Rock joint characterization in Montreal Island as a function of regional and local structural Geology

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ABSTRACT
Rock joint characterization is a vital part of rock engineering. A good understanding of rock discontinuities can help engineers establish their analyses based on reliable geotechnical data, save cost of construction and reduce risk of ground failures. This paper reviews the steps established to collect rock structural data in Montreal Island based on the regional geology and on the geotechnical investigation of six different projects. A database of rock joint characteristics has been established according to the regional geology. The effect of the structural geology and different fault zones on the structural characterization of rock mass, which has also a significant influence on rock mass parameters, is also discussed. The paper concludes with an appreciation of the discrepancies and similarities in rock joint properties as a function of regional geology.

RÉSUMÉ
La caractérisation des joints de roche est une partie essentielle de l'ingénierie des roches. Une bonne compréhension des discontinuités rocheuses peut aider les ingénieurs à établir leurs analyses sur la base de données géotechniques fiables, à réduire les coûts de construction et à réduire les risques de rupture. Cet article passe en revue les étapes établies pour recueillir des données structurales sur l'île de Montréal en fonction de la géologie régionale et de l'investigation géotechnique de six projets différents. Une base de données des caractéristiques des joints rocheux a été établie en fonction de la géologie régionale. L'effet de la géologie structurale et des différentes zones de failles sur la caractérisation structurale de la masse rocheuse, qui a également une influence significative sur les paramètres de la masse rocheuse, est également discuté. L'article se termine par une appréciation des divergences et des similitudes dans les propriétés des joints rocheux en fonction de la géologie régionale.

1 INTRODUCTION

Rock mass as a discontinuous material exhibits elastic, elasto-plastic or brittle behaviour. The joint and discontinuities are often of a main source of instability of the rock mass. Most joints are created when the overall stress regime is more in tension (extension) than compression. However, it is also possible for joints to develop where the overall stress regime is in compression where rock layers are folded. Under compressive forces, joints will be also created in an oblique direction to accommodate volumetric changes. The joint conditions vary from rough to smooth, planar to undulating and unweathered to slickenside surface to highly weathered. The characterization of rock joint helps engineering practice to realize more realistic analytical and numerical calculations.

Understanding of the rock joint systems and the correlation between the regional geology and the rock joint can reduce the risk of rock failure in each project and building.

This paper focuses on the determination of rock joint systems in relation with the structural geology of Montreal. Information of 6 major infrastructure projects recently carried out in Greater Montreal in different rock types has been compiled. Since the geological formations and fault zones have a significant influence on the rock properties, a detailed joint system analysis and joint characterization were performed to provide a geological model for Montreal Island in regard with the available information.

2 GEOLOGICAL CONTEXT

2.1 Geological Formations

Montreal Island is 50 km long and is bordered by the St. Lawrence, Ottawa, and Des Prairies Rivers. Most of the rocks in Montreal area belong to the geological Formations dating from the Paleozoic Era overlying Precambrian rocks. The main characteristic of this unit is the faulted structure and faintly deformed shelf assemblage of Cambro-Ordovician sedimentary rocks as summarized in Table 1.

The Ordovician assemblage consists of dolomites and limestones of the Beekmantown, Chazy, Black River and Trenton Groups with quasi- horizontal bedding planes with an overall regional dipping to the east which varies from a few degrees to 10°, averaging about 2° (Leroux *et al*, 2018). The shaly interbeds exist which control the mechanical properties of limestone and dolomite. The weathered shale and mudstone beds deposited on the Trenton Group constitute the Utica, Lorraine, and Richmond Groups (Boyer et al. 1985).

Another important feature of the Montreal Island geology is an alignment of Upper Mesozoic (Cretaceous) intrusions consisting of gabbro, diabase and syenite forming the core of Mount-Royal. In addition, other intrusions such as dykes, sills and associated breccia can be irregularly seen in sedimentary and igneous rocks with varying thickness from 1 cm to 10 m. The presence of intrusions gives rise for a harder rock mass (Boyer et al. 1985).

Table 1. Principal geological units of Montreal (Boyer et al.1985)

Age	Group/Formation		Lithology
Cretaceous	Monteregian		Dikes, sills, and Breccia
	Richmond		Sandstone& shale
	Lorraine		Shale, siltstone
	Utica/Lachine		Blackshale
	Trenton	Tétreauville	Limestone &shale
Ordovician		Montréal	Limestone
		Deschambault	Limestone
		Mile-Rockland	Limestone
	Black River	Leray	Limestone
		Lowville	Limestone
		Pamelia	Dolomite
	Chazy/Laval		Limestone
	Beekmantown/Beauharnois		Dolomite
Cambrian	Potsdam		Sandstone

2.2 Geological characterization (Structural Geology)

Figure 1 shows the main structures encountered in the Greater Montreal area. The region has undergone different episodes of disturbances that have left traces in the form of the faults and the large folds. The predominant limestone horizons, specially in Trenton Group, has been deformed slightly into wide fold in the northeast-southwest direction. The dip of the beddings in the synclines and anticlines rarely exceeds 6 or 7° except in the fault zones as well as the zone with a presence of intrusions which affect the bedding dipping.

In the central-north strip of the island, there are two large parallel folds in northeast-southwest directions (strikes). These are the Ahuntsic syncline and the Villeray anticline. The orientation and position of the latter is close to Zone 2 (Figure 2). According to Clark (1972), and later supported by Rocher and Tremblay (2001), the Montreal region is distinguished by three main - faulting systems:

1) East – West (N090)
2) North-West – South-East (N135)
3) North-East – South-West (N025)

The excavation of underground openings in the last decades as well as the recent tunnels has confirmed that three faulting systems are often accompanied by secondary faults which create a discontinuities network in various directions, according to the movement of their precursor. Those unknown faults are the ones that are least predictable and often encountered fortuitously during underground excavation projects.

In the center-north sector of the island, the main faults oriented North-West – South-East are predominant, intersected in the north by the east-west fault Bas-Sainte-Rose and limited in the south by the fault system Rapides-du-Cheval-Blanc.

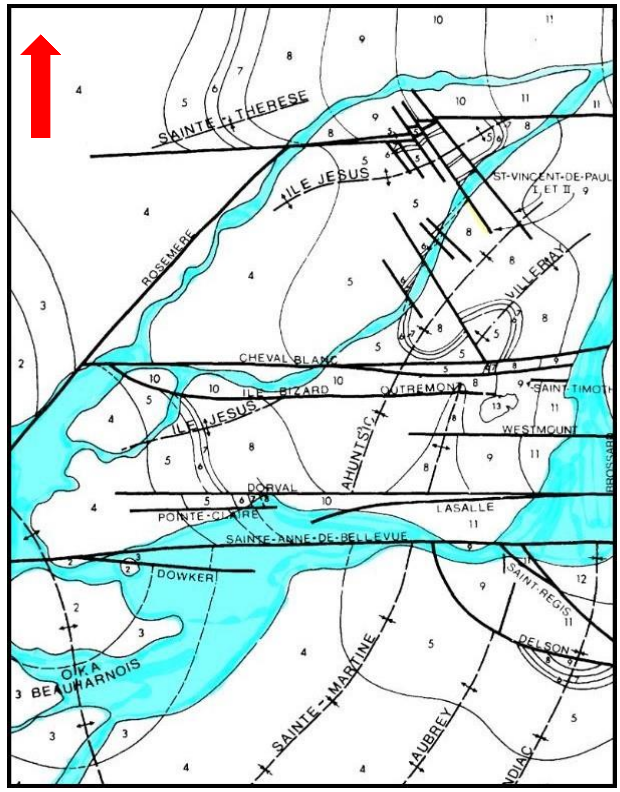

Figure 1. Regional structural map of the Montreal area showing two main fold axes and main fault systems (after Clark 1972)

Lack of information concerning the regional extension faults presented in the vicinity of Zones 2 and 3 (Figure 2) on the geological map established by Clark (1976) could be due to the absence of a major geotechnical investigation as well as the infrastructure projects. As a matter of fact, the hypothesis of an extension of the faults Saint-Vincent-de-Paul I and II, can be justified where one of which was possibly encountered during the recent excavation of the tunnel Jarry by a tunnel boring machine. The whole tunnel drowned possibly due to the faulting system.

On a smaller scale, faults with vertical throw of metric to multi-metric order have been identified in the old quarries (Miron and Francon) and current quarries (Demix, Lafarge, of east- Montreal) and the Blue Line Metro Extension project. In fact, joint conditions and fault movements are best observed in quarries. An inspection of a nearby quarry or a rock outcrop is always beneficial when analyzing discontinuities that may affect the feasible or detailed studies of project. In addition, it is easier to measure joint spacing for each joint set on a rock face than in a 5 cm borehole core.

Figure 2 shows the different zones corresponding to the recent infrastructure projects in Montreal. As can be seen, Zone 1, located in the west of the Montreal Island, does not appear to be in a major troublesome area in geological structural point of view. The geotechnical investigation showed that a major fault intersected the projected tunnel.

This fault was probably associated to the E-W faulting system which is located in between the Dorval fault and the Westmount –Ile-Bizard fault.

Moreover, Zone 4, located northwest of the Mont-Royal intrusive, is principally affected by the Outremont E-W fault and a highly disturbed area due to the metamorphic contact aureole.

The proximity of Zone 5 to Mont-Royal, located downtown Montreal, can affect the structural conditions of rock mass. The site is located between the intrusion and the St-Lawrence valley. Consequently, some structures could be controlled by the topography and are discovered by the engineering works for which numerous references can testify. Also, it is important to mention that a post-glaciation decompression (isostatic uplift) in this marked topographic environment can produce numerous glaciotectonic features (Durand and Ballivy, 1974). The structural signature in these environments is not straightforward.

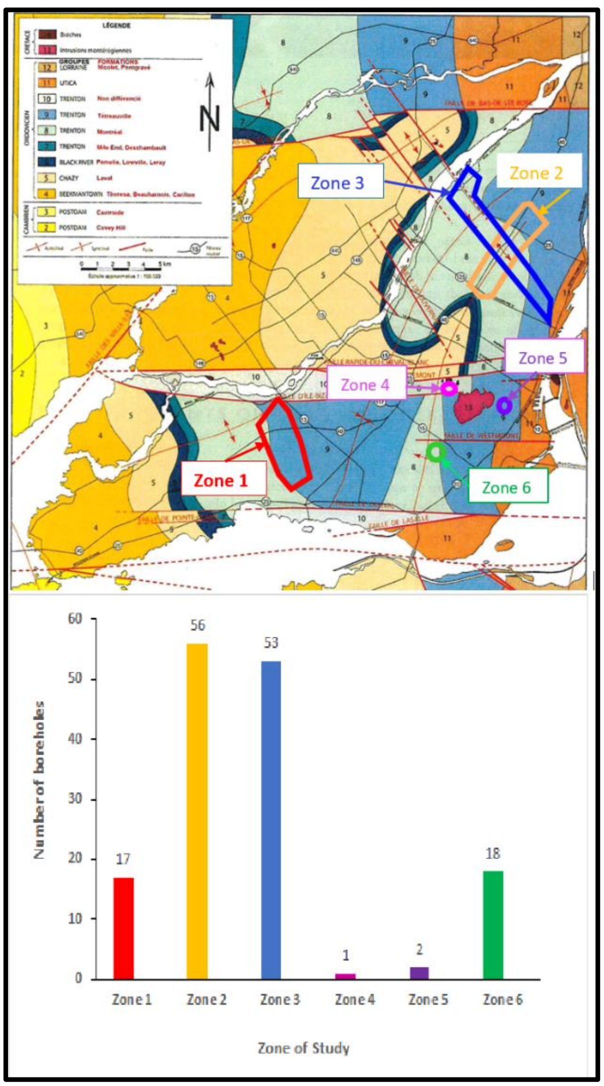

Figure 2. Plan of rock joint investigations in Montreal Island (after Clark, 1972) and number of boreholes with televiewer data available for each study zones.

3 DATA COLLECTION AND SITE INVESTIGATIONS

3.1 Statistical Analyses of Rock Joint

The results of the investigation programs of 6 major projects, including three long tunnels (3km to 8 km), one large subway garage and two underground stations, have been studied for this paper. To determine the rock joint systems, the information of more than 147 boreholes, corresponding to more than 4500 meters drilled rock, was studied and geologically analyzed. The televiewer data and rock cores pictures, the petrographic and lithological descriptions and location of each project were used for these analyses based on the information availability.

The analysis of more than 147 vertical and inclined boreholes resulted in a specific geological and rock joint database. Therefore, the rock joint can be classified according to its characterization and the project location. Figure 2 presents the distribution of chosen zones on the Montreal geological map where televiewer data was available from projects. As can be seen, most of the investigations are carried out in the east (Zones 2 and 3), the west (Zone 1), and the center (Zones 4, 5 and 6) of Montreal.

Figure 2 also shows the distribution of the rock joint investigations as a function of the geological units. As can be seen, most of the boreholes were carried out in rocks of the Trenton Group. Based on petrographic description performed on the rock samples, the lithology of the Trenton Group is composed of fine-to-coarse grained limestone with or without shaly interbeds. The primary joint system observed in these sedimentary rocks is near-horizontal joints representing the bedding planes with vertical and sub-vertical joints. Random joints are also observed in the rock samples. The spacing of the joint sets, including bedding, varies from a few centimetres to more than 2 metres. In general, joints surfaces are slightly weathered to highly weathered.

3.2 Rock Joint Classification

To classify rock joints in Montreal, four sets of characteristics derived from core logging data have been analyzed, including:

- Number of joint sets
- Roughness
- Alteration
- Spacing

These characteristics for each zone are shown in the following figures.

3.2.1 Number of joint sets

As can be seen in Figure 3, the rock mass can be classified as massive, i.e., no or few joints (J_n=1), to jointed rock, i.e., one joint set (J_n=2) or one joint set plus random joints (J_n=3). In the vicinity of the major known faults or of zones of pre-fractured rock (due to existing underground structures), the joint number is increased in the boreholes, as observed by televiewer investigation. A good example of this increase can be seen in the joint number of Zone 1 where the project layout intersects three major faults (which are missing in Clark geological map, Figure 1). The complexity of the structures in Zone 5 is also demonstrated by a high joint number.

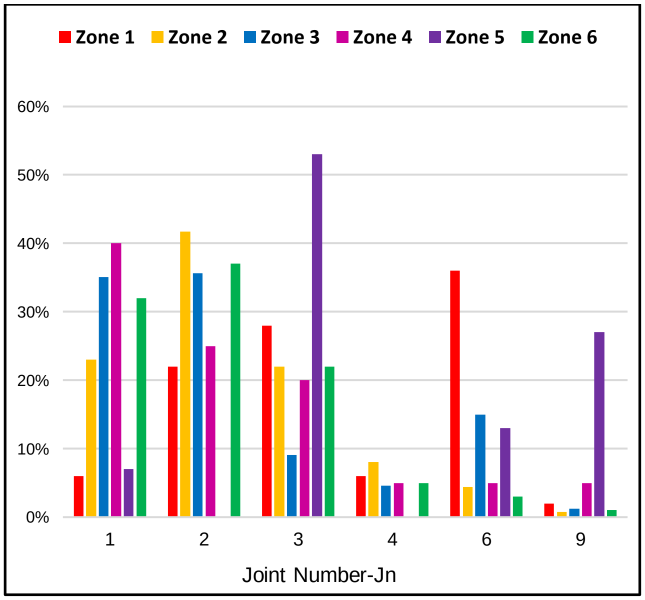

Figure 3. Joint set number (Jn) of rock mass in different zones of Montreal

3.2.2 Joint Roughness

The results of joint roughness characterization reveal that most joint surfaces may appear rough/irregular/planar (J_r=1.5) to rough/irregular/undulating (J_r=3) in all zones (Figure 4). The smooth/planar joints (J_r=1) have a significant percentage of 22% and 47% of all joints in the zones 3 and 5, respectively. The smooth/planar to rough/irregular/planar characteristics can be related to the presence of three faults in zone 1 and the damaged zone surrounding of an existing pedestrian tunnel in Zone 5. The results of the borehole observations have also confirmed that the joint surface condition may change to smooth/planar in vicinity of the faults in other zones, i.e., 3.

3.2.3 Joint Alteration

The results of joint alteration in Figure 5 indicate that the rock joint can be classified from unaltered joint walls ($J_a \leq$ 1) to slightly altered joint walls (J_a =2) in all zones except in Zone 1 in which the joint alteration is predominantly high when compared to the other zones. As mentioned before, three faults have been determined during investigation program in Zone 1. The joint alteration number is at its highest with 45% and 33% of joints being strongly altered in Zone 1 and Zone 5, respectively. This high degree of alteration is potentially caused by presence of the faults identified in the vicinity of Zone 1 and due to the damaged rock surrounding the existing pedestrian tunnel in Zone 5.

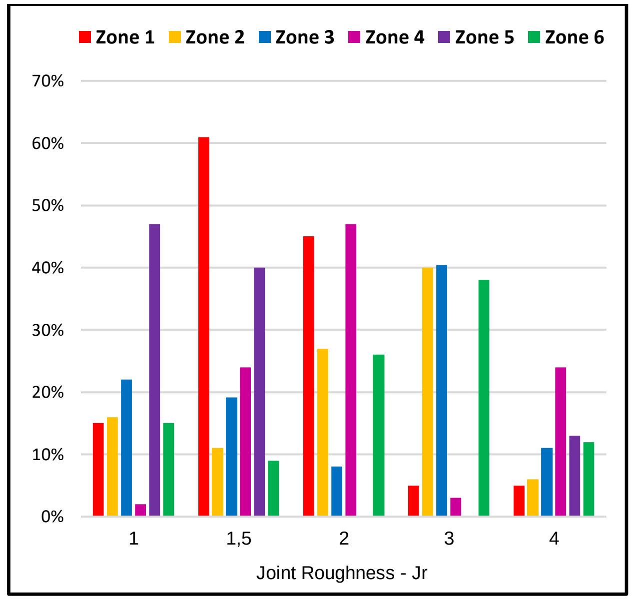

Figure 4. Joint Roughness number (Jr) of rock mass in different zones of Montreal

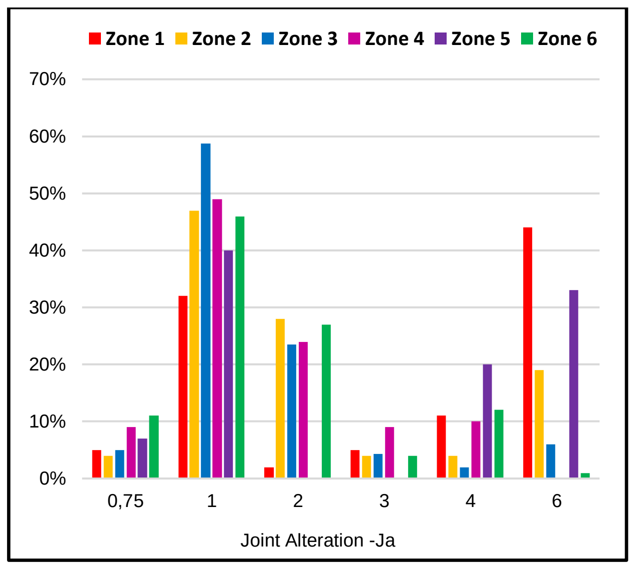

Figure 5. Joint Alteration number (Ja) of rock mass in different zones of Montreal

3.2.4 Joint Spacing

Figure 6 shows the joint spacing in the rock mass of each zone. The results show that the joint spacing varies between 0.06 m to 0.6 m in the majority of the studied zones. The joint spacing is a function of bed thickness for the same types of lithologies. Since the projects are primarily taking place in a similar lithologies, including limestone and shale beddings, it would be interesting to see the correlation of the joint spacing in different local projects: 1) small spacing (60 mm or less) in thin beds, 2) medium spacing (200 to 600 mm) in Trenton limestone, and 3) the bed thickness which are often in the range of 10 to 30 cm. The data could be filtered depending on the number of the inclined boreholes in each project, which allow to intercept more subvertical joints, by which the spacing could be changed. The weakness of the bed (or stiffness) also controls joint spacing. The stiffer the material, the narrower the spacing.

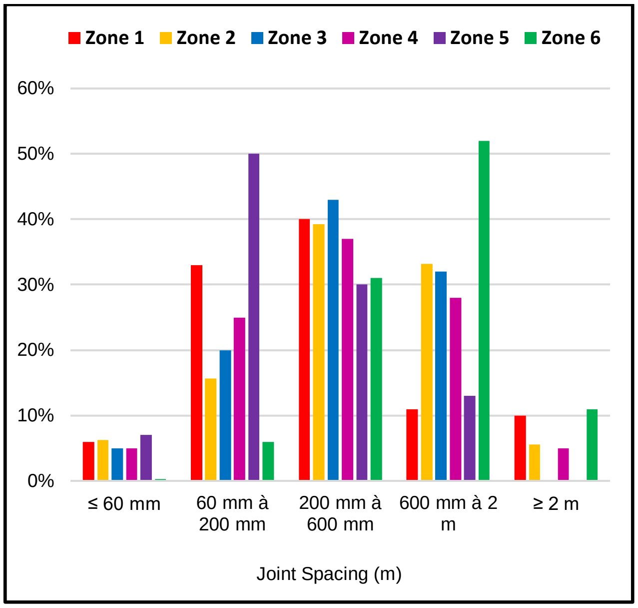

Figure 6. Apparent joint Spacing (m) of rock mass in different zones of Montreal

3.3 Joint sets

The Rocscience Dips software (Ver. 08) is used for the structural analysis of bedrock in the studied zones. According to the televiewer data, the main joints (minor opening, partial opening and major opening) and the bedding joints were taken into account in order to determine the joint sets in these zones. Table 2 summarized the joint sets in each zone based on their occurrences.

Table 2. Joint sets observed in the studied zones in Montreal

Zones	J1	J2	J3	J4	J5
	Dip/Dip Direction				
Zone 1	01/003	76/207	71/025	46/022	
Zone 2	02/104	45/351	88/187	77/285	77/082
Zone 3	01/066	60/023	79/202	78/298	78/091
Zone 4	15/356	75/360	28/187	69/177	
Zone 5	01/306	60/230	84/014		
Zone 6	03/249	36/173	83/210	71/133	

As can be seen in Table 2, the primary joint set (J1) is associated to the horizontal to the sub-horizontal joints (0 to 15º of dip) observed by televiewer. More than 76% of the measurements belonging to this joint set corresponds to the regional bedding of limestone and shaly limestone. The average dipping of J1 is 15° to the north in Zone 4 which reflects the particular strata «pushed up» by the intrusion of the Mount-Royal pluton. The subvertical secondary joint set J2 seem to be affected by the Subparallel E-W Île-Bizard and Outremont fault system.

The analyzes show that minimum two secondary joint sets (J2 and J3 dipping between 71 and 88º) are associated to the vertical and the sub-vertical joints in all zones. Moreover, an inclined joint set (28º to 60º) with different dip direction is observed in all zones.

It should be noted that the number of joint sets in Zones 2 and 3 are affected by folding systems and a fault zone as shown in Table 2 (Saint-Vincent-de -Paul). Therefore, the number of joint sets has been increased compared to other zones.

The rock mass with a good quality (Class II or I) has two to three prominent joint sets including bedding planes plus a random joint set. The fractured rock mass (Class III or Class IV) has three to four joint sets plus random joints. In the fault zones, it is difficult to distinguish the joint sets as the rock mass is completely crushed. Figure 7 is an example of the stereographic projection of the number of joint sets in the vicinity of an identified normal fault in Zone 2.

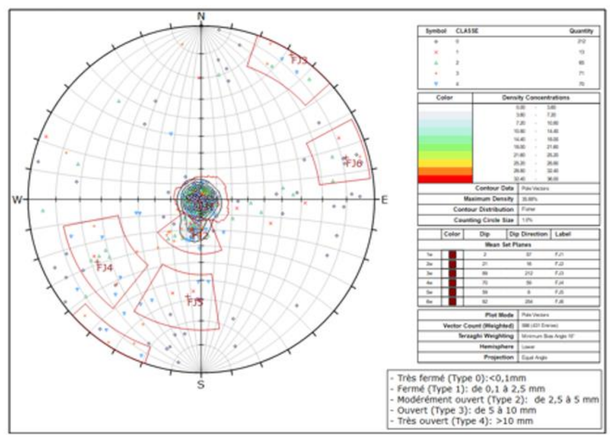

Figure 7. Stereographic projection of joint sets in the vicinity of a possible extension of the fault zone Saint-Vincent de Paul I-II

3.4. Impact of regional geology on joint characterization

To study the impact of regional and local geology on the joint characterization, the joint sets obtained in each zone have been projected in Rosette Plot to illustrate radial histogram of the strike of the joint planes. Figure 7 shows an example of rose diagram for one of the tunnels in Zone 2.

The joint observation in different zones has been projected in the form of rosette plot (rose diagram) on the geological map (Rocher et al, 2003) of Montreal. This type of representation allows for a comparison with what has been observed by other researchers in Montreal Island. Moreover, it helps us to study the impact of a fault zone on rock mass fracturing process and the orientation of different joint sets. The orientation of the joints for each zone in the form of rosette plot is presented in Figure 8.

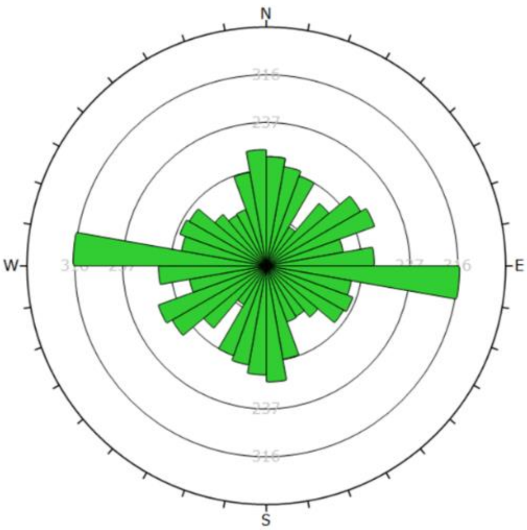

Figure 7. Rosette plot of the joint sets of one of the tunnels of Zone 2 showing a strong E-W joint strike direction.

As can be seen in this figure, the joint orientation is fairly consistent within each of the studied zones. The zones located in the same geographical area of the island show similarities which suggesting the influence of the major structural folds and faults on the joint sets. The north-west/south-east (NW-SE) joint set is present to a certain degree everywhere in the region except in close vicinity of major fault zones oriented differently (i.e. E-W).

The fault associated with the major E-W systems between Dorval Fault and the Ile-Bizard Fault has a strong influence on the joint orientation of Zone 1. As can be seen in Figure 8, the joint orientation is consistent across this zone. However, in the mid part of this zone, the joint rosette shows presence of one additional joint set (NNE-SSW) which is possibly linked to a conjugate fault. No televiewer observations have been carried out directly in the fault zone to determine more precisely the joint sets in this area.

Figure 8 also suggests that the joint orientation along the tunnel alignment in the east portion of Zone 2 (as shown by the red rosettes) is influenced by the presence of the Saint-Vincent de Paul fault system. This zone is also strongly influenced by the major E-W faulting system existing everywhere in the island. The rosette diagram in the upper-left corner of Figure 8 shows the representing data of three boreholes carried out in the vicinity of the fault Saint-Vincent-de-Paul I. This figure illustrates that the joint orientation in the fault has a significant difference compared to overall joint orientation in the vicinity of the presumed extension, which could include the development of a shear zone or conjugated fault.

An occurrence of glaciotectonic uplift (decompression) has also been interpreted along the tunnel alignment of Zone 2 within 500m east of the extension of the fault Saint-Vincent-de-Paul I. The blue rosette in this zone shows a significant change on the joint orientation possibly due to the glaciotectonic phenomena. A profoundly statistical study correlating the depth of the measured joints would help in identifying the stress directions and offset between the joint sets related principally to the glaciotectonics. A few hundred meters east of the presumed glaciotectonic zone, the joints almost follow the same orientations observed along the tunnel alignment further west.

At the north end of Zone 3, the joint set orientations are significantly different than those in the center and south portions of this zone as they approach the two major fault planes of Saint-Vincent Paul (I and II). The two red rosette diagrams at the north end of Zone 3 shows conflicting information suggesting that other secondary or subordinate faults could occur (in a smaller scale) between the two main faults causing a change in maximum horizontal stress. It also may represent stress associated with a post–glacial uplift, a strong hypothesis interpreted in this area of the project.

The other example of changing of orientation can be seen in Zones 5 and 6 which are located at opposite direction (90° from each other) radially from the Mount-Royal pluton (intrusive). The strong NW-SE strike direction of the main joint set in Zone 5 is parallel to one of the three main fault families on the island. It is also probable that the Mount-Royal intrusion be responsible in large part in changing the stress regime. The relationship between the joint sets observed in Zone 6 and the Westmount fault remains unclear. The Westmount fault has been interpreted by Rocher *et al,* (2003) as a normal E-W striking fault forming the north wall of a graben structure. The strong NE-SW strike orientation follows the direction of the St. Lawrence graben (extension). Its 90° opposite joint set direction shown by the rosette diagram is sub-parallel to the south side of the Mount-Royal pluton that could suggest another extension controlled by topography.

Folds also influence joint set directions. The proximity of a syncline or anticline axis will likely create joints parallel to the axis while diagonal (30 t0 45° with the axis) and perpendicular sets form on the slopes. The relationship between fault type and joint sets is not as straightforward as one would like to be, but it may give indications if a fault mobilizes with a shear component. Intrusive bodies such as the Mount-Royal pluton and its associated dykes will form primary joints during emplacement and cooling. Also, decompression of the sedimentary beds which occurred during post-glacial events (isostatic rebound) would be responsible for creating a large number of open bedding joints which has facilitated the displacement of large sedimentary rock slices. Correlations can be made between recent (young) joint sets and ice movement when this movement is known.

4 DISCUSSION

To study rock joint properties, the televiewer observations along with the rock core photos have been used. The results of the statistical studies of rock joints indicated that the number of joint sets, joint roughness, joint alteration and joint spacing are affected by the presence of folds and major known fault zones in Montreal.

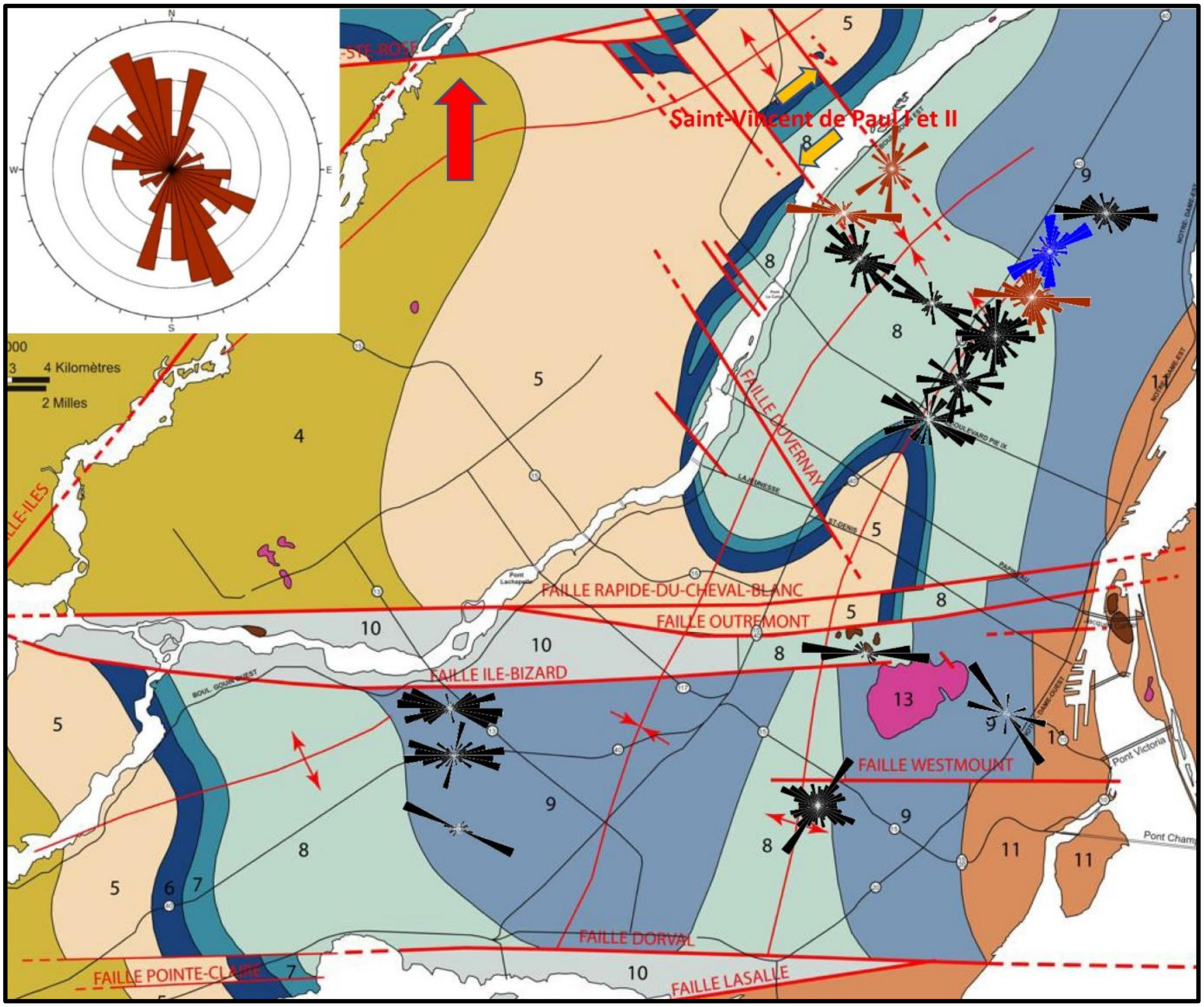

Figure 8. Rosette diagram of joint measurements carried out in Montreal for different infrastructure projects (geological legend presented in figure 2). The left corner picture represents the rose diagram for the joint sets of 3 boreholes near Saint-Vincent-de-Paul I fault (Zone 2)

Not only faults but folding, glaciotectonics and previous underground works can influence the main characteristics of the joints. Regional extension faults bring a definite signature to joint orientation. Additional new information such as shear stress and the presence of unsuspected conjugate faults can be inferred when analyzing rose diagram representations. It is important to compare similar rock formations across a wide area when analyzing the joint set characteristics and the effects of different structural phenomena affecting the joints characteristics.

There is a definite relation between joint orientation and the extension of major fault systems, but these can strongly be influenced by later structural events.

Even though strike-slip faults are rarely represented in the Montreal Structural maps, the rose diagrams used in the present analysis indicates the presence of the shear stress in some parts of Montreal Island.

The orientation of in-situ stress can be estimated based on the rock joint orientation and the fault type. As the strike-slip and normal faults can be produced by the compressive deformation, therefore a local stress rotation might occur when a conjugate fractured formed.

Moreover, the presence of intrusive rocks through sedimentary sequences such as that surrounding Mount-Royal pluton and associated dykes and sills shows a definite signature in joints set characterization for certain locations.

It should be mentioned that glaciotectonics recognized in several areas of Montreal Island with dislocated rock slices and thick deposits of till seem well-represented on rose diagrams with a typical pattern in which the effect of the surrounding faults is less representative.

5 CONCLUSIONS

The quantitative assessment of data collected from more than 147 drilled boreholes in different rock types has been carried out to stablish the statistical distribution and classify rock joint properties in Greater Montreal. The analysis of the joint set data from 6 projects on the island of Montreal (Québec) shows that relationships can be made between the orientations of joint sets and the presence of major regional geological structures.

The results of this study show that the joint spacing is a function of bed thickness for the same types of lithologies. Also, the number of joints is increased in vicinity or in the fault zones.

This study also depicts that the principal joint set in Montreal associates to horizontal to sub-horizontal joints corresponding to bedding plane of limestone/shaly limestone. In addition, two to three vertical and sub-vertical joint sets can be observed in all studied zones as secondary joint sets.

However, in the vicinity of fault zones, where more than one regional fault is implicated or when a shearing component is added, three to four joint sets plus random joints can be determined. All joint sets could also be related to several post depositional episodes of compression (principal folds) and extension (faults and grabens) and by a major intrusive period.

The Rosette diagrams allow us to better understand the effect of the presence of the major faults, the Mount-Royal pluton, and the glaciotectonics on the orientation of jointing systems. Three major fault systems in Montreal have a great influence on the joint characteristics and their orientations. This study also shows that due to lack of pervious investigations, only a limited data of fault zones has been indicated on geological map developed by Clark (1972) in some area of Montreal Island. Zone 1 is an example for lack of information.

It has been observed that normal faults in the Montreal area have subvertical walls. Therefore, joint sets in the studied zones show a correlation between dip angle and the type of fault.

A statistical joint set analysis in terms of the joint characteristics may help in identifying the responsible phenomenon of creating different sets of joints, considering the stress regime and history of the geological activities. To do so, the geological data from different projects carried out in Montreal can be used to create an effective tool in mapping structural geology and defining the stress regime.

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