resistance value according to Koch (2005). This method consists in applying a force (up to 50 kN) at a load increase of 50 Ns^{-1} perpendicular to a dowel fixed in the side of the sample and registering the maximum force at which it breaks down.

The flexural strength under concentrated load is determined by the norm DIN EN 12372 in samples with 150 mm length, 50 mm width and 25 mm height. The procedure consists in placing the sample over two supporters with 125 mm distance between them. In the middle of the sample a maximum linear force of 50 kN is applied with a load increase of 50 Ns^{-1} until the rock failure. The equation used to calculate the flexural strength is the following:

$$\sigma_F = 3Fd/2wh^2 \quad (8)$$

where F is the maximum force at which the samples breaks down, d is the distance between the supporters, w is the sample width and h is its height.

Abrasive resistance was performed by the Böhme Method as described in the DIN 52108. A square sample with side lengths of 71 mm (with a surface area of 50 cm^2) and a height of 25 mm is placed in a grinding path with some pressure above it and an abrasive powder underneath it. The grinding path rotates at a speed of 30 rmp and after 22 revolutions it stops. The sample is then rotated in 90° and another 22 revolutions are started. After the sample has been rotated four times its weight is measured. This procedure is repeated another four times. The value of the abrasive resistance is expressed in the volume lost per 50 cm^2 of sample ($\Delta V_{50\,cm^2}$) and is calculated by the following equation:

$$\Delta V_{50\,cm^2} = (\Delta m \cdot 50)/(\rho_r a_r) \quad (9)$$

where Δm is the loss in mass, ρ_r is the apparent density and a_r is the real area of the sample surface.

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