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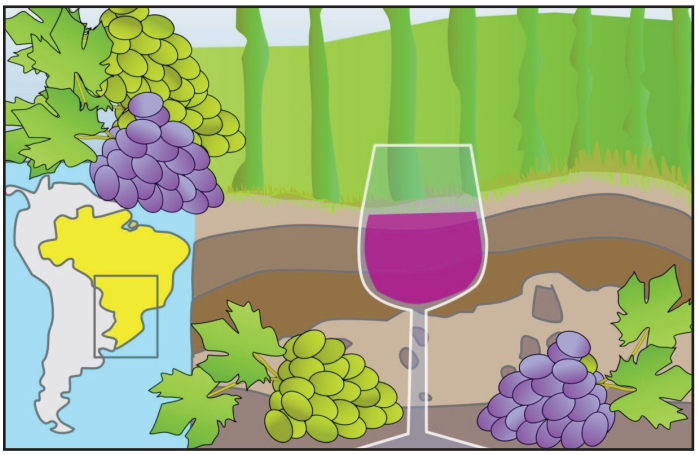

Geology and Wine 15. Producing Wine at Altitude: The *Terroir* of São Joaquim, Brazil

Erico Albuquerque dos Santos[1], Luana Moreira Florisbal[2], Arcângelo Loss[3], Marcell Leonard Besser[4], Denilson Dortzbach[5]

[1]Instituto de Geociências
Universidade Federal do Rio Grande do Sul
Avenida Bento Gonçalves, 9500, Agronomia
91501-970 – Porto Alegre, Rio Grande do Sul, Brazil
E-mail: ericogeologia@gmail.com

[2]Departamento de Geociências
Universidade Federal de Santa Catarina
Campus Universitário Trindade
88040-970 – Florianópolis, Santa Catarina, Brazil

[3]Departamento de Engenharia Rural
Universidade Federal de Santa Catarina
Rodovia Admar Gonzaga, 1346, Itacorubi
88034-000 – Florianópolis, Santa Catarina, Brazil

[4]Serviço Geológico do Brasil (CPRM)
Avenida Antônio Sales, 1418, Joaquim Távora
60135-101 – Fortaleza, Ceará, Brazil

[5]Empresa de Pesquisa Agropecuária e Extensão Rural de Santa Catarina, Avenida Admar Gonzaga, 1347, Itacorubi
88034-901 – Florianópolis, Santa Catarina, Brazil

SUMMARY

The municipality of São Joaquim, located in the Planalto Catarinense viticultural region, is the coldest wine-growing region of Brazil, and contains the highest-altitude vineyards in the country. These vineyards were established within the last 20 years, so this is a young and still-developing viticultural region. Information on the *terroir* of São Joaquim is needed in order to identify potential vineyard sites and to help improve the viticulture in the region. This work aims to characterize the terroir of São Joaquim, where wines are produced from grapes cultivated above 900 m of altitude, through a description and analysis of meteorological, physiographic, pedological, geological and viticultural factors. With respect to these factors, the São Joaquim region presents the following characteristics:

1 It has an annual mean temperature of 13ºC, annual mean precipitation of 1680 mm/year and an annual mean solar radiation of 1832 hours/year.
2 It has altitudes between 715–1638 m and generally steep slopes, 43% of the slopes have declivities between 20–45% and show no preferred orientation.
3 It has both deep (> 150 cm) and shallow (< 100 cm) soils with clayey texture, an average pH (water) between 4.68–5.52 and an average soil organic matter (SOM) content of 6%.
4 It is underlain by two units of volcanic rocks. These are a mafic unit (50.53–55.09 wt.% SiO_2) and a felsic unit (66.58–70.12 wt.% SiO_2). The mafic unit tends to consist of thicker flows than the felsic unit and is characterized by generally steeper slopes.
5 There is a correlation between the geological unit and the soil types, in which thicker inceptsols are preferentially developed on the mafic volcanic rocks and thinner entisols are preferentially developed on the felsic volcanic rocks.
6 Currently, the region produces more than 27 grape varieties planted mostly on the Paulsen 1103 rootstock. The existing vineyards are mostly underlain by the mafic volcanic unit in areas of steep north-facing slopes.

This preliminary study suggests that there are correlations between the bedrock, the soils that they give rise to and the declivities of the slopes. Knowledge of these relationships should assist in the evaluation and planning of future grape and wine production.

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RÉSUMÉ

La commune de São Joaquim, située dans la région viticole de Planalto Catarinense, est la région viticole la plus froide du Brésil et abrite les vignobles les plus élevés du pays. Ces vignobles ont été établis au cours des 20 dernières années; c'est donc une région viticole jeune et en développement. Des informations sur le terroir de São Joaquim sont requises pour identifier les sites viticoles potentiels et contribuer à l'amélioration de la viticulture dans la région. Ce travail vise à caractériser le terroir de São Joaquim, où les vins sont produits à partir de raisins cultivés à plus de 900 m d'altitude, au moyen d'une description et d'une analyse des facteurs météorologiques, physiographiques, pédologiques, géologiques et viticoles. En ce qui concerne ces facteurs, la région de São Joaquim présente les caractéristiques suivantes:

1 Sa température moyenne annuelle est de 13ºC, ses précipitations moyennes annuelles de1680 mm/an et son rayonnement solaire moyen annuel de 1832 heures/an.
2 Son altitude est comprise entre 715 et 1638 m et ses pentes généralement abruptes. 43% des pentes ont des déclivités comprises entre 20 et 45% et ne présentent aucune orientation préférentielle.
3 Ses sols sont profonds (> 150 cm) et peu profonds (<100 cm) de texture argileuse, avec un pH moyen (eau) compris entre 4,68 et 5,52 et une teneur moyenne en matière organique du sol (MOS) de 6%.
4 Elle repose sur deux unités de roches volcaniques. Il s'agit d'une unité mafique (50,53 à 55,09 % en poids de SiO_2) et d'une unité felsique (66,58 à 70,12 % en poids de SiO_2). L'unité mafique est généralement constituée de coulées plus épaisses que l'unité felsique et se caractérise par des pentes généralement plus raides.
5 Il existe une corrélation entre unité géologique et types de sol, dans lesquels des inceptsols plus épais sont préférentiellement développés sur les roches volcaniques mafiques et des entisols plus minces sont préférentiellement développés sur les roches volcaniques felsiques.
6 La région produit actuellement plus de 27 cépages principalement plantés sur le porte-greffe Paulsen 1103. Les vignobles existants reposent principalement sur l'unité volcanique mafique dans des zones de pentes abruptes exposées au nord.

Cette étude préliminaire suggère qu'il existe des corrélations entre la lithologie, les sols qu'elles engendrent et les déclivités des pentes. La connaissance de ces relations devrait faciliter l'évaluation et la planification de la production future de raisins et de vin.

INTRODUCTION

Altitude has a significant influence in viticulture. Every 100 m increase in altitude produces a decrease of 0.6ºC in the mean temperature, which can make regions that are close to one another, but at distinct altitudes, very different in terms of their viticultural suitability. The highest vineyard in the world is located in Argentina (Salta, 3100 m), followed by vineyards in Chile (Elqui, 2500 m), China (Yunnan, 2300–2600 m), the USA (Colorado, 1950 m), Lebanon (1700 m), Spain (Tenerife, 1650 m), Mexico (1500–1700 m) and Brazil (Santa Catarina, 1427 m) (Easton 2016). In Brazil, these high-altitude vineyards are located in the Planalto Catarinense viticultural region, in the State of Santa Catarina (Fig. 1), characterized by high relative altitude, strong relief and soils of volcanic origin. In this region, according to Rosier (2003), the altitude generates climatic conditions that displace the entire productive cycle of the vine. In most viticultural regions of Brazil, grapes sprout in early September and harvested in February, but due to the unique climatic condition of the Planalto Catarinese, bud break occurs in mid-October and maturation occurs in mid-April, when precipitation is less common and the temperatures are milder, causing the vines to prioritize fruit development rather than vegetative growth (Rosier 2003).

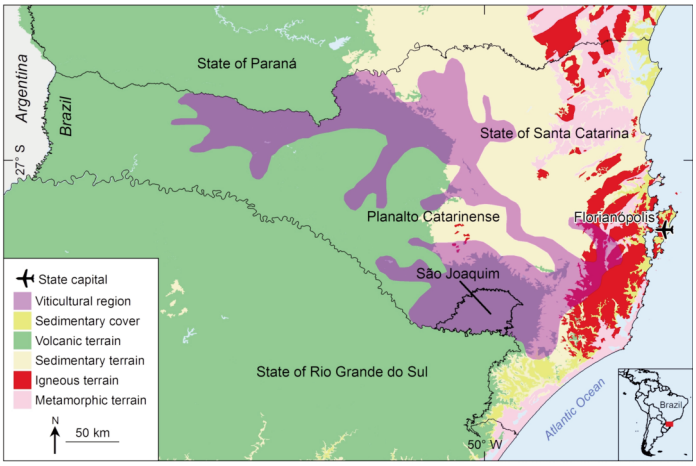

Figure 1. Location map of the Planalto Catarinense viticultural region and the municipality of São Joaquim, State of Santa Catarina, Brazil. Geological data from CPRM (2015).

São Joaquim is the municipality with the largest number of properties dedicated to viticulture in the State of Santa Catarina and the number of vineyards has significantly increased in the last few years (from 181 vineyards in 2009 to 268 in 2013, according to Vianna et al. 2016). As shown by the data collected from the "2013 vineyards of altitude geo-referencing of Santa Catarina" completed by Empresa de Pesquisa Agropecuária e Extensão Rural de Santa Catarina (EPAGRI), the municipality of São Joaquim contains 21 properties comprising 268 vineyards that occupy a total area of 168.13 ha (Vianna et al. 2016).

São Joaquim includes the 8th highest vineyard in the world (Vinícola Hiragami, 1427 m) (Fig. 2) and is the best example of high-altitude viticulture in Brazil. The most common cultivated varieties are Cabernet Sauvignon, Merlot, Sauvignon Blanc, Pinot Noir, Chardonnay, Sangiovese, Touriga Nacional, Montepulciano and Cabernet Franc. The aim of this work is to evaluate this peculiar Brazilian terroir, where wines are produced from grapes cultivated at altitudes higher than 900 m, based on the principles outlined by Haynes (1999), through a description and analysis of meteorological, physiographic, pedological, geological and viticultural factors.

Figure 2. The 8th highest vineyard in the world (Vinícola Hiragami, at 1427 m): (A) during the harvest and (B) during the winter. Photograph provided by Celito Soldá.

REGIONAL GEOLOGY

The Paraná-Etendeka Magmatic Province (Fig. 3) was formed by a large volcanic event in the Early Cretaceous that lasted approximately 3 Ma (~134.5–131.5 Ma; Janasi et al. 2011), and which preceded the rifting of Gondwana and the opening of the Atlantic Ocean. Lava flows and shallow intrusive bodies form a sequence of magmatic rocks composed of continental tholeiitic basalt (90%), tholeiitic andesite (7%) and subordinate dacite, rhyodacite and rhyolite (Bellieni et al. 1986). These rocks are now found in the southern and central-western regions of Brazil (termed the Serra Geral Group), in south-eastern Paraguay, in northern Argentina, in eastern Uruguay and also in Namibia, which was adjacent to South America at ca. 134 Ma.

The rocks of the Serra Geral Group (Rossetti et al. 2018) have an estimated volume of at least 600,000 km^3 of which about 75% is represented by extrusive rocks and the remainder by related shallow intrusive rocks, in the form of sills and dikes. Collectively, rocks of the Serra Geral Group cover an area of approximately 917,000 km^2 (Frank et al. 2009).

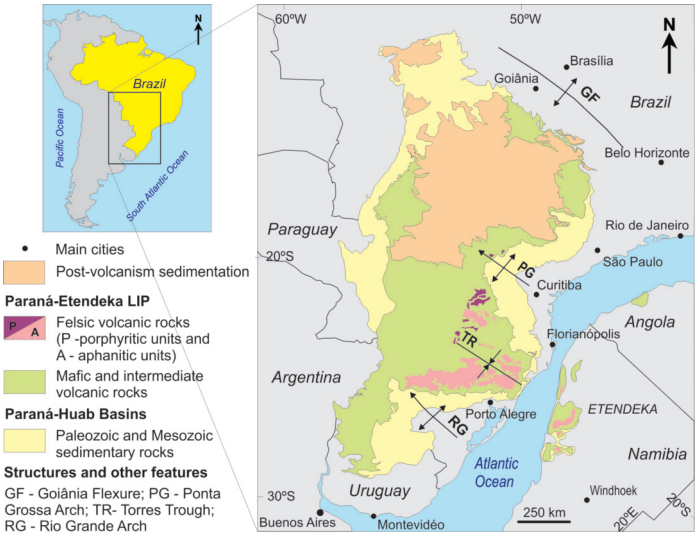

Figure 3. Geological map of the Early Cretaceous Parana-Etendeka Magmatic Province in South America and Africa. Modified from Licht (2018).

METHODOLOGY

Our integrated study of the terroir of São Joaquim used meteorological, physiographic, pedological, geological and viticultural data and a geographic information system (GIS) to analyze and describe these factors. The meteorological data were obtained from the São Joaquim meteorological station (at latitude 28°18'00"S, longitude 49°55'48"W, elevation 1415 m), sourced from the Brazilian Instituto Nacional de Meteorologia (INMET 2016). The mean monthly and annual values for maximum temperature (ºC), mean temperature (ºC), minimum temperature (ºC), precipitation (mm) and solar radiation (hours) were calculated from these data. The meteorological maps were obtained from the Climatological Atlas of the State of Santa Catarina (Pandolfo et al. 2002).

The physiographic data were obtained from the Geomorphological Map presented in the Atlas of Santa Catarina (Santa Catarina 1986) and from the digital elevation model (DEM) of the municipality of São Joaquim, sourced from the Aerophotogrammetric Survey of the State of Santa Catarina (SDS 2010). The DEM was imported into ArcGIS® software (Release 10), for analysis. The altitudes were classified in intervals of 100 m. The steepness (declivity) of the slopes was calculated in percentage (%) using the *Slope tool* and their orientation was calculated using the *Aspect tool*.

Samples of soil were collected, along with the bedrock underlying the soil, to obtain pedological and geological data from the same sites. The pedological data were obtained from Potter et al. (2004) who published the map of the Soils of the State of Santa Catarina. The granulometric composition of the soil (sand, silt and clay proportions), pH (water) and soil organic matter content (SOM = 1.724*total organic carbon) were obtained using the methods in EMBRAPA (1997) and

Tedesco et al. (1995). The geological data were obtained from the Geological Map of the State of Santa Catarina (DPNM 1986), and from Besser (2017), who presents a detailed geological map from São Joaquim region. The geochemical analyses (13 samples of mafic volcanic rocks and 29 samples of felsic volcanic rocks), were performed by X-ray fluorescence in two laboratories (UNESP-Rio Claro and LAMIR-UFPR). Major elements (SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O and P_2O_5), were analyzed from glass pellets and are expressed in weight %. Trace elements (Cr, Ni, Ba, Rb, Sr, Zr, Y, Nb, Cu, Zn, Co and V), were analyzed from pressed pellets and are expressed in ppm.

The viticultural data were obtained from the "2013 vineyards of altitude geo-referencing of Santa Catarina" (EPAGRI 2013). In addition to these numerical data, bibliographic research of the other factors that might contribute to the terroir of São Joaquim was completed.

RESULTS

Meteorology

São Joaquim is the coldest Brazilian viticultural region, with an annual mean temperature of 13ºC (Table 1). The highest temperatures are in the summer (December–February), when the maximum mean temperature is between 22–23ºC and the lowest temperatures are in the winter (June–August), where the minimum mean temperature is between 6–7ºC. In the spring (September–November) mean temperatures range from 12–15ºC and in the autumn (March–May) from 11–16ºC. As shown in figures 4A, B and C, the observed temperatures all tend to be lower towards the northeast part of the municipality, where the altitudes are higher.

Precipitation is evenly distributed throughout the year, with a mean annual amount of 1680 mm/year (maximum of 175 mm in September and minimum of 92 mm in April) (Table 1). There is a variation in the amount of precipitation during the seasons of the year, with the highest rainfall in the summer (474 mm) and the lowest rainfall in the autumn (331 mm). As shown in Figure 5A, rainfall tends to be greatest towards the southeast part of the municipality.

The region receives abundant solar radiation, with a mean annual amount of 1832 hours/year (maximum of 173 hours in November and minimum of 128 hours in June). There is a small variation in the amount of solar radiation received during the seasons of the year: the highest values are in the summer (476 hours) and the lowest in the winter (417 hours). As shown in Figure 5B, the annual solar radiation received tends to be greater towards the western part of the municipality.

According to the Köppen (1936) criteria, Alvares et al. (2013) classified the climatic type of São Joaquim as type Cfb - Humid subtropical (C), Oceanic climate, without dry season (f) with temperate summer (b).

Physiography

The municipality is divided into two geomorphological units (Fig. 6A). The Iguaçu River/Uruguay River Dissected Plateau is characterized by deep valleys embedded in plateaus. The Campos Gerais Plateau is characterized by isolated high-relief

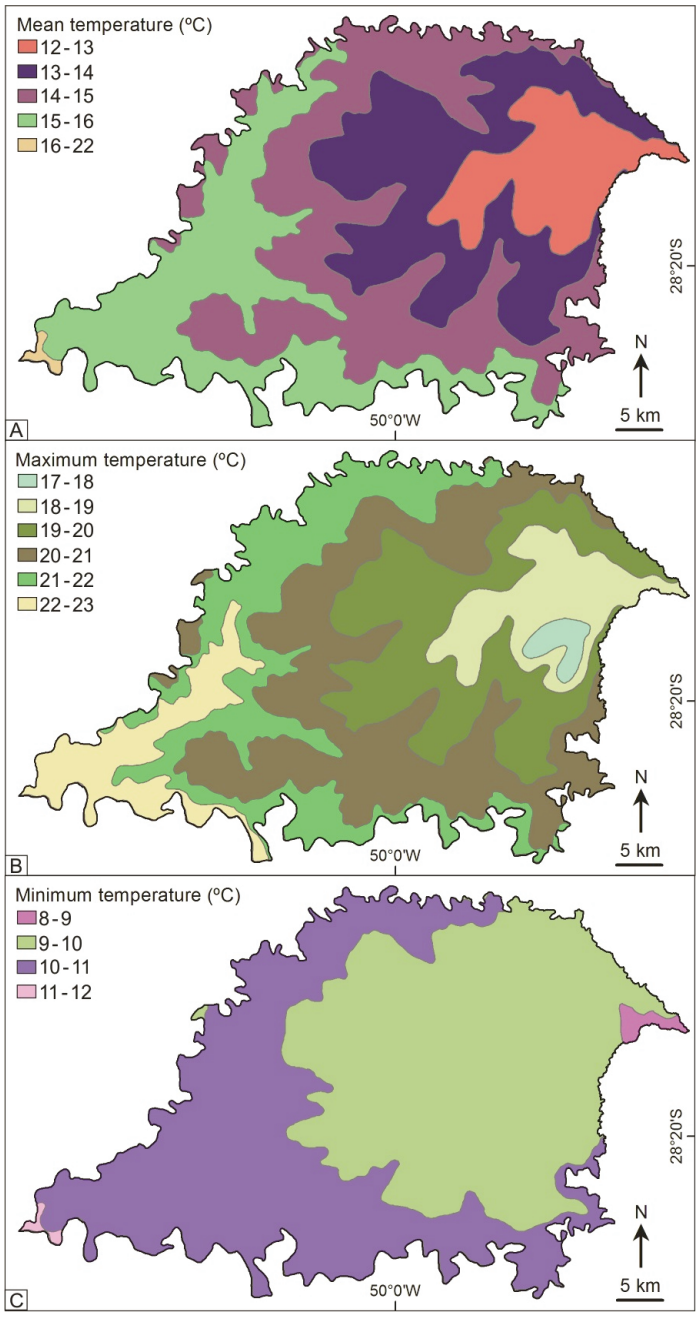

Figure 4. Meteorological maps of the municipality of São Joaquim: (A) annual mean temperature, (B) annual maximum temperature and (C) annual minimum temperature. Modified from Pandolfo et al. (2002).

blocks situated topographically above the surrounding areas (Santa Catarina 1991) that, in the municipality of São Joaquim, coincides with the area of the felsic volcanic unit, called the São Joaquim Plateau (Besser et al. 2015).

São Joaquim is the highest Brazilian viticultural region, with altitudes ranging from 715 m in the southwest portion to 1638 m in the northeast portion of the municipality (Fig. 6B, Table 2). Slopes within the municipality tend to be steep, with most slopes (43% of the total) having declivities between 20–45% (Fig. 6C, Table 3) and showing no preferred orientation (Fig. 6D, Table 4).

Table 1. Historical meteorological data for temperature (ºC), precipitation (mm) and solar radiation (h) in the municipality of Sao Joaquim (1961–2015).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual mean	Annual amount
Mean maximum temperature (°C)	23	23	22	19	16	15	15	17	17	19	21	22	19	-
Mean temperature (°C)	17	17	16	14	11	10	10	11	12	13	15	16	13	-
Mean minimum temperature (°C)	13	13	12	10	8	6	6	7	8	9	10	12	10	-
Precipitation (mm)	168	170	136	92	104	119	140	145	175	164	132	136	140	1680
Solar radiation (h)	164	143	164	157	151	128	146	144	141	154	173	169	153	1832

*Data from INMET (2016).

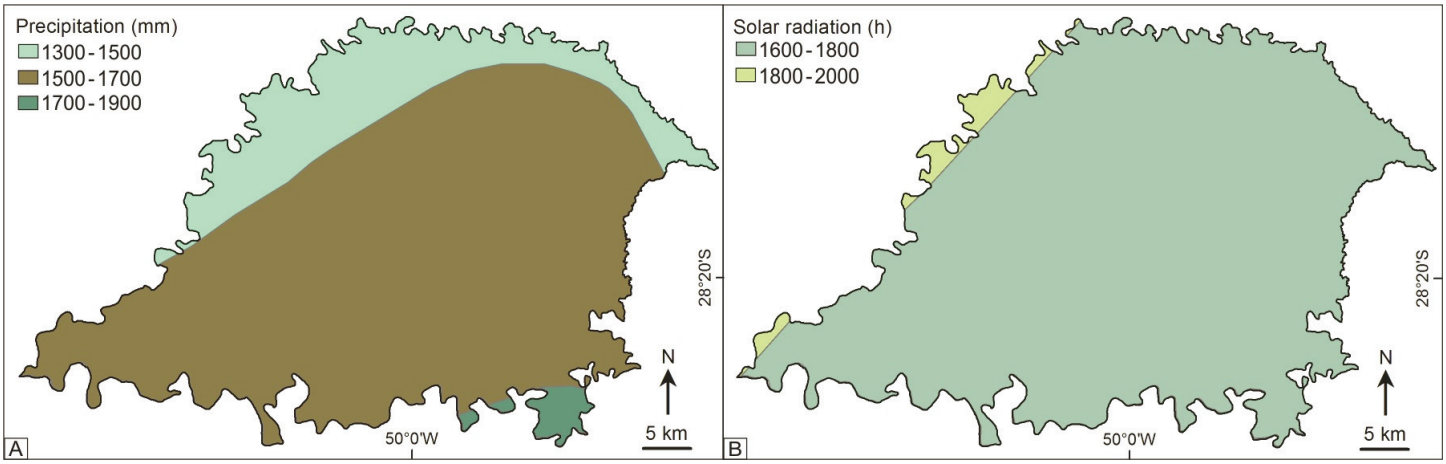

Figure 5. Meteorological maps of the municipality of São Joaquim: (A) annual mean amount of precipitation (mm) and (B) annual mean amount of solar radiation (h). Modified from Pandolfo et al. (2002).

Pedology

There are two types of soils, according to Potter et al. (2004) that predominate in the municipality of São Joaquim (Fig. 7A): *Cambissolos*, which are inceptsols, humic and haplic, that are 60 to 150 cm thick, and have a clayey to very clayey texture, and *Neossolos Litólicos,* which are entisols that are < 60 cm thick and have a clayey texture (Fig. 7A). Inceptisols are defined as soils of relatively new origin and are characterized by having only the weakest appearance of horizons, or layers, produced by soil-forming factors (e.g. Weil and Brady 2017, p. 99–100), and entisols are defined as soils defined by the absence or near absence of horizons (layers) that clearly reflect soil-forming processes (e.g. Weil and Brady 2017, p. 96–99). Representative soil profiles of the inceptsols and entisols from the region are listed in Table 5 and illustrated in Figures 8 and 9.

Geology

The geology of the municipality of São Joaquim is largely defined by the volcanic rocks of the Serra Geral Group, in which the mafic lava flows are overlain by the felsic flows (Fig. 7B). The mafic volcanic unit (50.53–55.09 wt.% SiO_2) occupies most parts of the region and is classified as Vale do Sol Formation at the base and Esmeralda Formation at the top. The lower flows are formed by low-Ti (~1.75 wt.%) and low Sr/Y (< 6.5) basaltic andesites that form thick rubbly pahoehoe flows. The upper flows are formed by low-Ti (~1.34–1.55 wt%) and high Sr/Y (> 7.5) pahoehoe flows that are typically thinner than the lower sequence (Besser et al. 2018). In addition, there are lava flows and some shallow sills of basaltic composition that have high Ti contents (> 3.5 wt.%), referred to as the Urubici magma type, according to Peate et al. (1992).

The felsic volcanic unit (66.58–70.12 wt.% SiO_2) is composed of at least eight tabular and lobate lava flows with total thickness of 150 m, occupying an approximate area of 270 km^2, with an estimated volume of 27 km^3. They are classified as low-Ti (0.86–1.08 wt.%) dacites with subordinate rhyolites, and are assigned to the Palmas Formation (Besser et al. 2018). Table 6 (major elements) and Table 7 (trace elements) give the average composition of the volcanic units in the municipality of São Joaquim, based on the samples collected in this study.

Viticulture

In the early 1990s, researchers from EPAGRI tested the adaptation of *Vitis vinifera* cultivars in several regions of the State of Santa Catarina, but the results were discouraging. However, the 1998 harvest from the Planalto Catarinense vineyards, such

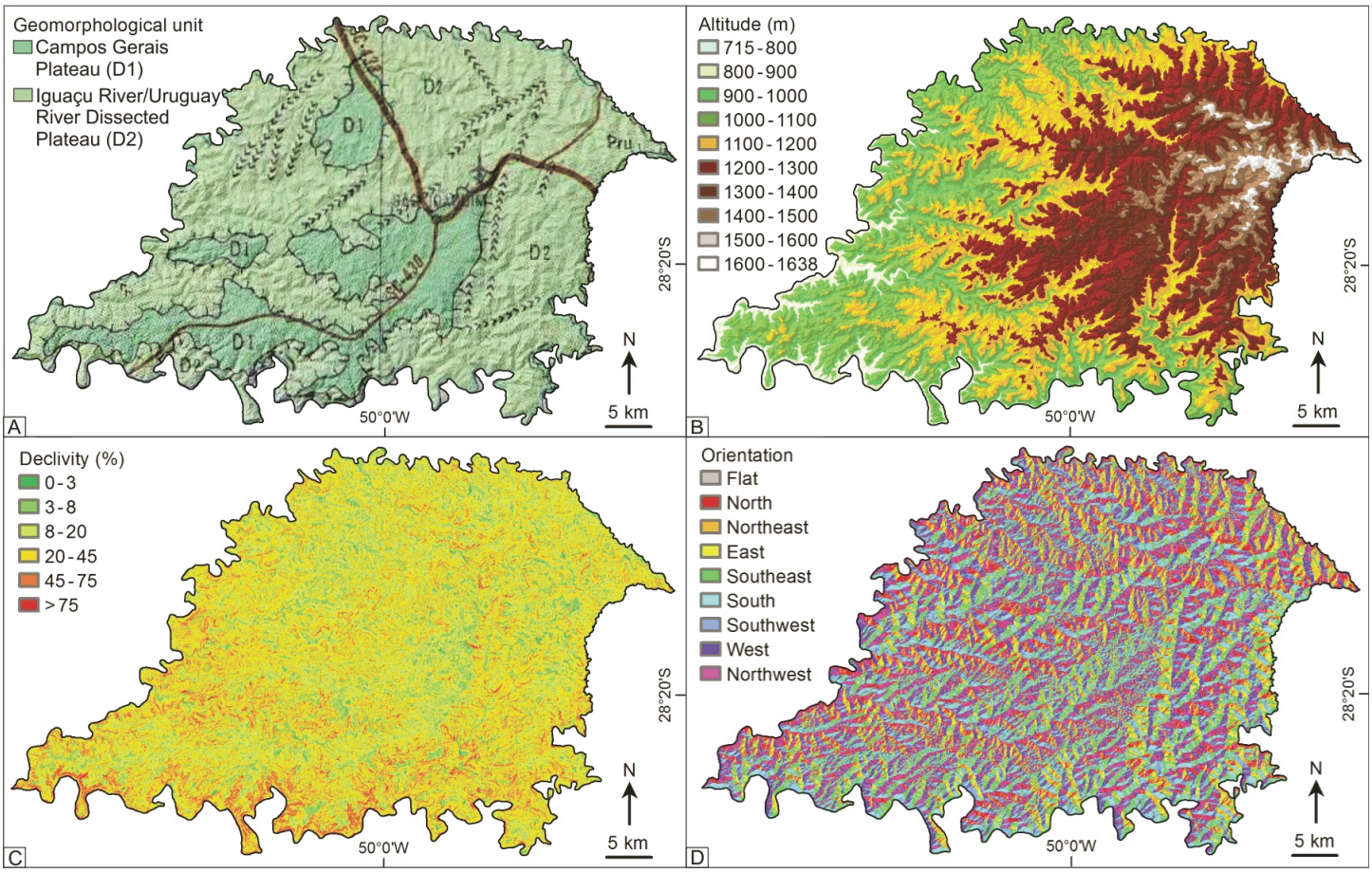

Figure 6. Physiographic maps of the municipality of São Joaquim: (A) geomorphological units, (B) altitude (m) in intervals of 100 m, (C) declivity (%) and (D) general orientation of the slopes. Modified from Santa Catarina (1986) and SDS (2010).

Table 2. Altitude data for the municipality of São Joaquim, classified in intervals of 100 m, with the area occupied by each interval expressed in km² and %.

Altitude (m)	Area (km²)	Area (%)
715 - 800	13	1
800 - 900	72	4
900 - 1000	192	10
1000 -1100	377	20
1100 - 1200	470	25
1200 - 1300	375	20
1300 - 1400	248	13
1400 - 1500	116	6
1500 - 1600	24	1
1600 - 1638	1.06	~0
Total	1887	100

*Data from SDS (2010).

Table 3. Declivity data for slopes in the municipality of São Joaquim, classified in classes of percentage, with the area occupied by each class expressed in km² and %.

Declivity	Area (km²)	Area (%)
0 - 3%	72	4
3 - 8%	214	11
8 - 20%	524	28
20 - 45%	813	43
45 - 75%	246	13
> 75%	18	1
Total	1887	100

*Data from SDS (2010).

as those of São Joaquim, produced sweet and balanced grapes (AL Notícias 2007). In 2000, EPAGRI started the "Technological Development for Vitiviniculture in the Planalto Serrano Project", to evaluate the adaptation of *Vitis vinifera* cultivars in the Serra Catarinense (BRDE 2005). A few years later, in November 2005, the "Catarinense Association of Producers of Fine Wines of Altitude" (Associação Catarinense dos Produtores de Vinhos Finos de Altitude - ACAVITIS) was founded. The organization is now known as "Wine of Altitude - Associated Producers of Santa Catarina" (Vinho de Altitude - Produtores Associados de Santa Catarina). This initiative consolidated the "Santa Catarina Fine Wine Program" in the State of Santa Catarina, and new projects were carried out in the municipality of São Joaquim, such as the Quinta da Neve and

Table 4. Orientation data for slopes in the municipality of São Joaquim, classified in classes of exposure direction (N, NE, E, SE, S, SW, W, NW and Flat), with the area occupied by each class expressed in km² and %.

Orientation	Area (km²)	Area (%)
North	257	14
Northeast	215	11
East	200	11
Southeast	224	12
South	244	13
Southwest	229	12
West	247	13
Northwest	271	14
Flat	0.16	~0
Total	1887	100

*Data from SDS (2010).

the Villa Francioni (Protas and Camargo 2011). Currently, these are two major wineries of the region.

The main grape varieties grown in São Joaquim are Cabernet Sauvignon, Merlot, Sauvignon Blanc, Pinot Noir, Chardonnay, Sangiovese, Touriga Nacional, Montepulciano and Cabernet Franc, totalling over 422,000 vines (individual plants). These represent 91% of all vines and 90% of the total vineyard area in the region (Table 8 and Fig. 10). Other varieties cultivated in São Joaquim are Alicante Bouschet, Longanese, Molinara, Raboso, Rondinella, Incrocio Manzoni, Moscato Giallo, Nebbiolo, Pignolo, Aglianico, Malvasia, Rebo, Ribolla Gialla, Grechetto, Marselan, Refosco dal Peduncolo Rosso, Gewürztraminer, Petit Verdot, Tempranillo, Malbec, Moscatel, Nero d'Avola, Pinot Nero, Teroldego, Syrah, Moscato Bianco and Vermentino (EPAGRI 2013).

The most used rootstock in the south of Brazil since the 1990s (Camargo et al. 2011), and also in São Joaquim, is the Paulsen 1103, due to its lower productivity (Brighenti et al. 2011) and resistance to fungariosis. The vines are planted mostly in the vertical shoot positioning (VSP) system with spacing between the plants of 1.27 m (minimum of 0.7 m, maximum of 2.5 m), and spacing between the rows of 2.97 m (minimum of 1.2 m, maximum of 4.0 m) (EPAGRI 2013).

DISCUSSION

Meteorological Data

Temperature

According to Tonietto and Mandelli (2003), from the end of winter to early spring, a temperature of 10ºC is considered the general minimum for bud break and vegetative development of the plant. Between late spring and early summer, temperatures equal to or above 18ºC are the most suitable. In the summer, the highest photosynthetic activity is obtained at temperatures between 20–25ºC.

The mean temperature in São Joaquim, during the end of the winter and early spring (August–September), is between 11–12ºC, which allows the bud break and vegetative development of the vine. Temperatures during late spring to early summer (November–December) are between 15–16ºC and during the summer (December–February) they are between 16–17ºC. This lower summer temperature is the key climatic factor differentiating the region from other parts of Brazil, and it is what makes the vine to delay its vegetative growth and focus on fruit production, leading to a more complete maturation compared with other regions of Brazil.

Precipitation

The pluviometric indices (rainfall) of the best wine-producing regions in the world range between 300 and 1000 mm/year (van Leeuwen 2010). Compared to these regions, the annual precipitation in São Joaquim is greater (average of 1680 mm/year). From September to April (the growing season), the mean amount of precipitation is 997 mm. September is the wettest month (175 mm) and April is the driest month (92 mm). The fact that the harvest of some grape varieties in São Joaquim can occur in April, when the rainfall is the lowest, reduces the occurrence of fungal diseases.

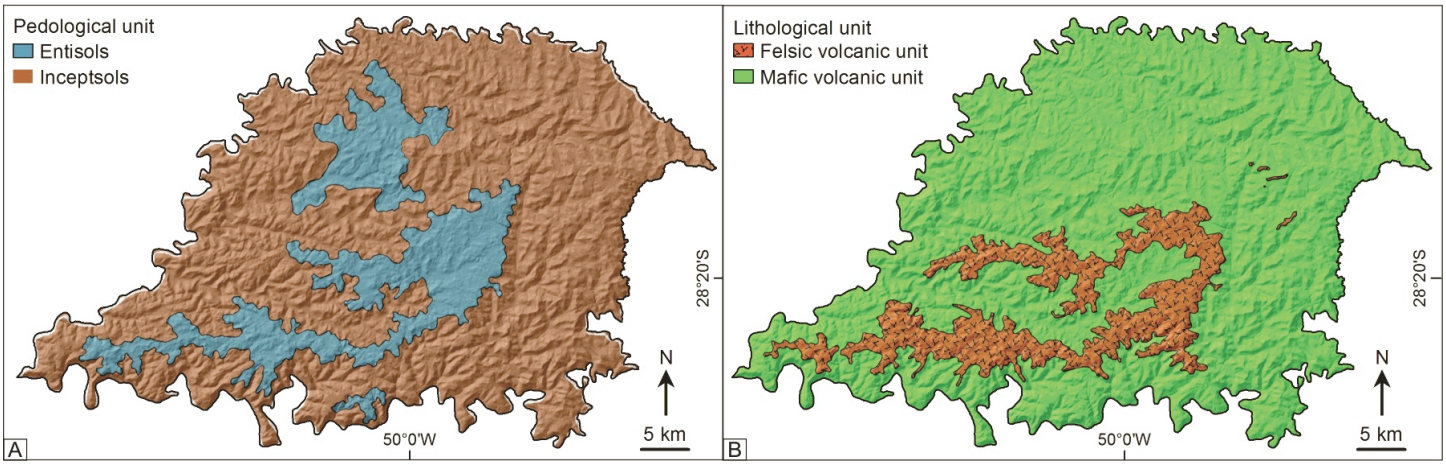

Figure 7. (A) Soil map of the municipality of São Joaquim, modified from Potter et al. (2004), and (B) lithological map of São Joaquim, modified from DNPM (1986) and Besser (2017).

Table 5. Pedological data of two representative soil profiles analyzed for chemical and physical properties in the municipality of São Joaquim: inceptsols (sample SJE-004) and entisols (sample SJE-006).

Sample	SJE 004 A1	SJE 004 A2	SJE 004 A3	SJE 004 AB	SJE 004 BA	SJE 004 B	SJE 006 A1	SJE 006 A2	SJE 006 A3	SJE 006 Cr
Soil type	Inceptsols						Entisols			
Depth (cm)	0 - 5	5 - 12	12 - 20	20 - 28	28 - 50	> 50	0 - 5	5 - 12	12 - 21	21 - 37
pH (water)	5.49	5.33	5.17	5.22	5.28	5.38	4.37	4.83	5.00	4.99
P^{-3} (ppm)	1.26	0.45	0.25	0.24	0.26	0.37	0.41	0.21	0.08	0.14
K^{+1} (ppm)	154	48	37	26	30	21	13	6	4	4
Ca^{+2} (ppm)	741	42	4	0	0	6	0	0	0	0
Mg^{+2} (ppm)	707	238	123	83	77	75	89	34	26	22
Al^{+3} (ppm)	63	246	310	288	308	250	470	511	477	533
SOM[1] (%)	11	8	7	5	4	2	7	6	5	3
Sand (%)	19	19	19	18	17	14	22	19	15	20
Silt (%)	36	33	32	26	25	30	32	26	27	27
Clay (%)	45	49	49	57	58	57	47	55	58	53
Silt/Clay	0.81	0.67	0.67	0.45	0.42	0.52	0.68	0.46	0.46	0.50
Textural Class			Clay						Clay	

[1]SOM = soil organic matter

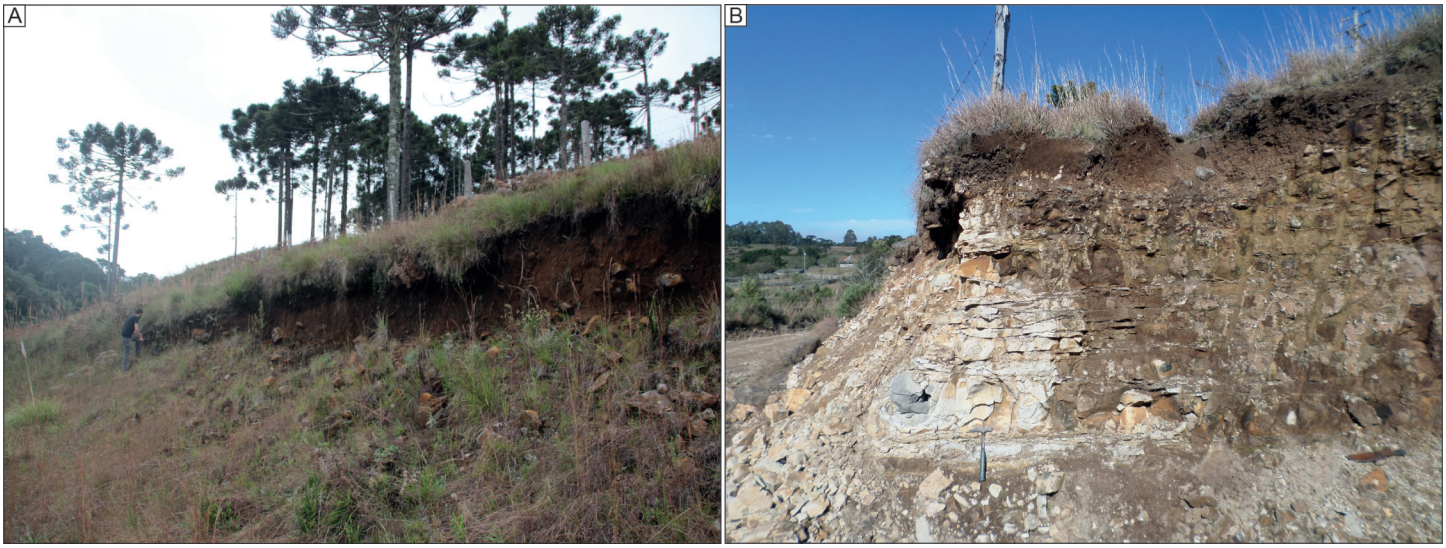

Figure 8. Representative soil profiles: (A) Inceptsols (sample SJE-004) and (B) Entisols (sample SJE-006). São Joaquim, State of Santa Catarina.

Solar Radiation

It is advisable that the vine, depending on the variety, receives between 1200 and 1400 hours/year of solar radiation to complete its vegetative cycle (Sentelhas 1998). São Joaquim receives a mean annual amount of 1832 hours/year. During the growing season (from September to Abril), the mean amount of solar radiation is 1264 hours, allowing the grapes to fully mature.

Viticultural Climate

According to the Geoviticulture Multicriteria Climatic Classification System (MCC; Tonietto and Carbonneau 2004), the viticultural climate of São Joaquim is classified as "Cold, of Cool Nights and Humid" (HI-2, CI+1 and DI-2) (Brighenti and Tonietto 2004). The climatic indices (see Table 9) are very similar to those of Freiburg in Germany, classified as "Cold, of Cold Nights and Humid" (HI-2, CI+2 and DI-2). Although located at very different latitudes (São Joaquim is at 28º17'S and Freiburg is at 48º00'N), both regions have similar night temperatures (12.1ºC in São Joaquim and 11.7ºC in Freiburg), probably due to the effect of altitude on the mean temperature (São Joaquim is at 1415 m and Freiburg is at 269 m).

The grape varieties cultivated in Freiburg include: Spätburgunder (Pinot Noir), Müller-Thurgau, Grauburgunder (Pinot Gris), Weissburgunder (Pinot Blanc), Silvaner (Braatz et al. 2014), Moscato Bianco, Riesling, Sauvignon Blanc, Chardonnay, Merlot, Gewürztraminer, Moscato and Scheurebe (see www.wine-searcher.com). Due to the meteorological similari-

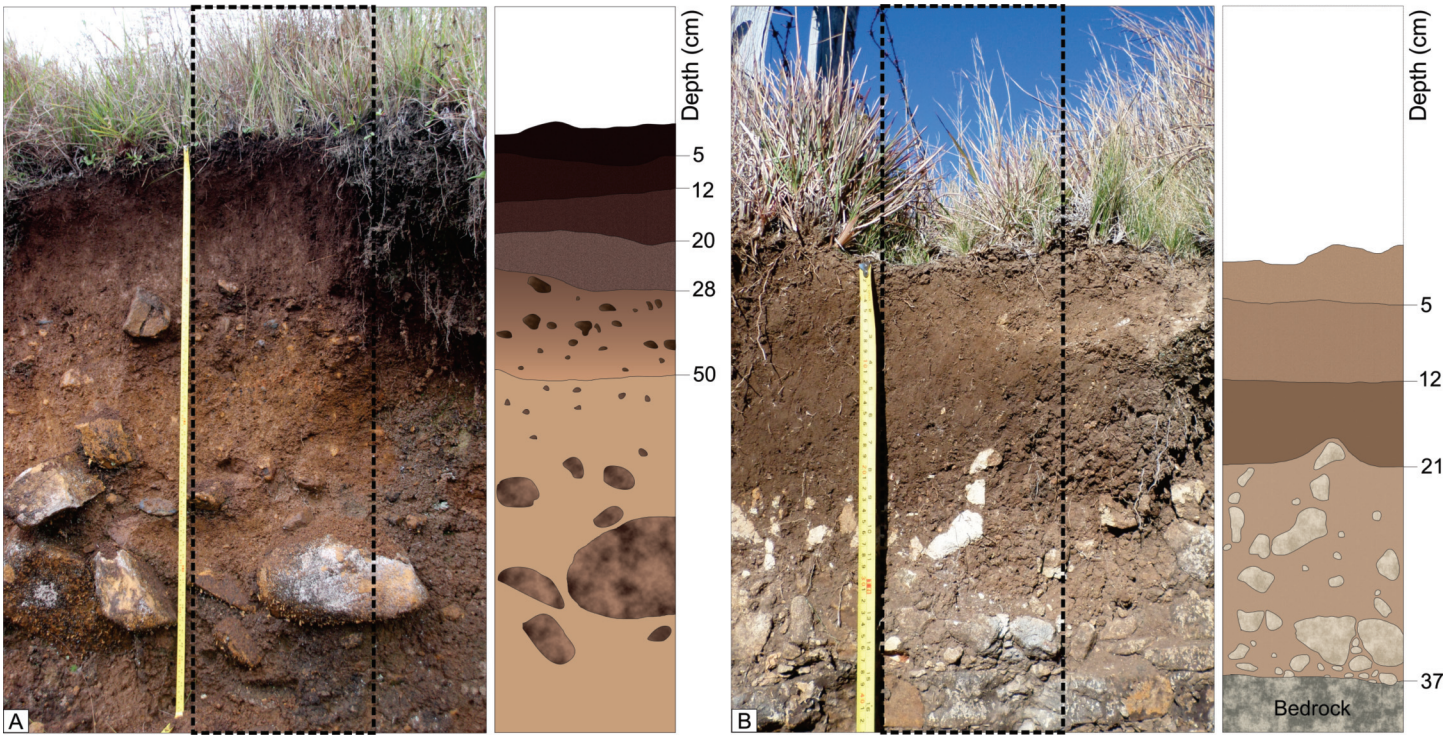

Figure 9. Detailed soil profiles: (A) Inceptsols (sample SJE-004) and (B) Entisols (sample SJE-006). Schematic drawings summarize soil horizons and depth. São Joaquim, State of Santa Catarina.

Table 6. Average chemical composition (major elements in wt.%) of the mafic and felsic volcanic units in the municipality of São Joaquim.

Major elements (wt.%)	Mafic unit	Felsic unit
SiO_2	52.93	68.87
TiO_2	2.05	0.94
Al_2O_3	13.69	12.88
Fe_2O_3	13.87	5.55
MnO	0.19	0.11
MgO	4.54	1.30
CaO	8.57	2.79
Na_2O	2.70	3.09
K_2O	1.16	4.19
P_2O_5	0.30	0.28
Total	100	100

*Data from Besser (2017).

Table 7. Average chemical composition (trace elements in ppm) of the mafic and felsic volcanic units in the municipality of São Joaquim.

Trace elements (ppm)	Mafic unit	Felsic unit
Cr	43	58
Ni	34	7
Ba	366	663
Rb	36	150
Sr	282	129
Zr	163	246
Y	33	43
Nb	15	21
Cu	144	68
Zn	98	75
Co	36	11
V	348	91

*Data from Besser (2017).

ties between these regions, the adaptation of these varieties in the São Joaquim region should be considered. The Sauvignon Blanc variety, which is cultivated in Freiburg, already stands out as one of the best suited to the terroir of São Joaquim.

Physiographic Data

Altitude

In general, a decrease of 0.6°C in the mean temperature occurs for every 100 m of elevation. In Brazil, the climate tends to be hot, so the search for potentially productive high- altitude areas is essential in the main wine-growing regions (Tonietto and Mandelli 2003). São Joaquim has altitudes ranging from 715–1638 m, which means that the region is approximately 4–9°C colder than areas at the same latitude that are located close to sea level. This variation in the temperature modifies the vegetative cycle of the vine, as described by Rosier (2003). This is what makes the Planalto Catarinense viticultural region distinct from the other wine-growing regions in Brazil.

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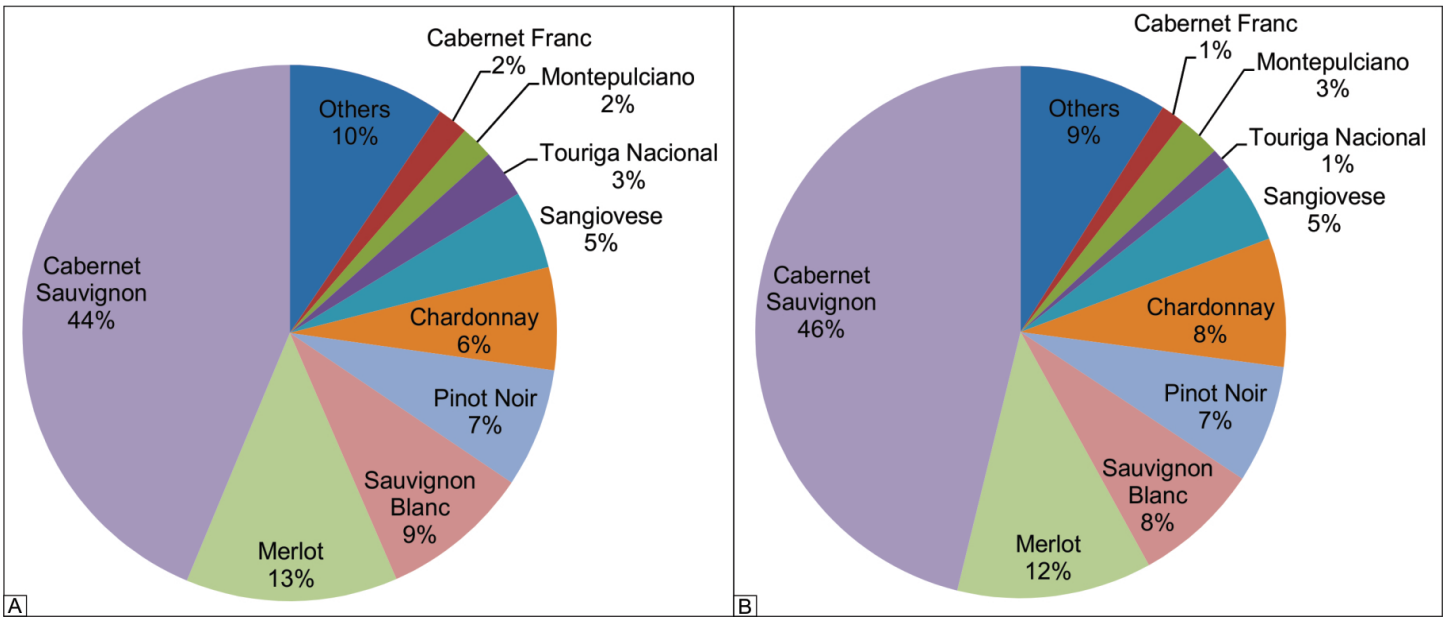

Figure 10. Comparison between the main grape varieties planted in the municipality of São Joaquim: (A) proportions by area (in hectares) and (B) proportions by the number of vines planted. Modified from EPAGRI (2013).

Table 8. The main grape varieties cultivated in the municipality of São Joaquim in terms of area (ha and %) and vines planted (number of vines and %).

Grape variety	Area (ha)	Area (%)	Vines planted	Vines planted (%)
Others	16	10	41,813	9
Cabernet Franc	3	2	6,814	1
Montepulciano	3	2	11,968	3
Touriga Nacional	5	3	5,953	1
Sangiovese	8	5	22,941	5
Chardonnay	10	6	36,229	8
Pinot Noir	12	7	33,299	7
Sauvignon Blanc	15	9	35,65	8
Merlot	22	13	55,065	12
Cabernet Sauvignon	73	44	214,103	46
Total	168	100	463,835	100

*Data from EPAGRI (2013).

To be part of the Santa Catarina "fine wines of altitude" collective brand, the vineyard must be located at altitudes of at least 900 m (Dortzbach 2016). According to the data analyzed from EPAGRI (2013), no vineyards in São Joaquim are located below 1093 m. The majority of the vineyards (61%) are located at altitudes between 1200–1300 m (Table 10), meaning that all vineyards in the region are influenced by the effects of altitude.

Declivity

The risk of erosion and the difficulty of mechanization are issues for slopes with declivities higher than 20% (Jordan et al. 1981). Slopes with declivities lower than 3% may be more amenable to mechanization, but may present problems related to poor draining of soils (Dortzbach 2016). Slopes with declivities between 3–20% are generally considered to be the most suitable for viticulture. According to the data analyzed from EPAGRI (2013), about half the vineyards (51%) in São Joaquim are located on slopes within this range of declivity (Table 11).

Orientation

In the Southern Hemisphere, the orientation of the slope towards the north allows the vines to receive solar radiation for a longer period of time and also protects the vines from cold southern winds (Melo 2003). According to the data analyzed from EPAGRI (2013), most parts of the vineyards in São Joaquim are located on slopes facing north (23%), northeast (13%) and northwest (18%) (Table 12). Broadly north-facing orientations account for 56% of the vineyards by area.

Pedological Data

In the cultivation of grapes, preference is given to soils with a loam texture (30–50% sand, 30–50% silt and 10–30% clay, according to Santos et al. 2013), well drained, with pH ranging from 5 to 6 and soil organic matter (SOM) contents of at least 2% (Melo 2003). The root system of the vine rarely exceeds 120 cm, with 90% of the roots distributed in the first 60 cm (Dortzbach 2016). In São Joaquim most of these characteristics, including pH and depth, are found in the inceptsols derived from the basalts and basaltic andesites of the mafic volcanic unit.

Geological Data

According to Jackson (2008), some cultivars are more adapted to soils derived from rocks of specific composition, but evidence on these aspects is still circumstantial and there is no experimental evidence. In this preliminary study of the munic-

Table 9. Geoviticultural Multicriteria Climatic Classification (MCC) System indices for São Joaquim (Brazil) and Frieburg (Germany).

Country	Region	Location Latitude	Location Longitude	Altitude	Geoviticulture MCC System[1] HI	CI (ºC)	DI (mm)
Germany	Freiburg	48º 00' N	7º 51' E	269 m	1684	11.7	200
Brazil	São Joaquim	28º 17' S	48º 55' W	1415 m	1714	12.1	200

*Data from EMBRAPA (2008).

[1]Geoviticulture Multicriteria Climatic Classification (MCC) System climatic indices (Tonietto and Carbonneau 2004):
Heliothermal Index – HI: very cold (HI -3: HI < 1500), cold (HI -2: 1500 < HI 1800), cool (HI -1: 1800 < HI < 2100), warm (HI +1: 2100 < HI < 2400), hot (HI +2: 2400 < HI < 3000) and very hot (HI +3: HI > 3000).
Cold Night Index – CI: cold nights (CI +2: CI < 12ºC), cool nights (CI +1: 12ºC < CI < 14 ºC), warm nights (CI -1: 14ºC < CI < 18ºC) and hot nights (IC +2: CI > 18ºC).
Dryness Index – DI: very dry (DI +2: DI < -100 mm), dry (DI +1: - 100 mm < DI < 50 mm), sub-humid (DI -1: 50 mm < DI < 150 mm) and humid (DI -2: DI < -150 mm).

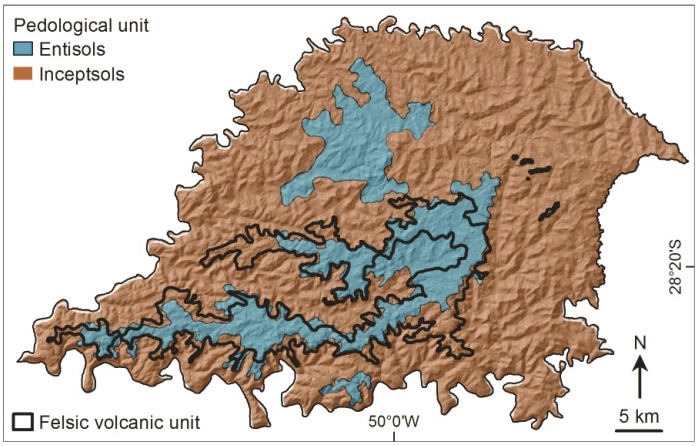

Figure 11. Pedological map of the municipality of São Joaquim, modified from Potter et al. (2004), showing the correlation between the entisols and the felsic volcanic unit.

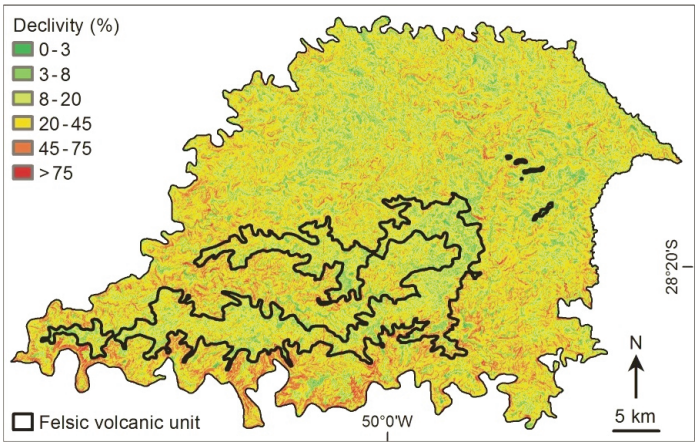

Figure 12. Declivity (%) map of the municipality of São Joaquim, modified from SDS (2010), showing the correlation between the slopes with low declivities and the felsic volcanic unit.

ipality of São Joaquim, we suggest that there is an influence from geology upon pedological and physiographic properties, and thus on the viticultural potential of the region.

Table 10. Area occupied by the vineyards (km² and %) at various altitudes in the municipality of São Joaquim.

Altitude (m)	Area (ha)	Area (%)
< 1100	1	1
1100 – 1200	40	24
1200 – 1300	103	61
1300 – 1400	18	11
> 1400	6	3
Total	168	100

*Data from EPAGRI (2013).

Table 11. Area occupied by the vineyards (km² and %) at various slope declivities in the municipality of São Joaquim.

Declivity (%)	Area (ha)	Area (%)
0 – 3	12	7
3 – 8	32	19
8 – 20	54	32
20 – 45	62	37
45 – 75	7	4
> 75	0	0
Total	168	100

*Data from EPAGRI (2013).

Across the municipality of São Joaquim, there is a correlation between the mafic volcanic unit and the development of inceptsols, and between the felsic volcanic unit and the development of entisols (Fig. 11). This correlation is confirmed by the physical and chemical properties of the soils analyzed in this study. Soils developed from mafic volcanic rocks (12 samples analyzed from 2 soil profiles) tend to be thicker (> 150 cm), have a clayey texture, and an average pH (water) of 5.52. They have an average content of 146 ppm Al^{3+}, 663 ppm Ca^{2+} and 271 ppm Mg^{2+}. Soils derived from felsic volcanic rocks (40 samples analyzed from 7 soil profiles) tend to be thinner

Table 12. Area occupied by the vineyards (km² and %) at various slope orientations in the municipality of São Joaquim.

Orientation	Area (ha)	Area (%)
North	39	23
Northeast	26	15
East	20	12
Southeast	12	7
South	11	7
Southeast	13	7
West	17	10
Northwest	30	18
Total	168	100

*Data from EPAGRI (2013).

(< 100 cm), have a clayey texture, and an average pH (water) of 4.68. They have an average content of 509 ppm Al^{3+}, 80 ppm Ca^{2+} and 67 ppm Mg^{2+}. Considering these data and the previous studies, the mafic volcanic unit in the municipality of São Joaquim appears more likely to provide inceptsols suitable for viticulture.

There is also a correlation between the felsic volcanic unit and the slopes with lower declivities and between the mafic volcanic unit and slopes with higher declivities (Fig. 12). Given that previous studies suggest that the 3–20% declivity interval is most suitable for viticulture, areas underlain by the mafic rocks are more likely to satisfy this criterion. The steeper slopes associated with the mafic volcanic rocks are likely related to the presence of thicker lava flows, whereas the felsic rocks consist of thinner tabular flows on the top of the volcanic pile. Of the 21 properties dedicated to viticulture in São Joaquim, fifteen properties are located in the mafic volcanic unit, four properties are located in the felsic volcanic unit and two properties have vineyards that include parts of both units (Fig. 13).

CONCLUSION

São Joaquim is the largest viticultural region in the State of Santa Catarina, producing award-winning wines with distinct characteristics due to its unique terroir. The region has 21 properties comprising 268 vineyards that occupy a total area of 168.13 ha and produces a total of 1,100,000 liters of wine per year (estimated). The municipality of São Joaquim includes the 8th highest vineyard in the world (Vinícola Hiragami, located at 1427 m), from which wines won prestigious awards in 2017. These include the *Concours Mondial de Bruxelles 2017* Gran Gold Medal (for the Torii Cabernet Sauvignon of 2013), the *Concours Mondial de Bruxelles 2017* Gold Medal (for the Torii Merlot of 2013) and the *Concours Mondial de Bruxelles 2017* Silver Medal (for the Torii Cabernet Sauvignon of 2008).

The unique terroir of São Joaquim is characterized by low temperatures (mean temperature of 13ºC) and high altitudes (terrains between 715–1638 m, with vineyards located above 1000 m). The mafic volcanic unit in the region is associated with thicker (deeper) soils (inceptsols) with an average pH (water) of 5.52, and also with steeper slopes. In contrast, the

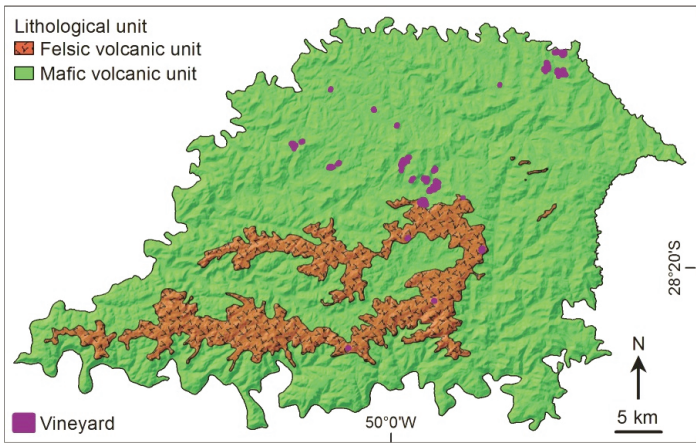

Figure 13. Lithological map of the municipality of São Joaquim, modified from DNPM (1986) and Besser (2017), with the location of the vineyards (purple).

felsic volcanic unit is associated with thinner (shallower) soils (entisols) with an average pH (water) of 4.68, developed on more gentle slopes or flatter terrain. The municipality of São Joaquim is dominantly underlain by mafic lava flows and felsic lava flows are less extensive. Both units are suitable for viticulture, but the distribution of vineyards suggests that the mafic volcanic unit is the more favourable, due to the preferential development of inceptsols.

The municipality of São Joaquim has the potential to become a viticultural region of national and international importance, as shown by the example of Vinícola Hiragami. The history of the viticulture in this region has less than 20 years of production. For this reason, research is being undertaken by EPAGRI to detail the physical characteristics of the municipality and test the adaptation of new grape varieties. There remains much to learn and to accomplish.

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