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"Those were the stories that stayed with you, that meant something. (...) Folk in those stories had lots of chances of turning back, only they didn’t. They kept going, because they were holding on to something."

J. R. R. Tolkien

(The Lord of the rings – The two towers)
To my parents, Francisco and Marina, my sister, Ingrid, and my best friend, Vitor.

For always giving me something to hold on to.
Characterizing the joint system is a very significant component of investigations on fractured rock aquifers, as the secondary porosity controls the groundwater flow. It is also important to analyze the types of interactions between the joints, e.g., the types of termination and the dominancy of a certain joint set, since such information helps to understand the tectonic events that were responsible for the generation of the joint systems in the aquifer. Moreover, the current stress field is usually the most significant in controlling joint aperture, which plays a major role in groundwater flow.

The main objective of this work is to characterize an aquifer in fractured crystalline rocks with a fairly homogeneous lithology, defining a hydrogeological model of the study area, through structural surveys at different scales and hydrogeologic data analyses. This study was carried out in the Kenogami uplands, within the Saguenay graben, Quebec. It aimed to answer the following questions: (1) is there a structured joint system in the bedrock, that is, is it possible to identify preferential joint orientations and structural domains? (2) Can joint systems be defined at different scales, e.g. regional and local scales? If yes, are there any relationships between the systems observed at different scales? (3) Can any correlation between the joint system(s) and the past and present stress fields be identified? (4) Is there a relationship between the hydrogeological properties obtained from boreholes and the joint system(s)?

The structural survey involved three main phases. First, a characterization at the regional scale of the joint system is derived from air photo interpretation, lineament analysis, and a general field survey at selected sites. The latter involves the investigation
of the spatial distribution of the main joint sets, and the study of the relative ages of joint
sets and past stress field components conducted on horizontal outcrops. Second, a
detailed structural survey of selected road cuts was carried out to define and characterize
the main joint sets that compose the joint system in the study area. Third, the realization of
geophysical borehole logging provided valuable information at depth, especially regarding
subhorizontal joint sets. These steps allowed to answer the questions proposed in the
beginning of this research.

This project allowed the characterization of an aquifer in fractured crystalline rocks,
regarding the following aspects: joint systems at different scales, past stress fields,
hydraulic properties and the possible relationships between these parameters. The
methodology adopted may be applied to other studies on fractured rock aquifers.

Finally, a conceptual model was developed for the fractured rock aquifer in the
Kenogami uplands, using the unit block approach. This model may be extrapolated to a
regional scale, and it reflects the predominance of the subvertical joints in the study area.
Other contributions from this work include the introduction of procedures for applying
Terzaghi's correction on computers without using specialized softwares and for analyzing
the orientation of the main horizontal component of past stress fields on horizontal
outcrops. Moreover, it highlighted the value of characterizing a fractured media with the
unit block, through a discussion of its association to hydraulic properties and their
incorporation into numerical models.
RÉSUMÉ

La caractérisation du système de joints est un élément très important lors de la réalisation de levés sur les aquifères fracturés, puisque la porosité secondaire contrôle l’écoulement des eaux souterraines. Il est également important d’analyser les types d’interactions entre les joints. Par exemple, les types de terminaison des joints ainsi que la prédominance de certaines familles de joints représentent des informations qui permettant de comprendre les événements tectoniques responsables de la génération des systèmes de joints dans l’aquifère. En outre, le champ de contrainte actuel est habituellement le paramètre le plus important dans le contrôle de l’ouverture des joints, laquelle joue un rôle majeur dans l’écoulement des eaux souterraines.

L’objectif principal de ce travail est de caractériser un aquifère dans des roches cristallines fracturées avec une lithologie relativement homogène, en définissant un modèle hydrogéologique de la zone d’étude. Ce modèle a été construit à l’aide de levés structuraux à différentes échelles et des analyses de données hydrogéologiques. Cette étude a été réalisée sur le seuil de Kénogami, dans le graben du Saguenay, au Québec. Elle visait à répondre aux questions suivantes: (1) est-ce que le système de joints dans le socle rocheux est structuré, c’est à dire, est-il possible d’identifier des orientations préférentielles de joints et des domaines structuraux? (2) Les systèmes de joints peuvent-ils être définis à différentes échelles, par exemples aux échelles régionale et locale? Si oui, y a-t-il des relations entre les systèmes observés à différentes échelles? (3) Est-il possible d’identifier des corrélations entre le(s) système(s) de joints et les champs de
contraintes passés et actuel? (4) Y a-t-il une relation entre les propriétés hydrogéologiques obtenues à partir de forages et le(s) système(s) de joints?

Le levé structural a comporté trois phases principales. Premièrement, une caractérisation à l'échelle régionale du système de joints a été effectuée à partir de l'interprétation de photos aériennes, de l'analyse des linéaments, et d'un levé général de terrain sur des sites sélectionnés. Ce dernier type de levé implique l'étude de la distribution spatiale des principales familles de joints, et l'étude des âges relatifs des familles de joints et des champs de contrainte passés, menée sur des affleurements horizontaux. Deuxièmement, un levé détaillé sur des coupes de routes sélectionnées a été réalisé afin d'identifier et caractériser les familles de joints qui composent la fracturation dans la zone d'étude. Enfin, la réalisation de diagraphies géophysiques dans des forages a fourni des informations sur les joints en profondeur, notamment les familles de joints subhorizontaux. Ces étapes ont permis de répondre à la problématique proposée au début de cette recherche.

Ce projet a permis la caractérisation d'un aquifère dans des roches cristallines fracturées, selon les aspects suivants: les systèmes de joints à différentes échelles, les champs de contraintes passés, les propriétés hydrauliques et les relations possibles entre ces paramètres. La méthodologie adoptée pourra être appliquée à d'autres études sur les aquifères rocheux fracturés.

Enfin, un modèle conceptuel a été développé pour l'aquifère fracturé dans le seuil de Kénogami, en utilisant l'approche du bloc unitaire. Ce modèle peut être extrapolé à l'échelle régionale et il reflète la prédominance des joints subverticaux dans la zone d'étude. Les autres contributions de ce travail comprennent la mise en place de procédures : (1) pour appliquer la correction de Terzaghi sur ordinateur sans utilisation de
logiciels spécialisés, et (2) pour l’analyse de l’orientation de la composante horizontale principale des champs de contraintes passés sur les affleurements horizontaux. Aussi, ce travail a mis en valeur l’intérêt de la caractérisation d’un milieu fracturé avec l’approche du bloc unitaire, par une discussion de sa relation avec les propriétés hydrauliques, suivie de leur incorporation dans les modèles numériques.
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Fractured bedrock aquifers have been described as "complex hydrogeological systems that are essential for water resources" (Gleeson & Novakowski 2009). Igneous and metamorphic rocks in particular often show negligible matrix permeability, although featuring a great variability of their hydraulic properties due to their joint system (Gustafson & Krásný 1994, Lachassagne et al. 2001). Characterizing the joint system that cuts these aquifers is fundamental to a good understanding of the dynamics of the groundwater that flows through them.

Joints are an important object of study in several Geology fields; they influence mineral deposition by guiding ore-forming fluids and provide fracture permeability for water, magma, geothermal fluids, oil and gas (Pollard & Aydin 1988). The present study focuses on joints as a possible path for groundwater flow. The term "joints" is here considered as fractures that show no discernible relative displacements; a concept presented by several authors (Hodgson 1961; Price 1966; Hancock 1985; Dunne & Hancock 1987; Ramsay & Huber 1987). Joints are considered as the most common result of brittle deformation (Pollard & Aydin 1988). The term "fault" is reserved to cases when kinematic indicators allow the determination of movement in the discontinuity surface. Thus, following the nomenclature adopted in this work, "fracture" would be the general term, that is, it could
refer either to a joint or a fault; however, its use is restrained in this text in order to avoid misunderstandings regarding the discontinuities types. Additional useful definitions are found on Appendix 1.

This project was conducted in relation with a regional groundwater mapping program in the Saguenay – Lac-Saint-Jean (SLSJ) region, as part of the Programme d’acquisition de connaissances sur les eaux souterraines du Québec (PACES). PACES projects require the development of tools and approaches that allow a proper characterization of different aquifer types in Quebec, including the ones constituted by fractured rock units. Although Canada has only 0.5% of the world’s population (23.6% are in Quebec Province), its lands comprise about 7% of the world’s renewable water supply, and 3% are in Quebec alone (MDDEP 2000; Statistics Canada 2011; Environment Canada 2012).

The present work consists in a structural survey and the characterization of a fractured crystalline rock aquifer in the Kenogami uplands, within the SLSJ region (Fig. 1.1). In the SLSJ area, 27.9% of the population relies on aquifers for water supply, of which around 32% is obtained by private wells (MDDEP 2000).

The Kenogami uplands area (Fig. 1.1) forms a relative transverse topographic highground within the Phanerozoic Saguenay graben, in meridional Quebec, and are considered one recharge area for groundwater that flows toward the lowlands. The uplands correspond to a surface area of approximately 1,300km². Its crystalline rocks are relatively homogeneous, composed mainly of anorthosite, and also constitute a potential crystalline fractured rock aquifer. Two other points in favor of the selected area are: (1) the considerably large number of outcrops, especially in the southern part, and many of them located in roadcuts and quarries; and (2) the little number of studies of fractured crystalline
rock aquifers in Quebec, even though many important water supply reservoirs in the world are located in fractured media (Masoud & Koike 2006).

**Fig. 1.1** The Kenogami uplands (bottom) are located within the Saguenay-Lac-Saint-Jean region (top right). The study area is located within Quebec Province, Canada (top left). Top left image: adapted from Natural Ressources Canada (1999); top right and bottom images: adapted from Walter et al. (2010).

**1.1 Objectives**

The aim of the present work was to answer the following questions regarding the Kenogami uplands region:
1) Is there a structured joint system in the bedrock, that is, is it possible to identify preferential joint orientations and structural domains?

2) Can joint systems be defined at different scales, e.g. regional and local ones? If yes, are there any relationships between the systems observed at different scales?

3) Can any correlation between the joint system(s) and the past and present stress fields be identified?

4) Is there a relationship between the hydrogeological properties obtained from boreholes and the joint system(s)?

Once the questions above were answered, the objective was to develop a conceptual hydrogeological model of the bedrock aquifer in the Kenogami uplands, based on structural and hydrogeological data, coupling them with information of the present stress field, that is, its influence over the hydrogeological properties.

The importance of this kind of study relies on its utility on water resource management, a clearly important issue in Quebec (MDDEP 2000; Environment Canada 2012). Once the dynamic of the aquifer is well characterized, it allows a better development of plans of use and preservation of the water resource, preventing its overexploitation. Moreover, in the case of an anthropogenic contamination, knowing how the aquifer behaves contributes to predict the migration of the contaminant, e.g. to determine the wells or discharge points that will be affected by the contamination and at what time.

The bibliographic synthesis presented in chapter 2 covers a great range of possible approaches for studying fractured aquifers. The present project aimed to combine strong points of the methodologies described (e.g. lineament analysis, geophysical logging, detailed structural surveys, analysis of the relative ages of tectonic events) and to characterize a fractured crystalline rock aquifer on the basis of a unit block, which
represents the true joint distribution in the fractured media, as opposed to the observed one. A tectonic study was also carried on, where some of the stress fields responsible for generating the joint systems that constitute the Kenogami uplands were deduced by the study of the interactions between the joints. This kind of information is important because the tectonic events control the joint characteristics (connectivity, aperture, density, orientation), which control groundwater flow. The methods chosen shall provide greater precision and reliability to the conceptual model developed.

Publications related to the development of this work are: Pino et al. (2010; 2011a, b; 2012a, b) and Roy et al. (2011).
REVIEW OF PREVIOUS WORKS ON FRACTURED AQUIFERS

A discussion on the application of structural data for modeling fractured aquifers is presented in this chapter. The idea of using structural geology information for groundwater studies was already present in the 1980’s work, though it only became a more common practice in the late 1990’s. The survey approaches presented in this chapter do not intend to be exhaustive. Instead, selected previous works at various scales of observation are discussed, with special attention to the following aspects: the tectonic history and structural domains, the current stress field, and the relationship between hydrogeological properties and the structural domains. Finally, some categories of numerical modeling of fractured rock aquifers are presented.

2.1 Structural and hydrogeological surveys

The relevance of structural geology studies in hydrogeology relies on the importance of fractured rock aquifers to water supply; understanding the dynamics of groundwater flow in such systems highly depends on a good characterization of its joint systems and of the effects of faulting and folding events on them. The present work focuses on the effects of brittle deformation on fractured crystalline rock aquifers.
2.1.1 Scale of observation of the discontinuity systems

Different observation scales may influence the development of models of water flow through a fractured media, as different hydraulic properties might be estimated for the same system. Additionally, features that do not show up in a local scale may be of importance at a regional scale, or vice-versa. Structural observations made at different scales must be correlated in order to obtain a coherent model.

A suggested procedure to improve structural data collection, particularly with geophysical method, is the "top down" approach (Robinson et al. 2008), in which the survey begins with the smaller scale (e.g. airborne surveys for dominant structures) and goes to local logging. This is a commonly adopted methodology in regional hydrogeological studies.

The occurrence of scale effects of hydraulic properties of fractured rock aquifers has already been attributed to inhomogeneities of the rock (Gustafson & Krásný 1994). The variability of properties within the aquifer is supposed to be smaller for smaller scales; so that at a regional scale, a fractured aquifer might be considered approximately uniform (Gustafson & Krásný 1994; Nastev et al. 2004) (see section 2.2 for the equivalent porous media approach).

The absolute value of certain aquifer properties, e.g. hydraulic conductivity, was also demonstrated to be affected by the scale of measurement (Rouleau et al. 1996, Nastev et al. 2004). Hydraulic tests in fractured orthoquartzites have shown that hydraulic conductivity increases with the size of investigated volume, indicating a good connectivity of the discontinuities responsible for flow in the scales considered (Rouleau et al. 1996). When considering heterogeneous rock aquifers characterized by intermittent densely and sparsely fractured zones, large scale measurements tended to yield lower hydraulic
conductivities than small scale hydraulic tests (Nastev et al. 2004). This effect was attributed to the fact that small scale tests measure hydraulic conductivities over larger aquifer volumes, hence being more likely to encounter highly interconnected fractured zones and preferential flow paths (Nastev et al. 2004). It has also been considered that the scale effect may be a result of the aquifer heterogeneity and the spatial distribution of measurements (Nastev et al. 2004). These findings emphasize the importance of characterizing an aquifer in different scales, for a better appreciation of fracture-matrix interactions and of flow and transport processes.

Another interesting observation regarding well specific capacities in boreholes and scale effects is that wells located in lineaments parallel to extensional joints are usually more productive, though such interpretation may vary with the scale of the lineaments (Fernandes et al. 2007; Fernandes 2008).

2.1.2 Detection of structures by remote sensing

Remote sensing allows the identification of surface features, such as lineaments and potential outcrops for fieldwork, as it will be discussed in section 4.1 below.

Stereo aerial photographs may be used for structural analysis and for creating an inventory of hydrogeological features in a study area (Kresic 1995). The analysis of surface features often reveals the existence of structural discontinuities, which may influence groundwater flow. Likewise, satellite imagery may be used to detect lineaments and other major structures (Masoud & Koike 2006). These methods may be applied to different geological settings, e.g. karstic environments (Kresic 1995), fractured basalts (Fernandes & Rudolph 2001) and sedimentary aquifers in compression zones (Odeh et al. 2009). Remote sensing and geographic information systems are particularly useful for
correlating structural data with information on hydraulic properties distribution (Masoud & Koike 2006; Fernandes 2008), groundwater flow and chemistry (Odeh et al. 2009).

Overall, the importance of studying joints and well defined lineaments relies not only on the fact that they are indispensable elements of regional and local tectonic analyses, but also they provide insights into various fields, such as environmental geology and natural resource exploitation.

2.1.3 Geophysical surveys

Geophysical surveys provide valuable subsurface data, which should be combined with the surface data acquired on outcrops, allowing a 3D description of fractured aquifers. Not only these surveys may be useful to identify trends and recurrent patterns in physical characteristics, but also some of them yield direct information on the joint system or on its role within the aquifer.

The hydrogeological characterization of a fractured aquifer has been qualified a "challenging task" (Morin et al. 2007), as underlined by many examples in this chapter. The frequently suggested helpful methodologies for determining hydrogeologic properties of fractured aquifers include: geophysical loggings, geological mapping, rock core descriptions and pumping tests, with particular interest for geophysical logging for identifying trends in the hydrogeological characteristics of the aquifer (Morin et al. 2007; Robinson et al. 2008; Francese et al. 2009).

In geophysical loggings in boreholes, many probes may be used; some of the most recurrent are: fluid temperature and conductance, flowmeter, caliper, acoustic televiwer (ATV), natural gamma, rock resistivity and electrical resistivity (Morin et al. 1997, 2007) (see section 4.2.2 for information these probes provide to structural and hydrogeological
studies). In the case of fractured aquifers, the ATV is particularly interesting, as it provides information of joint orientation and dip at depth. Discussions regarding this method began in the late 1980's (Lau et al. 1987, 1988; Cruden 1988). Although the technology was relatively new at that time, it has been proved to be significantly efficient, as shown by later works (Morin et al. 1988, 1997, 2007).

Surface-geophysical survey methods are also useful for locating and determining the orientation of fractured zones in the bedrock (Degnan et al. 2004). An example is the coupling of geophysical (e.g. ground penetrating radar and resistivity profile) and surface structural analyses with the monitoring of water level to characterize the joint system of an aquifer and its water flow (Degnan et al. 2004). Other geophysical methods that improve the identification of subsurface structures – and, thus, of potential water flow paths – are the electric, magnetic and gravity (Grauch et al. 1999; Robinson et al. 2008). However, some regional scale methods, such as the airborne surveys (Grauch et al. 1999; Robinson et al. 2008), are usually part of larger and governmental projects due to their high cost, not always related to geological surveys, although they may be used in the studies such as the ones discussed here.

Successful examples of geophysical methods applied to study fractured rock aquifers may be found in many locations, such as: in Nevada, USA (Morin et al. 1988), in New Jersey, USA (Morin et al. 1997), near the frontier between Canada and United States (Morin et al. 2007), and in the Apennines, Italy (Francese et al. 2009).

In Nevada, USA, the combination of data obtained with ATV and fluid injection in boreholes allowed to quantitatively estimate the hydraulic conductivity across discrete intervals in the aquifer (Morin et al. 1988).
In an aquifer in central New Jersey, USA, two principal joint sets were identified in an apparently complex and heterogeneous fractured media (Morin et al. 1997). Likewise, the most transmissive joints in the population were distinguished using different geophysical logs: fluid temperature and conductance, flowmeter, caliper, ATV, natural gamma, rock resistivity and electrical resistivity (see also section 4.2.2).

In the Quebec portion of the Châteauguay River Basin, there was a general agreement between joint data from the geophysical logs and the observations in outcrops and quarries, as well as for the elastic properties and stress models associated (Morin et al. 2007). The probes used during the loggings were: caliper, natural gamma activity, sonic profile, ATV and flowmeter; pumping tests were also performed (Morin et al. 2007).

The local aquifers in the Apennines, Italy, are generally constituted by thinly-fractured reservoirs, often within low permeability formations (Francese et al. 2009). They were studied through an integrated multiscale approach, focusing on the definition of the geometry of brittle structures (Francese et al. 2009). The data analyzed included surface geology, with particular interest to joints and faults geometry, well productivity and surface geophysical surveys (ground penetrating radar and earth resistivity tomography) that allow the identification of geological structures in the subsurface. It is relevant to notice that there was a general good agreement between geological and geophysical data (Francese et al. 2009), which indicates that such merging of information is effective to define a good structural model of a study area.

2.1.4 Joint connectivity

The quantity of groundwater flow through low permeability rocks depends on the density, connectivity and aperture of the existing joints (Domenico & Schwartz 1990). A
higher degree of joint connectivity characterizes a media where most of the joints intercept each other, creating many possible paths for fluid flow. The importance of joint connectivity is clear, and defining this parameter is a frequently mentioned step in the development of hydrogeological models (Francese et al. 2009; Singhal & Gupta 2010).

An interconnectivity index was proposed to describe the degree of interconnection between two fracture sets (Rouleau & Gale 1985), considering the values of: the mean trace length $l$ and the average spacing $s$ for each joint set; and the average angle $\gamma$ between the joint sets (Fig. 2.1). This index was suggested during the structural and hydrogeological characterization studies in granitic rocks in Sweden.

The connectivity and density of joints has a clear effect on groundwater flow, influencing the values of hydraulic conductivity. These parameters will play an important role at different scales (Fernandes 2008, Francese et al. 2009).

Fig. 2.1 Calculating the joint interconnectivity index. Source: Rouleau & Gale (1985).
2.1.5 Tectonic history and structural domains

One or more tectonic events can be responsible for generating a joint system in a given area. The occurrence of one or more systems, as well as their possible groupings, allows the definition of one or more structural domains, each of which is characterized by a common tectonic history. A structural domain would tend to present its own hydraulic properties as well, due exactly to the distinct joint systems and history that formed them. Structural domains will clearly influence the groundwater flow, and therefore it is essential to characterize them properly during the study of a fractured rock aquifer. Nonetheless, a proper characterization of a structural domain requires a good understanding of the relationships among its joint sets and other existing structures.

When analyzing structural populations on joint pole density diagrams, the identification of patterns may be challenging. A statistical method was proposed in order to evaluate the presence of patterns, taking into account a contingency table analysis based on the frequencies of joint poles observed in corresponding parts of stereoplots being compared (Miller 1983). This allows the grouping of homogeneous structural domains. It is important to define correctly the structural domains during hydrogeological studies, as the corresponding hydrologic properties may vary from one domain to another (Miller 1983).

Studying various cases of joint interactions (Fig. 2.2) and their relationships with the stress field that generated them help to define a structural domain and its tectonic history (Pollard & Aydin 1988). Intersections are an essential element of the interpretation of joint patterns, as well as joint continuity, sequence of development and propagation direction at intersections (Pollard & Aydin 1988). This type of data is of extreme relevance for retracing the tectonic events responsible for the joint sets in a region, since they provide information
regarding relative ages and conjugate pairs of joints (Stearns 1969), as well as past stress field orientation. Joints are thought to be commonly initiated at material inhomogeneities (e.g. fossils, grains, clasts, pores, sole marks, microcracks), which concentrate local tensile stresses due to the compression of the rock mass (Pollard & Aydin 1988). Finally, by determining the relative ages of joints and other structures (such as faults, veins and dykes), it is possible to identify different phases of brittle deformation during the geologic time (Pollard & Aydin 1988).

In the case of orthogonal joints (Rives et al. 1994), it is suggested that a less continuous joint set might be the result of: (1) a stress change due to the development of
the first set, (2) tectonic stress reversals, (3) post-tectonic relaxation effects or (4) a new stress event. The case of mutual abutments in an orthogonal network of joint sets may be due to the presence of a tensile stress in the late stage of joint development or to successive reversals between the medium and the minimal stress field components ($\sigma_2$ and $\sigma_3$, respectively) (Rives et al. 1994).

Slikensides (Appendix 1) are another feature that may provide interesting information on regional structural characterization surveys and help to reconstruct the tectonic history of the study area, as they are parallel to the movement along faults (Tjia 1964; Angelier 1979). They are commonly associated to steps on the fault wall (Appendix 1), being strongly oblique to them, which help to infer the sense of movement on the wall. When no infilling or mineral growth is observed on the wall, the motion is contrary to the steps; if there is infilling or mineral growth on the fault wall, the motion is on the same sense as the step. Tjia (1964) uses the position of the mineral grain on the slickensides to prove the latter relationship (Appendix 1).

Another important observation regarding the tectonic history of a region is that the most recent events would have the most significant influence on the aperture of the joints in the system and, therefore, on the regional groundwater flow (Fernandes & Rudolph 2001; Zeeb et al. 2010). This remark is based on the role of in situ stress on joint aperture, which is important for rock hydraulic conductivity (Fernandes & Rudolph 2001) and should be considered within the joint system characteristics for fractured aquifer studies (Zeeb et al. 2010). Such consideration is fairly reasonable, as even a very small aperture, with less than 0.1mm, is of relevance for water flow. Moreover, hydraulic conductivity of a joint system in a rock mass is related to the cube of the joint aperture (Snow 1968, 1969) by the following equation:
In Eq. 2.1, $K$ is the hydraulic conductivity [m/s], $2b$ is joint aperture [m], $W$ is joint true spacing [m] (calculated after Terzaghi's correction; Terzaghi 1965), $\rho$ is the fluid density [kg/m$^3$], $g$ is gravity acceleration [m/s$^2$] and $\mu$ is the dynamic viscosity of the fluid [Pa.s]. When only one joint is considered, Eq. 2.1 may be rewritten as:

$$K = \frac{(2b)^2 \rho g}{W \cdot 12\mu} \quad \text{(Eq. 2.2)}$$

2.1.6 Current stress field

As discussed above, the orientation of the past stress fields determines the orientation of the joint sets and major structures such as faults. The current stress field, by its turn, has great influence on the opening or closing of joints, according to the orientation of the stress field components regarding the orientations of pre-existing joints. Therefore, the present stress field plays an important role in determining the most transmissive joints.

Numerical models are an interesting approach to study the effects of the present stress field on the joint system of a fractured rock aquifer. Examples may include, a three dimensional finite element simulation of the stress field, considering the effect of the mean principal stress and the direct effect of the deviatoric stress tensor on joint planes (Gaudreault et al. 1994) or even quantifying the closure of joints with depth when the joint system is submitted to a given stress regime (Mortimer et al. 2011a, b). Another example of numerical method is the analysis of the present-day stress field and dilatation tendencies to estimate the probable orientations and relative transmissivities of conductive joints (Mattila & Tammisto 2012). A drawback to the latter method is that it requires the
knowledge of the full stress field tensor and not simply a two-dimensional approximation of the stress components.

The orientation of a joint set with respect to the main components of the present stress field will affect its hydraulic properties (Gaudreault et al. 1994), as the orientation of the stress field controls the current opening or closing of joints, and hence, their transmissivity (Barton et al. 1995; Morin & Savage 2003; Fernandes 2008). The possible effects of the present stress field on a given joint set have been classified in three main cases (Gaudreault et al. 1994): (1) closure with σ₁ almost perpendicular to the discontinuity plane; (2) opening with σ₃ nearly perpendicular to the joint plane; (3) shearing with σ₁ at an intermediate angle (between 30° and 60°) with the discontinuity plane.

2.1.7 Relationships between hydrogeological properties and structural domains

Studying the role of major tectonic structures is valuable for well location, evaluating groundwater use, its management and contaminant control (Apaydin 2010). This section presents a discussion on the possible relationships between lineaments (which may be considered as a surface expression of a geological structure) and hydrogeological aspects (such as well productivity and rock permeability).

Well productivity

Analyzing lineaments is an indirect way of evaluating the influence of joints in well production (Fernandes & Rudolph 2001; Fernandes et al. 2007; among others). When correlating the production of wells and the factors that induce the groundwater flow, it is important to evaluate the influence of factors such as: tectonic history and current stress field of the region, proximity of the wells to lineaments, nature and thickness of the
unconsolidated material, lithology, topography and depth of inflow into the well (Fernandes 2008). This, as a first approach, may provide important information for the understanding of the hydraulic properties of fractured aquifers (Fernandes 2008) and also homogeneous geologic blocks (Fernandes et al. 2007). It is then interesting to compare it with some lineament aspects, such as density, connectivity and structural trends, as well as to analyze the well productivity in relation with their proximity to lineaments (Fernandes & Rudolph 2001). Well productivity may be assessed by values of specific capacity, which indicates the aquifer potential more directly than the simple pumping rate, though the productivity might be influenced by well construction aspects (Fernandes et al. 2007). Although sometimes the most productive wells tend to be in the highly fractured domains (e.g. Sultan et al. 2008), some studies concluded the contrary, that is, the most productive wells are not in the areas with higher density of lineaments (e.g. Madrucci 2004). Therefore, a causal relationship between lineaments and most productive wells should not be automatically assumed, particularly because not all lineaments represent conduits for water flow, as discussed in the section below.

**Lineaments as flow barriers or conduits**

Faults, fracture zones and shear zones (all may appear as lineaments in a map) are usually considered as preferential conduits for groundwater flow; however, they may also act as barriers to groundwater, due to the configuration between fault core and damage zone at the fault zone (Francese et al. 2009; Gleeson & Novakowski 2009; Apaydin 2010). The fault core is the portion where most of the displacement is accommodated, while the associated damage zone is mechanically related to the growth of the fault zone (Caine et al. 1996). Assuming that lineaments are conduits for groundwater is overly simplistic, and
characterizing the lineaments and/or the joint system is a very significant aspect of investigations on fractured aquifers (Gleeson & Novakowski 2009).

Evaluation schemes for permeability of fault-related structures, using field data, laboratory permeability measurements and numerical models of water flow near and within fault zones were developed in order to assess the role fault cores and fault damage zones play as barriers and conduits, respectively (Fig. 2.3; Caine et al. 1996). In crystalline rocks, the fault core (less permeable) and the associated damage zone (more permeable) tend to form an anisotropic structure that is a hydraulic conduit, a barrier or a conduit-barrier system, depending on their architecture and on the direction of the flow (Caine et al. 1996; Gleeson & Novakowski 2009). The behavior of the ensemble will be determined by the relative importance of fault core and damage zone structures, as well as by the lithology affected and its degree of weathering.

![Fault zone architectural components](image)

**Fig. 2.3** Conceptual model of a fault zone. The relative magnitude and bulk two-dimensional permeability tensor that may be associated to the components of the fault zone are shown on bottom right. After: Caine et al. (1996).
The permeability of faults also depends on their stage of development (UNESCO 1984; Tirén 1991; Caine et al. 1996); fault core materials may not always act as a barrier, especially during deformation (Caine et al. 1996). Nonetheless, damage zones are usually better conduits as compared to the fault core and the protolith (Fig. 2.3; Caine et al. 1996): a damage zone may have permeability values that are three to four orders of magnitude higher than a fault core, while an undeformed fractured rock would present intermediate values (Evans et al. 1997).

2.2 Mathematical and numerical models of fractured aquifers

Some of the models of fractured aquifers proposed in the literature are grouped here according to porosity type. This criterion allows distinguishing models of fracture network with impermeable matrix, double porosity (discussed jointly with models based on unit blocks\(^1\)) and equivalent porous media (discussed jointly with the permeability tensor approach). Finally, some possibilities of integrating the numerical models of fractured aquifers with data of an in situ stress field are presented. Regardless of the model that is considered, Neuman (2005) states that it is truly important to treat a fractured aquifer considering the “highly erratic heterogeneity, directional dependence, dual or multicomponent nature and multiscale behavior of fractured rocks”.

2.2.1 Models of impermeable matrix and the discrete joint network approach

Most of the discrete joint network models consider the rock matrix as impermeable, that is, only the secondary porosity is taken into account (Neuman 2005). The discrete joint network model allows the estimation of the fluid flow velocity within the joints and might

\(^1\) A unit block is a basic structural unit that defines a fractured rock mass. See section 4.3.4 for detailed definition of the unit block.
represent either small or relatively large networks. The small networks usually comprise one to ten joints, so the application of a deterministic method is feasible, in which the position of joints is known (e.g. Tezuka & Watanabe 2000; Selroos et al. 2002). In the case of larger networks, a hundred or more joints are considered, which may be generated using a stochastic approach (e.g. Schwartz et al. 1983; Rouleau 1984; Rouleau & Gale 1987; Neuman 2005; Mortimer et al. 2011a).

The development of both the discrete fracture network model and the unit block are based on true (corrected) joint data. They differ with respect to joint connectivity: in the discrete network model, the joints are not necessarily connected, while in the unit block, the joints are assumed to be always connected. Nonetheless, compilations of distribution of the length of visible joint traces (for each of the main joint sets) on an observation face and the number of the observed intersections between the joint sets might aid to achieve a more reliable model.

2.2.2 Double porosity approach and models based on unit blocks

The concept of unit block was largely developed in the oil industry, starting in the 1970's and the 1980's, because it is fairly important to characterize the fluid flow on both joints and matrix of a reservoir, in order to consider possible fluid exchanges between these two reservoir components (Kazemi et al. 1969; Ghez & Janot 1974, Kazemi et al. 1976, Streltsova 1976; Aguilera & Poollen 1977; Boulton & Streltsova 1977; Gilman & Kazemi 1983; Sonier et al. 1988). These models are based on the double porosity approach, first proposed by Barenblatt et al. (1960) and Warren & Root (1963). These models consider both primary and secondary porosities.
Barenblatt et al. (1960) proposed an equation of hydraulic diffusivity (ratio between hydraulic transmissivity and storativity) in fractured rocks, describing a fractured media composed of porous blocks separated by fractures of infinite extent. Warren & Root (1963), on the other hand, applied an analytic method and cubic blocks (Fig. 2.4) to represent a given joint system, assuming that the primary porosity contributes significantly to the pore volume, but that it is negligible to the flow capacity.

![Fig. 2.4](image)

**Fig. 2.4** Relatively simple fracture networks used to be considered for modeling. They were an idealization of the heterogeneous media. Nowadays, models with more complex networks are available, as discussed in the text. Source: Warren & Root (1963).

Major flaws of the double porosity approach are the assumption of uniform matrix properties throughout the system and of a uniform, cubic joint network. Some solutions were later proposed: the development of parallelepiped unit blocks (Barker 1985) and the model of two separate sets of matrix properties (Abdssah & Ershaghi 1986). As the double porosity approach continued to be used (Almeida & Oliveira 1990; Dutra & Aziz 1992; Lough et al. 1997) and more recent works also discussed the flow through the matrix-
fracture interface (Zhang et al. 2006; Weatherill et al. 2008), the coupling of the unit block data with a double porosity model is here suggested as a possible way to integrate the structural data into a numerical model of fractured aquifers.

2.2.3 Equivalent porous media models and the permeability tensor

Models based on an “equivalent porous media” concept may be developed with the hydraulic conductivity tensor approach. In this case, it is possible to estimate the hydraulic conductivity tensor of the whole rock mass by summing the tensor calculated for each joint, using Eq. 2.2. The interesting point of this approach is that it takes into account the joint system characteristics, such as geometry and orientation. However, equivalent porous media models usually suppose that each joint is infinite, that is, each one crosses the entire analyzed zone, which is rarely realistic. Nonetheless, a case in British Columbia, Canada, has shown that equivalent porous media model may return valid results and be useful for characterizing and quantifying hydraulic properties of fractured rock aquifers at a regional scale (Surrete 2006). Structural domains were defined by using joint density data and modeling with a stochastic, discrete joint system of equivalent porous media (Fig. 2.5) (Surrete 2006). The results obtained are in accordance to data independently obtained in pumping tests in the same area (Surrete 2006). Other works that adopted the equivalent porous media approach include: Nastev et al. (2005), Chesnaux & Allen (2008) and Chesnaux et al. (2009), both in fractured sedimentary rocks. An interesting particularity of the latter two is that they use an impermeable matrix model with the discrete joint system approach to construct a hydraulic conductivity tensor that represents an equivalent porous

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2 The double porosity approach, however, is not advised for crystalline rock aquifers, given that their matrix permeability is much lower than the joint permeability, even though the matrix porosity is higher than joint porosity. A double porosity model is more interesting in the case of fractured sedimentary rock aquifers.
media. The authors also emphasize the contributions of modeling fractured rock aquifers to understand their behavior and to evaluate their exploitation.

**Fig. 2.5** Scheme based on the work of Surrete (2006) for generating a numerical model of a fractured aquifer by combining two different model approaches: equivalent porous media model and discrete fracture network. Adapted from: Surrete (2006).

The example from Fig. 2.5 uses a permeability tensor to develop the equivalent porous media model. This approach has long been discussed for homogeneous and anisotropic media (Bianchi & Snow 1968; Snow 1968, 1969, 1970; Rocha & Franciss 1977; Long *et al.* 1982; Oda 1985; Raven 1986). For illustration purposes, two of these studies of permeability tensors are further described.

Bianchi & Snow (1968) applied the theory proposed by Snow (1968) for analyzing the directional permeability of any fracture model, computing the permeability from fracture geometry (orientation and measured apertures). It is assumed that the contribution of all
fractures measured at a sampling site is given by the sum of all individual contributions, and so the equivalent permeability of the medium may be given by the average of values obtained for several sites.

Next, Oda (1985) argues that a joint system cannot be replaced by an equivalent porous media unless there are a sufficient number of joints in the representative elementary volume; that is, this model is subjected to the scale effect and it is, thus, more recommended for regional studies. When that is the case, the fractured rock mass can be treated as an equivalent homogeneous and anisotropic porous media. Although this representation does not consider the high velocity of fluid flow in the joints, it might be better designed by introducing a symmetric tensor (the "joint tensor") which relies only on the geometry (aperture, size and orientation) of the related joints (Oda 1985). The permeability tensor is defined as a unique function of the joint tensor (Oda 1985), and it yields valuable information: the degree of anisotropy in hydraulic response of rock masses, the principal axes of the permeability tensor and a quantitative comparison between rock masses.

2.2.4 The effect of an in situ stress field

Considering the three modeling approaches discussed above, it is also interesting to add to the model the effect of an in situ stress field. As previously discussed in this chapter, the present-day stress field has great control on joint aperture, and, consequently, on groundwater flow. A number of existing software codes are capable of simulating the effects of stress field on fluid flow through joints, such as the Universal Distinct Element Code (UDEC; Itasca™), used by several researchers (Fernandes & Rouleau 2008; Noël 2009; Mortimer et al. 2011a, b). It allows to capture, for instance, the closure of joints with
depth when the joint system is submitted to a given stress regime. Some works with UDEC models also tested the potential influence of a determined stress field on the permeability tensor of their model (Mortimer et al. 2011a, b). The deformed and undeformed models were compared through the estimation of two dimensional planar hydraulic conductivity ellipses at different depths, in order to also take into account the effect of decreasing joint densities. Studies on the effect of normal stresses to individual joint planes in a discrete joint network can also be found (e.g. Grégoire 1988).

2.3 Final considerations

In brief, all of these previous studies underline the importance of structural hydrogeology. Proper characterization of the structural discontinuities is essential for a good understanding of the aquifers in fractured media, either for academic purposes or for water management. The previous sections presented investigation methods that lead to the development of conceptual models of an aquifer, as well as different possibilities of numerical models for groundwater flow in a fractured media.

Some of the works that were reviewed discuss the effects of scale of observation on hydraulic properties. The present work shall analyze structural geology data at different scales in order to determine if they may really be compared. The hydraulic properties of the Kenogami uplands discussed in chapter 6 come from a regional study, which applied an analytic model of groundwater flow (Chesnaux [accepted]).

The use of remote sensing is widely accepted among researchers to identify regional structures, as previously seen. Given the data available, this project used aerial photographs to identify lineaments and major outcrops.
Regarding geophysical logging, some of the techniques proposed were adopted (e.g. the ones by Morin et al. 1997). Geophysical logging shall be used here as a complement to surface structural survey, and not as the main source of data, unlike many of the works described above.

Although the joint interconnectivity index was not quantified for the Kenogami uplands, the relationships among joints were studied in order to infer the orientation of the main component of past stress fields (much like Pollard & Aydin 1988). This approach helps to understand tectonic history of the region. The relations between joints were analyzed at the outcrop scale and data from the different observation sites were later combined. A detailed approach for this particular study is also described.

One of the objectives of identifying the past stress fields is to define the most recent one, and for that, it is important to know the tectonic history of the studied region. A compilation of the current regional stress field data both in the SLSJ area and surrounding areas in southeastern Canada is further presented.

Finally, in the present work, hydrogeological properties from the Kenogami uplands are related to the unit block, considered as the basic unit that characterizes a fractured media, as described in upcoming chapters.
GEOLGY AND HYDROGEOLOGY OF THE STUDY AREA

The bedrock geology in Quebec is divided in three large regions: the Canadian Shield, the Saint-Lawrence Platform and the Appalachian Orogen (Fig. 3.1). The Canadian Shield is divided in four geological provinces, according to deformation style and age: Grenville, Superior, Rae and Nain (Fig. 3.1). As the study area is located in the Canadian Shield, in the Grenville Province, attention will be focused on this Province.

3.1 The Grenville Province

The Canadian Shield was formed between 2850 and 850Ma and covers 90% of the Quebec province (Hocq 1994). The Grenville Province is located in the southeastern part of the Shield, and is characterised by a generally high metamorphic degree and by a large quantity of magmatic rocks crystallized at high temperatures, such as mangerite and anorthosite (Tollo et al. 2004). Three lithotectonic zones subdivide the province (Rivers et al. 1989): Paraautochthonous Belt, Allochthonous Polycyclic Belt and Allochthonous Monocyclic Belt (Fig. 3.2). The tectonic boundaries between them are (Rivers et al. 1989): Grenville Front, Allochthon Boundary Thrust and Monocyclic Belt Boundary Zone (Fig. 3.2).
Fig. 3.1 Geological provinces in Quebec. The area of the present study is located in the Grenville Province, near Chicoutimi city. Adapted from: Roy et al. (2006).
The Grenville Province constitutes the youngest orogenic belt in the Canadian Shield (Tollo et al. 2004). Its multiple episodes of orogenesis were recognized in the 1970’s (e.g. Wynne-Edwards 1972; Moore & Thompson 1980).

3.2 The Kenogami uplands

The Kenogami uplands, the area of the present study, are sometimes referred to as "Kenogami horst", a name probably first proposed by Blanchard (1953). However, a horst is defined as "an elongate uplifted block bounded by faults on its long side" (USGS 2010). Therefore, the expression "Kenogami horst" is a misuse of the term, since the
discontinuities that delimitate these uplands on their “long side” (east and west sides) are major regional lineaments, with no faults being identified until the present day. Nonetheless, as these lands clearly constitute a subregional topographic high, they will be referred to as Kenogami uplands.

The Kenogami uplands are located in the center of the Saguenay graben (Fig 3.3). The southern and northern walls of the graben are parallel to the WNW-ESE trend of the end of the Grenvillian orogeny. This orientation is also reflected in other regional structures, such as the Ottawa graben (Kumarapeli 1981; Rimando & Benn 2005) and the transform faults in both Canada and United States (Kumarapeli 1970; Thomas 1991).

Fig. 3.3 Topography and approximate delimitation (red dashed line) of the Kenogami uplands. Adapted from: Walter et al. (2010).
The Kenogami uplands are limited to the south and to the north by the Kenogami and the Tchitogama Lakes, respectively (Fig. 3.3). Their western and eastern limits are not defined by known faults, but by major lineaments: the western side appears as a continuation of the lineament suggested by the trend of Peribonka River located to the north (Fig. 3.3); the eastern side could correspond to the lineament suggested by the Gélinas bay (in the Kenogami Lake) to the south, which is in line with the La Motte Lake to the north of the graben (Fig. 3.3). These regional linear structures were already identified in the maps presented by Lasalle & Tremblay (1978). It is also interesting to notice that Woussen et al. (1988) present a map from the SLSJ area with a shear zone oriented approximately N-S that is near the western limit of the Kenogami uplands considered in this work; those structures may be related, even though this shear zone was not identified in the field in the present study.

Other important regional brittle structures to the west of the Kenogami uplands are oriented NNW and NNE. Such structures are in continuation with the Hudson-Champlain lineament (in the USA), prolonged to Quebec by the Richelieu and Saint-Maurice Rivers axes (Kumarapeli & Saull 1966; Isachsen 1989). The main regional structures are completed by the ones oriented NE-SW, parallel to ductile shear zones and to the Saint-Lawrence and the Appalachian axes, and by some NW-SE structures. They also follow the Late Precambrian – Early Paleozoic trend of rift segments in the Iapetus Ocean described by Thomas (1991).

The study area is mainly composed of anorthosite (Fig. 3.4), from the large Lac-Saint-Jean Anorthosite massif (LSJ Anorthosite). Exposures of granitic rocks and of syenite, monzonite, granodiorite and diorite can also be found in the northwest and northeast
Fig. 3.4 Bedrock geology of the Saguenay region, showing the location of the visited outcrops and the three wells submitted to geophysical logging. Geological map source: Avramtchev (1993).

portions of the Kenogami uplands (Fig. 3.4). The LSJ Anorthosite, covering more than 20,000 km$^2$, is one of the largest anorthosite massifs of the world (Dimroth et al. 1981).

3.3 Tectonic history

The oldest geologic events identified in the Saguenay area occurred between 1900 and 1000Ma (Stockwell 1962; Dimroth et al. 1981; Hébert 2004; Roy et al. 2006). This period corresponds approximately to the formation of the oldest worldwide orogenic belts and of the amalgamation and dispersion of the supercontinent Columbia3 (Santosh et al. 2009). Paragneisses, granitic gneisses and amphibolites were the first rocks emplaced in the study area, around 1800Ma, being intruded later by other granitic and amphibolite dykes (Dimroth et al. 1981). This sequence is locally known as Chicoutimi Gneiss Complex (Woussen et al. 1981). It was folded and metamorphosed around 1700±150Ma, during the Hudsonian Orogeny (Stockwell 1962), after which voluminous sheets, dykes, and stocks of granite were put in place. The Chicoutimi Gneiss Complex is nowadays in tectonic contact with the LSJ Anorthosite (Hébert & van Breemen 2004). Some works discuss the origins and ages of this granitic bedrock; e.g. Hervet (1986), Dickin & Higgins (1992), Hervet et al. (1994).

The Grenvillian Orogeny occurred between 1190 and 980Ma, and it comprises three clear pulses of NW-directed crustal shortening (Rivers 1997): 1190-1140Ma, 1080-1020Ma and 1000-850Ma (Table 3.1). This thrust orientation is largely acknowledged in literature, as summarized by Tollo et al. (2004). The periods of crustal extension that separated these three pulses were coeval with the emplacement of intrusions of

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3 The supercontinent Nuna refers to the Paleozoic amalgamation of North American terrains, that is, the portion of Columbia that corresponds to the nowadays North America (Hoffman 1989).
Table 3.1 Summary of the main magmatic and tectonic events in the Grenville Province, focusing in the SLSJ region, in the period 1200-850Ma. $D_1$, $S_1$, and $P_1$ indicate, respectively, deformation, foliation and folds generated during a tectonic event.

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<td>1</td>
<td>1160-1140Ma 7 ages of AMCG</td>
<td>1190-1140Ma Deformation and metamorphism in terrains in the Ontario area</td>
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<td>Emplacement and largely synchronous deformation</td>
<td>$D_1$: thrusting E-W</td>
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<td>$S_1$: E-W to ESE-WNW oriented, usually moderately dipping to N.</td>
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<td>2</td>
<td>1082-1050Ma 6 ages of AMCG</td>
<td>1080-1020Ma Thrust of terrains in Ontario area</td>
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<td></td>
<td>Predominance of strike-slip faulting</td>
<td>Crustal thickening in the Mauricie region to the southwest of the SLSJ area</td>
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<td>$D_2$: NE-SW shear zone in Saint Fulgence, non-co-axial deformation with NE-SW dextral strike-slip motions; affects the LSJ Anorthosite early $D_2$: thrusting late $D_2$ (after collision): strike-slip movement</td>
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<td>$S_2$: NE-SW foliation, often dominant and penetrative</td>
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<td>$P_2$: open to tight, with plunge parallel to the stretching lineation</td>
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<td>3</td>
<td>1020-1010Ma 5 ages of AMCG</td>
<td>1000-850 Thrusting closer to the Grenville Front</td>
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<tr>
<td></td>
<td></td>
<td>Crustal thickening in the Ontario area</td>
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<td></td>
<td>$D_3$: NNW brittle-ductile faults, non-co-axial deformation; sinistral slip en echelon</td>
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anorthosite, mangerite, charnockite and gabbro (AMCG) across the whole Grenville Province, guided by the shear zones previously and simultaneously formed (Higgins & van Breemen 1996; Rivers 1997; Higgins et al. 2002). A fourth period of AMCG magmatism is also recognized (1327±16Ma), although neither deformational nor tectonic events were
particularly related to it yet (Higgins & van Breemen 1996; Rivers 1997; Higgins et al. 2002).

The NW oriented thrusting in the Grenville Orogen resulted in penetrative deformation (Corrigan & Hanmer 1997), while the final emplacement of solid anorthosite at the present crustal level resulted in local superposed structures. The nature of the process of gravitational ascent of the LSJ Anorthosite through the lower crust remains uncertain, despite proposed hypothesis (Dimroth et al. 1981; Woussen et al. 1981; Rivers 1997, Duchesne et al. 1999). The principal tectonic and magmatic events from the Grenvillian Orogeny are summarized in Table 3.1 and are discussed in the following paragraphs, presenting both the Grenville Province and the SLSJ's aspects.

The first phase of crustal shortening (1190-1140Ma) in the Grenville Province is reflected in the deformation and the metamorphism of the Central Mineral Belt and Parry Sound terrane, in the Ontario region (Rivers 1997). Later, between 1080-1020Ma, these two land masses were emplaced by thrust over the Central Gneiss Belt, also in the Ontario area (Rivers 1997). From this period, an event of crustal thickening was dated at ~1062Ma in the Mauricie region, about 150km south of the LSJ area. Finally, the last phase (1000-850Ma) was characterized by a change in the locus of the thrusting, closer to the Grenville Front (Fig. 3.2; Krogh 1994; Rivers 1997) and by a later extension between 990 and 950Ma in the Central Mineral Belt and the Central Gneiss Belt (Rivers 1997).

More particularly in the SLSJ region, three main events of ductile deformation (Table 3.1) are identified (Hébert 2004; Hébert & van Breemen 2004; Roy et al. 2006). The first event is related to a major period of thrust E-W to ESE-WNW, to which can be associated a foliation or a gneissosity (Hébert 2004; Hébert & van Breemen 2004) imprinted over a magmatic bedding (which was described by Woussen et al. 1988). The characteristics of
this first fabric were strongly deformed by the second event, which is associated to a period of ductile shear oriented ENE-WSW (Hébert 2004; Hébert & van Breemen 2004). The foliation then formed is recognized throughout the SLSJ and it is usually the dominant one (Hébert & van Breemen 2004). Finally, the third event is related to the formation of NNW-SSE brittle-ductile fault zones, really common in the SLSJ (Hébert 2004; Hébert & van Breemen 2004). These fault zones induced sinistral *en echelon* slipping, originating shifts of dozens of meters; e.g. in the contact of the anorthosite with the bedrock in the Kenogami Lake area (Hébert & Lacoste 1998).

A compilation of U-Pb data regarding the SLSJ region (Higgins & van Breemen 1996) proposed three phases of its Mesoproterozoic magmatism: 1160-1140Ma, 1082-1050Ma and 1020-1010Ma (Table 3.1). The first two phases are also correlated to magmatism elsewhere in the Grenville Province (Higgins & van Breemen 1996).

The first phase of magmatism is defined by seven age estimates obtained for the AMCG suites, including the one from the LSJ Anorthosite massif (1156Ma; Higgins & van Breemen 1992). Its early stages were coeval with strike-slip faulting (Higgins & van Breemen 1992, 1996), which is suggested as the upward magma motion mechanism. Both anorthosite and gneiss terrains were plastically deformed in the first phases of ascent; as temperature decreased in the anorthosite, the deformation concentrated in ductile deformation zones (Dimroth *et al*. 1981). The faults generated later guided intrusions of ferrodiorite and leucotroctolite in the anorthosite (Higgins & van Breemen 1992, 1996; Hervet *et al*. 1994). It has been indicated that the Ontario sector of the Grenville Province went under a period of magmatism without anorthosite between 1160-1140Ma (Van Breemen & Davidson 1988; Marcantonio *et al*. 1990), while there was a widespread AMCG magmatism elsewhere in the Province (e.g. McLelland & Chiarenzelli 1990; Doig
1991; Higgins & van Breemen 1992). Nonetheless, it has been affirmed that there is no evidence of collision-type orogeny in the SLSJ region in the period 1160-1010Ma, like thrusting, calc-alkaline magmatism or true regional metamorphism (Higgins & van Breemen 1996).

During the period 1082-1050Ma (Table 3.1), the AMCG magmatism was widespread in the Grenville Province (Higgins & van Breemen 1996). Strike-slip faulting was predominant (Hervet et al. 1994), except for the Ontario region, submitted to compression (Higgins & van Breemen 1996).

The last period of AMCG magmatism activity in the SLSJ (1020-1010Ma) seems to be absent in the rest of the Grenville Province, except for later smaller plutons in the Labrador region (Gower et al. 1991).

Around 1000Ma, the supercontinent Rodinia was completely assembled, with the completion of the break-up of Columbia (Santosh et al. 2009). The formation of Rodinia is related to the consuming plate boundaries that dominated the site of Grenvillian Orogeny, especially at collisional belts. The Grenville Orogeny ended with the emplacement of the last igneous masses and their crystallization at their present level, with the development of ductile shear zones (oriented NNE, ESE and ENE to E-W; Du Berger et al. 1991) cutting all Precambrian rocks (phase 3' in Table 3.1; Dimroth et al. 1981).

The rifting of Rodinia occurred between 750 and 600Ma. In the portion corresponding to North America, three main tectonic events followed the dispersion of the supercontinent: the Taconic (550-450Ma), the Acadian (410-380Ma) and the Alleghanian (300-250Ma).
During this whole period (550 to 250 Ma), the SLSJ region was marked by extensional faults, which probably formed the Saguenay graben (Hébert 2004).

Around 600 Ma, the opening of the Iapetus Ocean created various transcurrent and normal faults in the margin of the new “Quebec Gulf”, as well as several lineaments in the Saguenay region (Roy 2009). An extensional regime oriented 022° and transcurrent faults at 120° were then installed (Thomas & Astini 1996). It is possible that the Saguenay graben was formed at this time, and it would constitute an Iapetan aulacogen (Kumarapeli & Saull 1966; Kumarapeli 1985; Allen et al. 2009), although there is still no evidence to prove it. Moreover, the limestone found within the graben do not present indications of movement nor talus slopes related to this period (unlike the limestone at Charlevoix region; Rondot 1972).

With the Taconic orogeny, the extensional environment gave way to a collisional one (Osberg 1978). This tectonic event consisted essentially in the formation of new terrains by collision and obduction; e.g. the emplacement of the Appalachian allochthon, essentially to the south of the Saint-Lawrence River, and the displacement along many normal faults from the Iapetus Ocean (Du Berger et al. 1991). Some authors (Thivierge et al. 1983; Du Berger et al. 1991) argued that the Taconic orogeny did not affect the Saguenay area, as it appears to have been part of a “stable interior plateau” at that time, as indicated by the absence of slumping and sediment wedges associated to the walls of the Saguenay graben. However, it was recently indicated that this orogenesis promoted extension in some faults at the SLSJ region (Verreault 2000), due to the flexure of the subducted plate caused by the weight of the obducted portion and the loading of the allochtonous over the

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The Acadian and the Alleghanian orogenies have a strong dextral strike-slip component, representing brittle non-co-axial deformations.
autochthonous plate. Low angle (10°- 40°) faults are assumed to be formed in the collisional front, while the overweight would have reactivated higher angle faults (~60°).

The Acadian orogeny corresponds to the closing of the Iapetus Ocean, and it was characterized by the collision between Avalonia and Laurentia. The resultant dextral compression, with the main stress field component at 115°, affected the Appalachians (Trudel & Malo 1993). This orientation is parallel to the walls of the Saguenay graben.

The Alleghanian orogeny consisted in the collision between Laurentia-Baltica and Gondwana (Condie 1989; Faure et al. 1996). The changes in the orientation of the main stress field component affected major structures in the SLSJ region (Verreault 2000): (1) with $\sigma_1 = $ NNW-SSE, faults in the Tchitogama and Kenogami Lakes were submitted to compression and dextral movements; (2) with $\sigma_1 = $ NNE-SSW, the environment was still compressive, though with a sinistral movement; (3) with $\sigma_1 = $ WNW-ESE, the northern faults were submitted to a sinistral compression, while the southern ones, to a transcurrent environment. All these orientations come from a theoretical study of the stress environment in the Saguenay region that could have been generated by various plate motions through time (Verreault 2000).

It is here suggested that the Saguenay graben was formed between the Acadian and the Alleghanian orogenies, during the Carboniferous, given the compression transformational system that was then installed (Fig. 3.5). Although the normal faults that constitute the northern and southern walls of the graben were already identified, its shear limits were not yet defined. Some possibilities are the shear zone identified by DuBerger et al. (1991) and the en echelon lineament that defines the contact between the host rock and anorthosite near the Kenogami Lake (Hébert 2004), or even another en echelon lineament but in the La Baie area, located to the southeast of the Kenogami uplands,
within the SLSJ. This compressional regime is compatible with twisting movements of the graben floor, which could have generated structural basins and saddles.

**Fig. 3.5** Suggested stress system that would have originated the Saguenay graben during the orogenies in the Carboniferous. The extensional boundaries would correspond to the north and south walls of the graben, while the shear limits were not defined yet.

The fragmentation of Pangea took place between 180 and 60Ma. It started with the opening of the Atlantic Ocean and the formation of great N-S oriented structures, such as the Hudson-Champlain lineament (Roy *et al.* 1998) and the basins of Newark and Connecticut, all in the New York region. The Hudson-Champlain lineament seems to extend to Canada by the Richelieu and Saint-Maurice Rivers, and to the north of the Saint-Jean Lake by a series of segments of large rivers (Fig. 3.3) more or less parallel to the Mistassini River (Roy *et al.* 1998). Thus, it is reasonable to infer that the opening of the Atlantic Ocean probably promoted normal and lateral movements of the Saguenay graben faults (Roy *et al.* 1993, 1998). The influence of the opening of the Atlantic Ocean over the structures of the Saguenay graben has recently been reinforced by apatite fission-track ages obtained in fault zones in the Saguenay region, among other regions in Quebec.
(Megan et al. 2010; Roden-Tice et al. 2011). Initially, the extensional movement was oriented NW-SE, and it probably reactivated the great N-S regional lineaments by sliding (the same orientation as the structures identified in the USA). With the progressive opening of the Atlantic Ocean, the extensional orientation changed to E-W around 140 Ma, then reactivating the north and south walls of the Saguenay graben (oriented approximately WNW-ESE) by strike-slip movements. It could have generated a transverse horst within the graben, by one of the structural saddles previously formed, that is, it would have created the uplifted area that is here referred to as Kenogami uplands.

Finally, it has already been indicated that the opening of the Labrador Sea has affected the formation and the pre-existing structures in Canada (Srivastava 1978).

3.4 Local hydrogeology

The main superficial hydrological entities in the study area are the Kenogami Lake and the Saguenay River (Fig. 3.3). The Kenogami Lake is 28 km long and 1 to 6 km wide. It is locally a hundred meters deep (Walter et al. 2010). The Saguenay River is 165 km long and around 2 km wide. It is up to 275 m deep (Walter et al. 2010).

Two main types of aquifers are present in the SLSJ region (Fig. 3.6): (1) bedrock aquifers and (2) aquifers constituted of Quaternary granular deposits. The bedrock aquifers are constituted mostly of Precambrian bedrock, overlayed locally and unconformably by remnants of subhorizontal Ordovician limestone units.

The Precambrian bedrock in the region is constituted of crystalline lithologies with very low matrix permeability. The hydrogeological importance of this bedrock is due to the fact that it occurs at the entire region and consequently it accommodates a large proportion of the regional groundwater flow systems (Fig. 3.6). Nonetheless, this bedrock includes a
number of higher permeability zones and structures that constitute local aquifers. Bedrock aquifers in the SLSJ region fit in the three types of aquifers present in Precambrian terrains according to Roy et al. (2006): (1) along brittle shear zones, (2) in carbonate bands favorable to the formation of karst networks, and (3) in some sedimentary rocks with none or little deformation and not metamorphosed that cover other rocks in discordance. In the latter case, the undeformed sedimentary rocks are Ordovician in age, not Precambrian.

Fig. 3.6 Diagram of the different aquifer types in the Saguenay area. The Kenogami uplands are constituted of a fractured crystalline rock aquifer. Adapted from: Rouleau et al. (2011).
The structural survey involves three main phases, selected after the topics discussed in chapter 2. First, a characterization at the regional scale of the joint system is derived from air photo interpretation, lineament analysis, and a general field survey at selected sites. The latter involves the investigation of the spatial distribution of the main joint sets, completed mostly at sub vertical cuts (247 outcrops), and the study of horizontal outcrops (18 visited, 13 analyzed in detail) in order to identify past stress fields components and joint sets relative ages. The second phase is a detailed structural survey of selected road cuts (18 outcrops) to better define and characterize the main joint sets that constitute the joint system in the study area. In the third phase, geophysical borehole logging is realized in three wells, which provides valuable information at depth, especially regarding subhorizontal joint sets. The first two phases helped answer questions 1 to 3 (identification of joint sets, including at different scales, and their relations with past stress field components) stated as objectives of this study; and the third phase aims at question 4 (possible relationships between joint sets and hydraulic properties). The topics related to these three phases are described below.
4.1 Photo Interpretation and lineament analysis

The interest of analyzing lineaments through aerial photographs and elevation models is that this kind of study provides helpful information to later verify their correlation with the main structural trends, whether related to brittle or ductile structures.

The available digital aerial photos were viewed in stereovision using the software DVP\(^5\). These photos are from the Ministère des ressources naturelles et de la Faune (MRNF), and were taken in 2007\(^6\). The aim was to select potentially interesting sites for fieldwork and to visualize lineaments at a quasi local scale.

Further lineament analyses were made with the digital elevation model (DEM) of the Kenogami uplands region with the software ArcGIS\(^7\). The scales selected for the analyses were 1:20.000 (DEM's scale) and 1:1.000, in order to obtain both regional and local observations. The analyses were concentrated within the public intramunicipal territories (TPI – territoire publique intramunicipal), as those areas could more easily allow further work such as borehole drilling. However, no holes were made in these areas in the scope of this project, because: (1) fieldwork did not reveal more intense fracturing near identified lineaments, although the latter correspond to geomorphological features; (2) the verification in the field of all the lineaments identified with the DEM would take a longer campaign than the one planned for this project.

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\(^5\) Groupe Alta. (2007). DVP version 7 (version 7.2.0.2).

\(^6\) The photos used are from the following flight lines, performed on the respective days: Q07100, May 19\(^{th}\) 2007; Q07101, May 22\(^{nd}\) 2007; Q07103, June 7\(^{th}\) 2007. All flight lines are from the MRNF.

4.2 Fieldwork

4.2.1 General survey

In the general survey phase, large outcrops are identified (Fig. 4.1a to d) and first submitted to a general description and a limited number of measurements (Appendices 2 and 3). The location and the lithology are described at each visited outcrop; then the most important structures are measured, such as joints (Fig. 4.1d), faults (Fig. 4.1i), foliation, dykes, veins and shear zones (Fig. 4.1e). A total of 265 outcrops were visited during the 2010 and 2011 fieldwork campaigns (total of 3 months) in the Kenogami uplands; these are mostly subvertical road cuts (Fig. 4.1a, d to f) and some quarries (Fig. 4.1b, c, g to i), with a limited number of horizontal exposures (Fig. 4.1h). Whenever possible, at least four measurements were taken for each joint set in the same outcrop. A total of 1217 joints were measured during the general survey. Other discontinuities measured in this phase include: 9 dykes, 12 veins, 5 foliation orientations, 14 striae, 4 shear zones and 28 faults.

A few days were dedicated to survey by boat along the shores of the Saguenay River (22 outcrops) and of the Kenogami Lake (25 outcrops) (Fig. 4.11, m). The landing difficulty and the boat motions at most shore outcrops resulted in a reduced number of measurements for each joint set.

Analysis of the relative ages of joint sets and tectonic events

Thirteen horizontal outcrops were visited in order to observe joint patterns that could provide information on the relative age among the observed discontinuities. This survey was led by Dr. A. J. Fernandes, from the Geological Institute of São Paulo (IG), Brazil. This detailed study consists in the analysis of the interactions between the joints, by
Fig. 4.1 Photos of selected outcrops visited; their identification numbers are indicated, as well as the municipality where they are located. (CONTINUES)
Fig. 4.1 (CONTINUATION)
Fig. 4.1 (CONTINUATION) (a), (b) General view of well fractured outcrops in anorthosite. (c) Large joint oriented E-S, dipping N in anorthosite. (d) ENE-WSW to ESE-WNW set of joints is clear along a roadcut, despite the bias introduced by the measurement face orientation (E-W). Outcrop in anorthosite. (e) Shear zone in anorthosite. (f) Intensely fractured zone of a few tens of meters in anorthosite; less intense fracturing is also observed on the same outcrop. It might indicate a shear zone. (g) Contact between an Ordovician unit (limestone) and the Pre-Cambrian basement (granitic rocks). (h) Orthogonal fracture pattern in limestone. (i) Normal faults in the limestone. (j) Steps and striae dipping to SW that indicate the movement of a normal fault in a granitoid. (k) Dark aphanitic rock with a vitreous aspect observed on a supposed fault wall in anorthosite. This material could be formed by fault gouge. The clear steps observed in this aphanitic rock strongly suggest that it is really a fault wall. (l) Outcrops of granite on the shores of the Kenogami Lake and (m) on the Saguenay River. Photos: (h) D. S. Pino and A. J. Fernandes; (m) M. Chabot; (others) D. S. Pino.

considering the types of termination and the dominancy of a certain joint set, which yield information on the relative ages between the observed sets (Pollard and Aydin 1988, Rives et al. 1994, Fernandes 2008).

This information is important because it helps to understand the sequence of tectonic events that generated the joint systems in the fractured aquifer. Identifying the most recent
tectonic event is particularly relevant as it is likely the most significant in controlling joint aperture, which plays a major role regarding groundwater flow (Fernandes & Rudolph 2001; Fernandes 2008; Zeeb et al. 2010).

Make drawings of sub-horizontal outcrop is a key step of the procedure, which is described hereafter.

1) Take a general look at the outcrop, determining the most representative features and the area to be drawn. In order to properly draw the joint system, it is important to realistically represent their angular relationships. For large or discontinuous outcrops, it is recommended to make more than one drawing.

2) For each of the most important joint sets, start drawing the most remarkable ones. While doing so, pay attention to details that help to understand the interactions between the joints, such as angles between them and terminations. Depending on the size of features, zooms may be needed. Some valuable steps are:
   a. Place some markers on the outcrop, (e.g. a hammer, a compass, a knife) that should show up on the drawing. They help to later correlate the photo with the drawing, or to go back to specific points while working in the outcrop.
   b. Use a specific type of texture in order to represent materials (e.g. lichen) that obscure the relations between joints, as it is important to report the fact that, at those specific locations, the interactions were not observed.

3) After most of the drawing is done, see if any joint pattern emerges (e.g. en echelon, conjugate joints, etc.). Also verify whether the drawing is truly representative of what has been observed in the outcrop.

4) Take photographs of the drafted area with the markers still on it. It is recommended that the photographs are taken perpendicularly to the outcrop face, i.e. looking straight
downward in most cases, and that they are all taken at about the same height, so the observed angles between the joints are more accurate. This also allows further inference of joint spacing of vertical joints. When more than one photograph is needed for the same drawing, showing two markers on every photo also helps to correlate them later and construct back the whole picture.

5) Measure the strike and dip (when the joint is subvertical, measuring only the direction of its trace is reasonable) of all joints and indicate the values in the drawing. Another option is to give a sequential number to each joint and record on a separate data sheet the measurements and observations about each joint.

Examples of results of the procedure described are found in Fernandes et al. (2011; 2012).

4.2.2 Geophysical logging

Geophysical loggings provide subsurface data, which are extremely useful complements to the surface information obtained on rock exposures. Geophysical logging was carried out in three wells located in private properties in the study area (Fig. 3.4). This work was conducted by a U. S. Geological Survey (USGS) team, led by R. H. Morin.

Five probes were used in each well (Table 4.1): caliper, multifunctional probe (natural gamma, rock and water resistivity, fluid temperature), acoustic televiwer (ATV), sonic probe and flowmeter. Among these tools, the ATV is the most interesting for structural surveys, as its resulting image is oriented and provides the direction and dip of the identified joints and their location along the borehole (Table 4.1).

Regarding the three wells that were logged, the ATV allowed the identification of a total of 352 joints on 380m of borehole.
Table 4.1 Probes used for geophysical logging in this project.

<table>
<thead>
<tr>
<th>Probe</th>
<th>Feature measured</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caliper</td>
<td>Well diameter</td>
<td>Evaluate the quality of other loggings (tool coupling); Identify zones of weak and fractured rock(^a).</td>
</tr>
<tr>
<td>Natural gamma</td>
<td>Natural gamma rays in the rock mass surrounding the borehole</td>
<td>Lithology identification(^a); Stratigraphic correlation among wells(^a).</td>
</tr>
<tr>
<td>Rock resistivity</td>
<td>Rock electrical resistivity</td>
<td>Locate zones of fluid exchange between the borehole and the formation(^a).</td>
</tr>
<tr>
<td>Water resistivity</td>
<td>Water electrical resistivity</td>
<td></td>
</tr>
<tr>
<td>Fluid temperature</td>
<td>Fluid (usually water) temperature</td>
<td></td>
</tr>
<tr>
<td>Acoustic televiewer (ATV)</td>
<td>Transit time of an acoustic wave sent by the probe</td>
<td>Locate joints in depth(^a). Measurement of orientation and dip at depth of identified joints by means of a proper software(^a),(^b).</td>
</tr>
<tr>
<td>Sonic</td>
<td>Transit time of a sonic wave sent by the probe</td>
<td>A proper software(^c) provides: the elasticity and shear modulus, Poisson's coefficient and Young's module.</td>
</tr>
<tr>
<td>Flowmeter</td>
<td>Water flow</td>
<td>Contribution of each joint to the water flow into the borehole.</td>
</tr>
</tbody>
</table>

\(^a\) Morin et al. (1997).
\(^b\) Morin et al. (2007).
\(^c\) The software WellCAD 4.2\(^a\) was provided by R. H. Morin (USGS).

4.2.1 Detailed survey

Detailed survey for characterizing joints sets

Two methods were tested to carry out the detailed structural survey: scanline and window sampling (Rouleau & Gale 1985; Priest 1993). In the preliminary fieldwork, three outcrops were tested with scanline, and one with window sampling. The most appropriate outcrops for both methods are clean, approximately planar rock faces that are large regarding the size and spacing of the exposed discontinuities (Priest 1993). Those rock

\(^a\) ALT – Advanced Logic Technology. (2007). WellCAD version 4.2.
exposures can be found on beach cliffs, gorges, road cuts, quarries and open pit mines. It is also important that the work place is safe; e.g. with no falling blocks. In the study area, the best available outcrops are located on road cuts and in quarries.

On a scanline survey, all the features that intercept the measuring tape laid on the outcrop are recorded (Fig. 4.2; Appendix 2). The measuring lines tested were about 100m long. In window sampling, on the other hand, area-based measurements are made, that is, all joints with a portion of their trace within a defined area ("window") of the rock face are measured (Fig. 4.3; Appendix 2; Priest 1993). In this study, windows were made of 1x1m² cells, which were disposed in two rows, one above the other, along 30m of the test outcrop, which was a vertical road cut.

Window sampling allows a better assessment of the joint pattern and of their distribution in the outcrop, as all features larger than a specified minimum size are measured. They also contribute to identify the distribution of the visible joint length for each major joint set. This approach could be more interesting in the case of a characterization study of an underground mine gallery. On the other hand, scanline sampling provides direct estimate

![Fig. 4.2 Scheme for scanline method. Only the discontinuities (in black) that cross the scanline (in blue) are measured. The distance at which a discontinuity intercepts the line is always noted (in this example, from 0 to 80m).](image-url)
Fig. 4.3 Scheme for window sampling method. All joints are measured within each window cell (e.g. 1A, 2A, 2B, etc), and it should be noted whether the same joint appears in more than one cell. Panoramic photographs (Appendix 4) may be helpful for locating properly the measured joints. This approach works better in smaller outcrops.

of joint spacing and density, these parameters being required in a number of further analysis procedures.

A total of 18 scanlines were made, with lengths varying from 10 to 150m, according to the size of the available outcrops in the study area. They were divided in two orientation groups: E-W (approximately the main orientation of outcrops in the Kenogami uplands) and N-S. The analysis of perpendicular outcrops provides more complete information on the joint system by sampling a wider range of joint orientations. On a total of 888m of scanlines, 1111 joints and 6 veins were measured.

4.3 Processing structural data

4.3.1 Interaction between joints

A second step in the study of the interactions between joints is to analyze the data obtained in the field, comparing the photographs taken, the drawings made and the joint orientations data, in order to define the joint sets and identify the orientation of the
horizontal components of the stress field that generated them. It is assumed here that the orientation of $\sigma_1$ is the bisectrix of the acute angle between two conjugate joint sets. The drawings may be first analyzed individually, although it is essential to compare drawings from different sites in order to verify if a certain pattern is only local or if it appears at different sites.

Joint patterns also provide valuable information regarding the relative chronology of joints generation (Fig. 4.4; Pollard & Aydin 1988). The most continuous joints tend to be the oldest, while the smaller ones and those that abut on another joint are the youngest (Dunne & Hancock 1994). On the other hand, alternating abutting relationships between joint sets indicates they were formed by the same tectonic event. The sense of shear

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**Fig. 4.4** Interactions between joint sets. (a) Older joint displaced by a younger one. (b) Younger joint abuts in the older one. (c) Small older joints are sealed (filled) and cut by a longer and younger joint. (d) Two joint sets crossing each other, no formation order can be inferred from this interaction alone. Source: Dunne & Hancock (1994).

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9 In a brittle co-axial deformation, the theoretical acute angle between two conjugate joints is 60° for a homogeneous and isotropic material. As a real rock is neither, the acute angle may vary by ±10° or 15°. Usually, acute angles smaller than 45° suggest non-co-axial deformation, leading to a Riedel fracture pattern where acute angles range between 10° and 20°. Pre-existing planar fractures or weaknesses such as rock banding, foliation and schistosity may also affect the angle between the stress and the fracture.
displacement across the older joint set can also be useful (Fig. 4.4a; Pollard and Aydin 1988; Dunne and Hancock 1994).

4.3.2 Stereoplots

All data collected in the field were initially compiled in Microsoft® Excel 2007 sheets, later being transferred into Microsoft® Access files in the PACES-SLSJ database. Orientation data were processed with Stereo32 (Röller & Trepmann 2008), which allows to construct stereograms, rose diagrams and pole density diagrams. The selected plots use equal area projection in the lower hemisphere. This type of projection is amenable to statistical investigation, particularly pole density analysis (Terzaghi 1965). Other statistical analyses were done with Microsoft® Excel 2007. The density diagrams, along with the identified lineament trends and densities, helped to determine structural domains regarding the homogeneity of the joint system.

4.3.3 Correcting for orientation bias

Various sources of error may affect the characterization of joint systems, at the sampling, the measurement or the estimation phases of a survey. The orientation bias in particular may result in unreliable estimate of the relative abundance of joint sets in the study area (Terzaghi 1965; Rouleau & Gale 1985).

Orientation related errors may be reduced by making observations on a number of appropriately and differently oriented boreholes and/or rock faces. The orientation errors may also be reduced by corrections based on the solid angle $\alpha$ between the joint set and the observation line or the window plane (Terzaghi 1965). Indeed, a sampling bias is introduced in any joint survey by the solid angle $\alpha$ being usually different from 90°, that is,
joints making a small angle (e.g. $\alpha < 20^\circ$) with the rock face have fewer chances to be observed than those making a high angle (e.g. $\alpha \sim 90^\circ$).

The basic principles of Terzaghi's correction are here adapted to perform the correction with a computer, accelerating the process. This approach was applied to the data obtained from scanlines and ATV logging (vertical scanline). The computations involved are presented in Appendix 5; the concepts are discussed in the following. The application of Terzaghi's correction over a window is discussed in Appendix 4.

This method of correcting for orientation bias is particularly interesting because it yields an estimate of the true joint density, as opposed to the frequency of their observation. The corrected data can be combined with estimates of other joint system attributes, such as joint aperture and extent, providing significant information to characterize a joint system. Another usual approach is to plot density diagrams of the observed and the corrected data, in order to visualize the effects of the corrections that have been applied.

Other discussions on the application of Terzaghi's method may be found in the work by Mauldon & Mauldon (1997), who analyze one joint of a particular size at a time. In this approach, joints are assumed to be of a finite and known size, and of circular shape. The correction is proposed for two cases (Mauldon & Mauldon 1997): sampling joints over a borehole and over tunnel surfaces. It is indicated that, regarding the joint size, the orientation bias increases as the size of the borehole decreases, that is, the orientation bias is most pronounced for boreholes with radius equal to zero.

**Correction over a scanline**

The computadorized procedure for Terzaghi's correction over a scanline presented in
this work was developed at UQAC, at the Centre d’études sur les resources minérales (CERM), under the direction of Dr. D. W. Roy.

First, the angle $\alpha$ between each joint plane and the scanline is calculated using direction cosines. Then, a weight equal to $1/\sin\alpha$ is attributed to each observed joint. This weight indicates how many joints of a certain orientation should be observed along a virtual scanline of the same length as the one used in the survey, but normal to the plane of the joint (see section 4.3.3).

A blind zone of $\pm20^\circ$ is drawn around the scanline and indicated in the stereoplot, because the estimate of true joint spacing plotted in that zone becomes increasingly inaccurate (Terzaghi 1965). For the joints in that “blind zone”, a new weight equal to zero is attributed, while for the others it is kept at the value $1/\sin\alpha$. By dividing the new estimate of the number of joints, accounting for the weight, by the scanline length, one obtains an estimate of the average true joint density, while the inverse number gives their true spacing.

Because most commercial softwares for plotting a Schmidt stereonet do not consider weighted numbers of joints, each observation is plotted 10 times the value of its weight rounded to the nearest integer. This yields a total number of points in the stereoplot equal to about 10 times the sum of the weights, though the density plot still reflects the corrected density distribution of joints within the rock mass.

With the corrected density plot, it is usually possible to identify one or more pole concentrations that indicate the most important joint sets in the analyzed outcrop. An average pole is then determined for each joint set, and the average poles are used to characterize the type of joint spacing (see section 4.4.3) and to define the unit block (see section 4.4.4).
A complete survey of the joint system at a site requires at least three non parallel scanlines\textsuperscript{10} selected in order to cover all possible joint orientations outside of their overlapping blind zones – the angles between these scanlines should be higher than 50°. The observations from each scanline can be combined in the same stereoplot after applying two additional factors to the weights previously computed in order to correct for the bias of each individual scanline. The first factor reduces all the scanlines to the same arbitrary "standard length" (e.g. to 20m); this factor is equal to the standard length divided by the length of the scanline of the considered observation. The second factor is applied for each joint weight; for a given joint, it is equal to the inverse of the number of scanlines for which that joint orientation is outside of the blind zone. The resulting stereoplot gives the distribution of joint densities in a cubic volume with the size of the selected "standard length" and containing a number of joints equal to the sum of the corrected weights. The scanlines grouped this way define a station; several stations are used in the definition of the unit block.

\textit{4.3.4 Joint distribution analysis}

From Terzaghi's correction, it is possible to analyze the distribution pattern of the joint sets in an outcrop. Only one joint set must be considered at a time; e.g. the set represented by pole P1 (see Appendix 5 for how poles are named) at a given outcrop.

First, a line A is drawn (Fig. 4.5) parallel to the main orientation of the joint pole (e.g. pole P1); its length is that of the scanline on a given outcrop times \( \sin \alpha \). A virtual position of the joints along line A can be determined accordingly. A corrected distance diagram is plotted using the virtual position values of the joints on line A. This provides information on

\textsuperscript{10} Regarding Terzaghi's correction, the window sampling provides 2D information instead of the 1D from the scanline, that is, a minimum of 2 windows are required for a station, alternatively to the scanlines.
the type of spacing distribution, which may be: (1) random, (2) regular, (3) regularly variable or (4) regularly concentrated (Fig. 4.6).

**Fig. 4.5** Sketch showing the projection of the position of joints observed on the scanline to a projection line A which is parallel to pole P1 obtained with Terzaghi's correction applied to the measurements done over a scanline. The angle $\alpha$ is calculated by direction cosine. Line A is parallel to the pole P1 and is used to describe the spacing of the considered joint set (virtual position on the corrected distance). This procedure is applied to all poles of joint concentrations.

### 4.3.5 Unit block

The unit block is defined by the most frequent joint sets (Ruhland 1973), which can be determined by joint density. This requires the definition of at least three main joint sets. The elongation of the block is parallel to the set with the highest density. Common forms include bricks, prisms and plates; the unit block may further be truncated by less frequent joint sets.

The concept of unit block has been proposed in the oil industry (e.g. Ghez & Janot
Fig. 4.6 Possible configurations of the corrected distance diagram for pole P1 represented on Fig. 4.4. The joints from this pole may present: (a) random, (b) regular, (c) regularly variable or (d) regularly concentrated spacing distribution.

1974), as it represents the basic joint network and may provide information regarding the rock mass behavior and hydraulic properties, e.g. its permeability (Rives et al. 1992). In the study of fractured rock aquifers, the joint system and the hydraulic properties of the media are equally important; hence, using the concept of unit block for the structural characterization of this type of aquifers is as well valuable and useful.

Knowledge of the size and shape of the unit block allows the determination of the wet surface per unit volume of rock, which corresponds to the ratio between the total area of fractured surface within the unit block area and its volume. It is also possible to estimate
the water volume around the unit block, once a value of joint aperture is assumed or, conversely, of average aperture if the storage capacity of the fractured aquifer is known. Information on recharge or other hydrogeologic factors may still be combined with the previous data in order to evaluate the water flow through the joint system.

4.4 Defining a conceptual model

Finally, the results of these analyses shall provide the basis to define a conceptual model for the bedrock aquifer in the study area. It shall contain information on the following aspects: joint systems, particularly the orientation and density of the main sets; hydrogeological properties related to different lithologies and/or joint systems; the influence of the recent stress fields over the hydrogeological properties.
This chapter presents the results obtained by analyzing the data from the general and detailed surveys and from the borehole geophysical logging. First, the results regarding the main joint sets in the study area are presented, combining information from the general survey and the geophysical logging to characterize the joint system of the Kenogami uplands. Second, results from the application of Terzaghi's correction over scanlines and logging data are introduced, as well as the unit block determined for the Kenogami uplands. Finally, data on the interaction between joints are shown.

5.1 Main joint sets

The general survey data for structural characterization of the whole area of the Kenogami uplands is summarized by a histogram of the orientation of the subvertical observation faces (Fig. 5.1), and by a density diagram of the orientation of the poles of the joints observed in these outcrops (Fig. 5.2).

The distribution of outcrop face orientations shows two modes (Fig. 5.1): the main one, at about 120° (ranging between 80° and 130°), is roughly parallel to the axis of the Saguenay graben, while the other one is at about 170° (ranging between 165° and 10°). The low points of the distribution are at 30° and 160°.
Moving average of outcrop directions (n=197)

Fig. 5.1 Distribution of outcrop directions. Central moving average (step of 1°) of the number of outcrops with a given direction within a 15° range of directions at each step. Directions of outcrop faces all transformed to 0 to 179°. Ranges of directions below 8° and above 172° are completed by the opposite end of the direction scale.

The density diagram of joint poles (Fig. 5.2) shows five joint sets (A to E; Table 5.1), of which four are subvertical and one is subhorizontal. These five concentrations are all well distributed across the Kenogami uplands; in many of the visited outcrops, up to three of these sets are observed. Although the lithology in the Kenogami uplands is considered fairly homogeneous, this feature may be used to analyze the data from the general survey. Interestingly, the same order of importance among the five joint sets is observed even when the joints are considered according to the different lithologies (Fig. 5.3): the NW-SE set (set A) is always the most abundant. The common spatial distribution of the main concentration and their similar occurrence in the various lithologies indicate that the study area can be considered as a single structural domain.

A few outcrops of Ordovician limestone, also located within the Saguenay graben, but to the east of the Kenogami uplands, are included in this study. They exhibit joint
concentrations (Fig. 5.3e) very similar to those of the Precambrian crystalline rocks of the Kenogami uplands; regarding subvertical joint sets, the joint trend NW-SE is dominant, followed by the trend NE-SW. It should also be noted that subhorizontal fractures are more abundant in limestone than in the other lithologies.

![Stereoplot with density contours of the poles of joints measured during the general structural survey; A to E are the main concentrations of joints (see Table 5.1). Equal area projection, lower hemisphere. Software: Stereo 32 (Röllner & Trepmann 2008).](image)

**Table 5.1** Main concentrations of joints observed during the general structural survey, based on Fig. 5.2.

<table>
<thead>
<tr>
<th>Joint set</th>
<th>Direction</th>
<th>Dip</th>
<th>General trend</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>144</td>
<td>88</td>
<td>NW-SE</td>
</tr>
<tr>
<td>B</td>
<td>229</td>
<td>89</td>
<td>NE-SE</td>
</tr>
<tr>
<td>C</td>
<td>288</td>
<td>86</td>
<td>E-W</td>
</tr>
<tr>
<td>D</td>
<td>251</td>
<td>03</td>
<td>Hor.</td>
</tr>
<tr>
<td>E</td>
<td>126</td>
<td>83</td>
<td>WNW-ESE</td>
</tr>
</tbody>
</table>
Fig. 5.3 Density diagrams of poles of joints measured during the general structural survey, grouped by lithology. Density calculations by small circle count with area equal to 1%; stereoplots with 10 contour intervals. Equal area projections, lower hemisphere. Software: Stereo 32 (Röller & Trepmann 2008). (CONTINUES)
The acoustic televiewer (ATV) logging data from three boreholes provides information on joints at depth (Table 5.2). The first two boreholes (RM001 and RM004) are located along the western side of the Kenogami uplands, while the third (PZ-S18R) is to the east of it (Fig. 5.4). Rock type interpretations (Table 5.2) were made by J. Roy (IGP, Canada) and R. H. Morin (USGS).

Table 5.2: Vertical boreholes in which the ATV logging was performed.

<table>
<thead>
<tr>
<th>Well identification</th>
<th>Rock type(s) (from top)</th>
<th>Length (m)</th>
<th>Number of fractures</th>
</tr>
</thead>
<tbody>
<tr>
<td>RM001</td>
<td>Anorthosite?</td>
<td>120.40</td>
<td>105</td>
</tr>
<tr>
<td>RM004</td>
<td>Granite?</td>
<td>111.37</td>
<td>141</td>
</tr>
<tr>
<td>PZ-S18R</td>
<td>Limestone</td>
<td>31.59</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>Sandstone</td>
<td>1.86</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Anorthosite</td>
<td>5.57</td>
<td>9</td>
</tr>
</tbody>
</table>

The identifications used for the wells are the same as the one of the Hydrogeological Information System (Système d’Information Hydrogéologique, SIH), from the Ministère du Développement Durable, Environnement et Parcs (MDDEP).
Fig. 5.4 Location of the logged wells and nearby outcrops: (a) RM001, (b) RM004 and (c) PZ-S18-R. (a, b, c) These maps are details from Fig. 3.4, represented as an inset on every map. Black rectangles in the miniature maps show the location of the detailed areas in the study zone. Black stars indicate wells; red dots, visited outcrops; dotted black line is the limit of the Kenogami uplands. Geological map: Avramchev (1993). (CONTINUES)
The density plots of the joints identified with the ATV (Fig. 5.5) confirm that in vertical boreholes most of the joints observed are subhorizontal; in this case, dipping between 0° and 10°. Some more steeply dipping joints were identified, with dip angles reaching 70° (Fig. 5.5). Particularly in the case of the well PZ-S18-R, high angle dipping joints in the southeast quadrant and oriented around 350° and 095° are concentrated in the anorthosite, while the other joints identified belong to limestone (except for two joints in a thinner layer of sandstone) (Fig. 5.5d). The identification of rock types is based on the lithologic profile made during the construction of this well by members of the PACES-SLSJ team (Appendix 6). Moreover, the orientations of these higher dip angle joints observed at depth are not exactly the same as the ones observed on surface at the nearest outcrops (Fig. 5.6), maybe with the exception of well RM001 and outcrop DP-051 (Figs. 5.5 and
Fig. 5.5 Density diagrams of poles of joints identified with the ATV in the wells logged in the Kenogami uplands. Density calculations by small circle count with areas equal to 1%; stereoplots with 10 contour intervals. Equal area projections, lower hemisphere. Software: Stereo 32 (Röller & Trepmann 2008).
Fig. 5.6 Density diagrams of the joints observed in the nearest outcrops regarding the logged wells (Fig. 5.4). Density calculations by small circle count with areas equal to 1%; stereoplots with 10 contour intervals. Equal area projections, lower hemisphere. Software: Stereo 32 (Röllner & Trepmann 2008).
5.6). Distances between wells and outcrops vary approximately from 65m to 4,920m, depending on the outcrop availability in the area of the logged wells (Fig. 5.4).

Finally, regarding the lineaments identified within the public intramunicipal territories, the TPIs (Appendix 7; see also chapter 4), the main orientation is NW-SE, the same orientation as joint set A (Fig. 5.2) in the Kenogami uplands. Another important lineament trend is approximately WNW-ESE, parallel to joint set E (Fig. 5.2) and to the Saguenay graben axis orientation.

5.2 Fault planes and striae

In some fault planes, the presence of steps and striae (Fig. 5.7 and Table 5.3) indicates sense of movement along the faults, which was deduced from the criteria described by Petit (1987).

Faults in anorthosite may be divided in two trends (Table 5.3): NE-SW and NW-SE, both dipping between 60° and 90°. The faults identified in granitoid and in mangerite may also be categorized in these two orientation trends (Table 5.3). Most of the striae were identified in anorthosite (Table 5.3), and they are almost equally distributed between the two fault trends (Fig. 5.7).

The striae on generally steep dipping fault planes have mostly shallow to sub-horizontal plunges, indicating mainly strike-slip motions (Fig. 5.7): striae indicating dextral and sinistral movements are found in both NE-SW and NW-SE fault trends. This suggests the occurrence of two past stress fields or tectonic events. Nonetheless, most striae which did not provide information on sense of fault movement are plunging to SW.
5.3 Terzaghi’s correction and the unit block

The Terzaghi’s correction allows estimating the true density of the various joint sets from their observed abundance along scanlines or within observation “windows”. Then, the shape, orientation and dimensions of a representative unit block are derived from these corrected density values and the most frequent orientations over various scanlines. The scanline measurements were performed on 14 selected outcrops along an approximately
Table 5.3 Orientation data of faults and respective identified striae.

<table>
<thead>
<tr>
<th>Outcrop ID</th>
<th>Lithology</th>
<th>Fault Direction</th>
<th>Dip</th>
<th>Plunge</th>
<th>Plunge quadrant</th>
<th>Sense</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP-228</td>
<td>Anorthosite</td>
<td>140</td>
<td>70</td>
<td>04</td>
<td>NW</td>
<td>Dextral</td>
</tr>
<tr>
<td></td>
<td></td>
<td>146</td>
<td>56</td>
<td>09</td>
<td>NW</td>
<td>Dextral</td>
</tr>
<tr>
<td></td>
<td></td>
<td>125</td>
<td>81</td>
<td>13</td>
<td>NW</td>
<td>Dextral</td>
</tr>
<tr>
<td></td>
<td></td>
<td>174</td>
<td>89</td>
<td>24</td>
<td>NW</td>
<td>Sinistral</td>
</tr>
<tr>
<td></td>
<td></td>
<td>322</td>
<td>84</td>
<td>03</td>
<td>NW</td>
<td>Sinistral</td>
</tr>
<tr>
<td></td>
<td></td>
<td>150</td>
<td>74</td>
<td>08</td>
<td>NW</td>
<td>Sinistral</td>
</tr>
<tr>
<td></td>
<td></td>
<td>348</td>
<td>88</td>
<td>01</td>
<td>SE</td>
<td>N.I.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>205</td>
<td>89</td>
<td>09</td>
<td>NE</td>
<td>Sinistral</td>
</tr>
<tr>
<td></td>
<td></td>
<td>022</td>
<td>77</td>
<td>41</td>
<td>SW</td>
<td>N.I.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>034</td>
<td>88</td>
<td>23</td>
<td>NE</td>
<td>N.I.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>034</td>
<td>89</td>
<td>17</td>
<td>NE</td>
<td>Sinistral</td>
</tr>
<tr>
<td></td>
<td></td>
<td>039</td>
<td>89</td>
<td>16</td>
<td>NE</td>
<td>Dextral</td>
</tr>
<tr>
<td>DP-233</td>
<td>Mangerite</td>
<td>330</td>
<td>62</td>
<td>62</td>
<td>SE</td>
<td>Sinistral</td>
</tr>
<tr>
<td>DP-234</td>
<td>Granitoïde</td>
<td>278</td>
<td>90</td>
<td>N.I.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>117</td>
<td>77</td>
<td>N.I.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DP-235</td>
<td>Granitoïde</td>
<td>196</td>
<td>59</td>
<td>18</td>
<td>SW</td>
<td>N.I.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>175</td>
<td>50</td>
<td>11</td>
<td>SW</td>
<td>N.I.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>196</td>
<td>65</td>
<td>59</td>
<td>SW</td>
<td>Sinistral</td>
</tr>
<tr>
<td></td>
<td></td>
<td>180</td>
<td>60</td>
<td>N.I.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DP-236</td>
<td>Granitoïde</td>
<td>185</td>
<td>58</td>
<td>N.I.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(in contact with limestone)</td>
<td>029</td>
<td>81</td>
<td>N.I.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DP-255</td>
<td>Anorthosite</td>
<td>210</td>
<td>85</td>
<td>N.I.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>189</td>
<td>83</td>
<td>N.I.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DP-256</td>
<td>Anorthosite</td>
<td>125</td>
<td>46</td>
<td>N.I.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>219</td>
<td>57</td>
<td>N.I.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DP-259</td>
<td>Anorthosite</td>
<td>215</td>
<td>82</td>
<td>N.I.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* N.I.: not identified

E-W profile on the Kenogami uplands (Fig. 3.4), more or less coincident with the road 170, that crosses the study area. Scanline surveys were carried out in four other outcrops near the Kenogami Lake, further to the south. As the latter provided results very similar to the first 14 scanlines (Table 5.4) and a single structural domain was defined in the Kenogami uplands, all of the scanline data were considered together to determine the unit.

12 On outcrops DP-056, DP-059, DP-060 and DP-064.
block. This extrapolation is fairly reasonable, especially considering that the vertical height of the unit block is defined only on ATV measurements on three boreholes located in other parts of the study area than the scanlines (Fig. 3.4).

Table 5.4 Joint pole data obtained by applying Terzaghi’s correction to scanline data. These joint orientation values are represented on the density diagram of Fig. 5.9.

<table>
<thead>
<tr>
<th>Well ID</th>
<th>Trend</th>
<th>Plunge</th>
<th>Average joint spacing (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RM001</td>
<td>357</td>
<td>26</td>
<td>25.33</td>
</tr>
<tr>
<td>RM001</td>
<td>006</td>
<td>87</td>
<td>5.63</td>
</tr>
<tr>
<td>RM004</td>
<td>341</td>
<td>88</td>
<td>361</td>
</tr>
<tr>
<td>RM004</td>
<td>057</td>
<td>27</td>
<td>5.01</td>
</tr>
<tr>
<td>PZ-S18-R</td>
<td>332</td>
<td>83</td>
<td>3.21</td>
</tr>
<tr>
<td>PZ-S18R</td>
<td>007</td>
<td>32</td>
<td>3.92</td>
</tr>
<tr>
<td>PZ-S18-R</td>
<td>269</td>
<td>33</td>
<td>6.31</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outcrop ID</th>
<th>Trend</th>
<th>Plunge</th>
<th>Average joint spacing (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP-040</td>
<td>226</td>
<td>37</td>
<td>1.59</td>
</tr>
<tr>
<td>DP-040</td>
<td>333</td>
<td>05</td>
<td>3.09</td>
</tr>
<tr>
<td>DP-040</td>
<td>012</td>
<td>10</td>
<td>4.52</td>
</tr>
<tr>
<td>DP-055</td>
<td>067</td>
<td>03</td>
<td>0.52</td>
</tr>
<tr>
<td>DP-055</td>
<td>336</td>
<td>09</td>
<td>1.50</td>
</tr>
<tr>
<td>DP-059</td>
<td>183</td>
<td>03</td>
<td>1.00</td>
</tr>
<tr>
<td>DP-059</td>
<td>070</td>
<td>01</td>
<td>0.95</td>
</tr>
<tr>
<td>DP-060</td>
<td>281</td>
<td>03</td>
<td>1.04</td>
</tr>
<tr>
<td>DP-060</td>
<td>133</td>
<td>08</td>
<td>1.19</td>
</tr>
<tr>
<td>DP-060</td>
<td>043</td>
<td>06</td>
<td>2.91</td>
</tr>
<tr>
<td>DP-064</td>
<td>058</td>
<td>06</td>
<td>0.27</td>
</tr>
<tr>
<td>DP-064</td>
<td>153</td>
<td>05</td>
<td>1.06</td>
</tr>
<tr>
<td>DP-068</td>
<td>263</td>
<td>10</td>
<td>2.07</td>
</tr>
<tr>
<td>DP-068</td>
<td>309</td>
<td>05</td>
<td>2.19</td>
</tr>
<tr>
<td>DP-069</td>
<td>316</td>
<td>11</td>
<td>1.61</td>
</tr>
</tbody>
</table>

The comparison of a density diagram of the observed data on a scanline with the diagram of the corrected data (Fig. 5.8) illustrates the importance of such analysis in order
to correct the information biased by the angle between each measured joint and the scanline.

![Fig. 5.8 Comparison between (a) observed and (b) corrected (application of Terzaghi's method) density diagrams of scanline data at outcrop DP-156_face1 (scanline: 086/00). Number of points of corrected values is by ten times that of their weight (see section 4.3.2). Equal area projections, lower hemisphere. Software: Stereo 32 (Roller & Trepmann 2008).](image)

The pole orientation and true spacing data were obtained by applying Terzaghi's correction to all scanline and ATV logging data, and are summarised on Fig. 5.9 and listed on Table 5.4. The four main joint sets observed on Fig. 5.9 and listed on Table 5.5 are used to develop the unit block for the Kenogami uplands (Fig. 5.10). It is defined by the 4 main joint sets (Table 5.5) and it may be often segmented by other sets (smaller pole concentrations on Fig.5.9). Its size is based on the second spacing mode from Table 5.5. The edges from the hexagon that constitutes the base of the unit block Fig. 5.10 are
calculated using the law of sines\textsuperscript{13}. The values obtained are: 1.55m (edge from set 044/88), 1.36m (edge from set 139/84) and 0.19m (edge from set 095/86).

The spacing of joints that are part of the same set defined by a given corrected pole may be analyzed as discussed at section 4.3.3. As previously mentioned, the joints from a same set may be distributed: (1) randomly, (2) regularly spaced, (3) regularly variable spacing or (4) regularly concentrated (Fig. 4.5).

Fig. 5.9 Density plot of all poles of joint sets defined after applying Terzaghi's correction to the 18 scanlines and ATV logging data in 3 boreholes. The main pole concentrations (indicated by orange crosses) define the sides of the unit block. Equal area projection, lower hemisphere. Software: Stereo 32 (Röller & Trepmann 2008).

\textsuperscript{13} The law of sines is given by:

\[ \frac{a}{\sin A} = \frac{b}{\sin B} = \frac{c}{\sin C} \]

where \(a\), \(b\) and \(c\) are the lengths of the sides of a triangle and \(A\), \(B\) and \(C\) are the respective opposite angles.
Table 5.5 Joint sets that define the unit block in the Kenogami uplands. Their poles are indicated by orange crosses on Fig. 5.9.

| Direction | Dip | Spacing distribution | Spacing mode 1 (m) | Spacing mode 2 (m) | Type of spacing  
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>044</td>
<td>88</td>
<td>Bimodal</td>
<td>0.0-0.6</td>
<td>1.0-3.0</td>
<td>regularly concentrated</td>
</tr>
<tr>
<td>139</td>
<td>83</td>
<td>Bimodal</td>
<td>0.0-0.6</td>
<td>1.5-2.0</td>
<td>regularly variable</td>
</tr>
<tr>
<td>070</td>
<td>04</td>
<td>Unimodal</td>
<td>0.0-0.6</td>
<td>-</td>
<td>regularly concentrated</td>
</tr>
<tr>
<td>095</td>
<td>86</td>
<td>Bimodal</td>
<td>0.4-0.6</td>
<td>2.0-4.0</td>
<td>regularly concentrated</td>
</tr>
</tbody>
</table>

Fig. 5.10 Unit block defined for the Kenogami uplands, using corrected data from horizontal scanlines on outcrops (defining the subvertical sets) and from ATV in vertical boreholes (defining the subhorizontal set). Size is based on the second spacing mode in Table 5.5.

From the 45 poles representing joint sets identified after applying Terzaghi's correction to scanline and ATV logging data, the type of spacing could be defined for 33 sets (Fig. 5.11). In some cases, the classification was not done because there were too few joint
measurements of that particular set, preventing the appearance of one of the four patterns previously described. Although the randomness of joint spacing may seem to prevail, the regular types of spacing should not be neglected. They appear particularly as bimodal distributions of joint spacing values (Fig. 5.12; Appendix 8). This pattern was observed many times in the subvertical observation faces, e.g. where more densely fractured zones alternate with zones of a lower degree of fracturing, that is, with lower joint concentration. However, they do not present significant differences regarding indication of water flow. These two types of zones could also be observed in the same outcrop, e.g., DP-059 (Figs. 4.1f and 6.2a). However, the spacing between two densely fractured zones could not be defined within a single outcrop.

![Number of corrected joint sets per type of joint spacing](image)

**Fig. 5.11** Distribution of type of joint spacing of the joint sets defined after applying Terzaghi's correction to scanline and borehole logging data.
Fig. 5.12 Example of bimodal distribution of joint spacing. Horizontal scale is not uniform.

The suggestion of bimodal distributions by the spacing histograms allowed the determination of a second unit block. The latter was based on the first spacing mode in Table 5.5, with similar geometry but different size (Fig. 5.13) than the first unit block (Fig. 5.10).

Finally, it should be noted that the subhorizontal joints considered for the unit block were more frequently observed during the geophysical borehole logging than in outcrop faces.

5.4 Interaction between joints and relative ages

Thirteen horizontal outcrops were studied in order to determine the interactions between the observed joint sets and their relative ages. The joint sets were classified in 8 groups (Table 5.6 and Fig. 5.14), regarding their orientation and, mostly, their relationship observed in the field.
**Fig. 5.13** Second unit block defined for the Kenogami uplands, due to bimodal joint spacing distribution. Corrected data from horizontal scanlines on outcrops (defining the subvertical sets) and from ATV on vertical boreholes (defining the subhorizontal set) were used. Notice that this block is smaller than the one presented at Fig. 5.10, although they have a similar geometry.

These groupings have been helpful for defining relative ages among joint sets, in spite of the large number of joint sets considered. Establishing those groupings is important, specially because not all joint sets are observed in each outcrop. Thus, the set in one outcrop can be correlated to the one in another site and then provide a good inference of their formation order. Appendix 9 presents an example of all the steps of this analysis: the drawing and photograph in fieldwork and the later interpretation of the relative ages between the joint sets.
Table 5.6 Grouping of joint sets from horizontal outcrops, based on relative age order.

<table>
<thead>
<tr>
<th>Order</th>
<th>Joint sets</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>(I = oldest; V = youngest)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>060°-075° or 240°-255°</td>
<td>Coeval sets</td>
</tr>
<tr>
<td>090°-100° or 270°-280°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>140°-165° or 320°-345°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>020°-030° or 200°-210°</td>
<td>Coeval sets</td>
</tr>
<tr>
<td>170°-190° or 350°-010°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>050°-060° or 230°-240°</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>030°-045° or 210°-225°</td>
<td>En echelon</td>
</tr>
<tr>
<td>V</td>
<td>110°-120° or 290°-300°</td>
<td>Youngest set</td>
</tr>
</tbody>
</table>

Fig 5.14 Rose diagram of measured orientation of subvertical joints observed at subhorizontal outcrops. All measured values are adjusted to the range 270° to 090°. The indicated groupings are referred to in the text and colors correspond to the ones attributed to joints in Appendix 9. Relative age order (I to V) as indicated on Table 5.6.
6

DISCUSSION

In this chapter, the implications of the previously presented results are discussed: from the occurrence of joint sets to their relationships with each other, as well as their correlation to the Saguenay tectonic history; the definition of the unit block in the Kenogami uplands and its association with hydraulic properties; and, finally, possibilities of integration of these hydrogeological and structural data into numerical and analytical models of groundwater flow.

6.1 Joint sets and structural domains

The subvertical joints oriented NW-SE and WNW-ESE (sets A and E) stand out in the measured population (Figs. 5.2 and 5.3) despite the unfavorable bias due to the measurement face orientation, as most of the visited subvertical outcrops are oriented approximately E-W (Fig. 5.1). Nonetheless, it is also possible to analyze the joint orientation data within the two orientation modes of the outcrops (Fig. 6.1) identified on Fig. 5.1: 080° to 130° (mode 1), 165° to 010° (mode 2), and all the other orientations are intermodal. Regarding mode 1 (Fig. 6.1a), joint sets A, C, D and E are still identified. Next, with mode 2 (Fig. 6.1b), sets B and D are the most easily identified. Finally, in the
Mode 1: outcrops oriented from 080° to 130° (a)

Mode 2: outcrops oriented from 165° to 010° (b)

Mode 3: all other outcrop orientations (c)

Fig. 6.1 Density diagrams of joint poles grouped according to outcrop orientation modes. Joints measured at outcrops oriented (a) from 080° to 130°, (b) from 165° to 010° and (c) all other orientations. Orientation modes are taken from Fig. 5.1. Equal area projections, lower hemisphere.

Software: Stereo 32 (Röller & Trepmann 2008).
intermodal outcrop orientations, the joint sets A, B and E are recognized. The ensemble of these analyses indicates that those five joint set orientations are truly significant in the Kenogami uplands. Moreover, the lineament analysis on the TPIs (public intramunicipal territories) indicates that regional and local (outcrop scale) data are in accordance, as most lineaments are oriented WNW-ESE and NW-SE (Appendix 7).

The distribution of the five joint sets observed in the general survey (Fig. 5.2) throughout the entire area suggests that there is a single dominant structural domain in the Kenogami uplands. Another indication is that the same abundance of each joint set is observed regardless of the lithology (Fig. 5.3). The occurrence of a single structural domain allows the combination of the corrected data from all the scanlines to build the unit block. Finally, the joint sets A to E are all related to one of the faces of the unit block.

The subhorizontal joints (set D) are more easily observed in the limestone outcrops located to the east of the Kenogami uplands (Fig. 4.1h, i), although they were also very clear in some anorthosite outcrops within the study area (Figs. 4.1b, f and 6.2a, b). A subhorizontal pattern is also shown by the magmatic bedding observed at an outcrop to the east of Larouche town (Fig. 6.2c, d; outcrop DP-157). This texture was also observed at outcrop DP-217, although not as clear as at the former. The magmatic bedding of the LSJ Anorthosite, described by Woussen et al. (1988), includes both banded and massive anorthosite units at outcrop scale (these units form a banded massif at a map scale). However, most magmatic bedding features are believed to have been obscured by deformational events.

In the large limestone outcrops to the east of the Kenogami uplands (e.g. DP-232. DP-235 and DP-237), some of the open subvertical joints observed have been affected by dissolution, as shown by protuberances left within the openings (Fig. 6.3).
Another interesting feature is observed between limestone and granite at outcrops DP-232 to DP-237 (all large wall exposures at a quarry, to the east of the uplands). At this location, the subvertical N-S oriented joints occur mainly in the granite, hardly being observed in the limestone, where the main subvertical joint trend is E-W (secondary in

Fig. 6.2 (a, b) Examples of anorthosite outcrops in the Kenogami uplands where large subhorizontal joints are more evident. (c, d) Banded anorthosite. The rust color along some subvertical (and horizontal) joints indicates that there was water flow through these discontinuities. Each color division of the sticks measures 30cm (1ft). Photos: D. S. Pino.
Fig. 6.3 Protuberances clearly demonstrating that there was an important dissolution along joints in the limestone. Photo: D. S. Pino.

Granite. It should be noted that the occurrence of a joint set in both granite and limestone indicates that it is more recent than the Ordovician (when limestone were formed), or even suggest that previously formed joints in granite were reactivated. These interpretations are supported by similar observations reported for joint systems in Ontario (Clarke 1959; Andjelkovic & Cruden 1998, 2000). Finally, many normal faults are observed in that quarry, as shown on the sketch on Fig. 6.4 (part of which presented on Fig. 4.1i).

On the outcrop represented on Fig. 6.4, a fault oriented 180/60 placed the limestone right beside the gneiss, with an important vertical offset, of about 6m. Nonetheless, striae (oriented 207/18 and 184/11) observed on wall 180/60 suggest an oblique movement.

6.2 Interaction between joints, their relative ages and the stress field

The stress fields and relative chronology of joint sets presented on this section are suggestions, based on the field observations of subhorizontal outcrops and on literature review (chapter 3).
Fig. 6.4 Corner of faces in a quarry, showing a sinistral strike motion of the unconformity, with a small normal dip slip component. The 180°/60° fault plane forms the left face of the corner. The normal faults in the center of the sketch cut both granite and limestone. Dykes occur on the right hand side. Sketch from outcrops DP-234 and DP-235 (also the view from DP-232 and DP-237).

The frame corresponding to Fig. 4.11 is indicated by the green rectangle.

The three groups (Fig. 5.14) oriented 060°-075°, 090°-100° and 140°-165° are coeval, and constitute the dominant joints in most outcrops. The second most important group is 020°-030°. The group 170°-190° is less expressive, even though it seems coeval to the group 020°-030°. Next, the group 050°-060° appears to be younger. Nevertheless, it is interesting to notice that indications of joints of the younger groups being coeval to joints of older groups were observed, as the older ones are also observed abutting in the younger

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14 If Fig. 6.5b is also taken into account, it is possible to infer that the group 060°-075° would represent P (synthetic shear joint) in the Riedel system, while 090°-100° and 140°-165° would be R (synthetic Riedel shear joint) and R' (antithetic Riedel shear joint), respectively.
ones. This may suggest reactivation of older joints, an expected phenomenon in the study area. Finally, the group 030°-045° often appears to form en echelon structures; while the group 110°-120° is suggested as the youngest, never being the dominant one.

Conjugate pairs of joints were inferred based on the relations between those groups of joints (Fig. 5.14), as well as the orientation of \( \sigma_1 \) (the major principal component of the stress field) by the time of their formation, yielding four different tectonic events or stress fields (Fig. 6.5). Different sites may be compared as they are all in the same structural domain. Based on the orientation of the inferred major principal stress component and of the conjugate pairs, the four tectonic environments suggested may be related to the tectonic events that affected the SLSJ region (Fig. 6.5).

The correlations shown on Fig. 6.5 were determined by comparing the collected data (angular relationships and relative ages between the joints observed in the field) with information discussed on chapter 3 on the tectonic events that affected the SLSJ region. The comparison between field and theoretical data is presented on the next paragraph; other relationships between the groups are described afterwards, by relative age order of joint set.

The stress field represented on on Fig. 6.5a may be associated with the closing of the Iapetus Ocean (Acadian Orogeny, 410-380Ma), when the main component of the stress field was recognized at 115° (Trudel & Malo 1993). It may also be related to the Alleghanian Orogeny (300-250Ma), as in its phase 2, \( \sigma_1 \) was oriented WNW-ESE (Verreault 2000). Next, the sketch on Fig. 6.5b may be related to phase 1 from the Alleghanian Orogeny, when \( \sigma_1 \) was oriented NNW-SSE (Verreault 2000). The representation of Fig. 6.5c is better (though not perfectly) related to the phase 2 from the
Fig. 6.5 Suggested conjugate pairs of the joint sets identified in 13 horizontal outcrops in the Kenogami uplands. The outcrops where these pairs could be identified are indicated. A correlation is also suggested between the conjugate pairs and the respective main stress field component, with some tectonic events that affected the SLSJ region. The sketches are presented in chronological order, from the oldest tectonic event (a) to the youngest (d).
Alleghanian Orogeny. Finally, the extensional regime on Fig. 6.5d may be related to the opening of the Atlantic Ocean (or the fragmentation of the Pangea; started around 180Ma), given that at that time large N-S structures (e.g. the Hudson-Champlain lineament; Roy et al. 1993, 1998; Megan et al. 2010; Roden-Tice et al. 2011) were originated and/or reactivated.

Finally, regarding the current stress field in the Kenogami uplands, it may be inferred that its main compressional component ($\sigma_1$) is oriented NE-SW, as such orientation is consistently found in eastern Canada (Arjang 1991; Hasegawa 1991; Zoback 1992, Assameur & Mareschal 1995) (Appendix 10). This orientation is comparable to the tectonic environments presented on Figs. 6.5a and d, but it differs from the most recent stress field identified in the horizontal outcrops. The trend NE-SW of the current stress field is perpendicular to joint sets A and E (Fig. 5.2) from the Kenogami uplands, and to set 139/84 from the unit block (Fig. 5.10). Joints of these sets would tend to close due to the action of the current stress field, while the joints of sets B (Fig. 5.2) and 044/88 (Fig. 5.10) would tend to remain open.

6.3 The unit block and hydraulic properties

An important issue regarding the correction proposed by Terzaghi (1965) is that it does not account for polymodal distributions of joint spacing; it simply considers the average spacing of all joints over the scanline. In the case of the Kenogami uplands, bimodal distributions were observed along many of the scanlines performed (Appendix 8). Thus, standard statistical parameters which assume an unimodal symmetrical distribution of values, such as the average and the standard deviation, are meaningless. Therefore, intervals corresponding to the bimodal distributions were considered instead (Table 5.5).
Therefore, two unit blocks (Figs. 5.10 and 5.13) were defined for the Kenogami uplands; the average joint spacing values of each unit block were calculated within the range of the respective distribution modes presented on Table 5.5.

The geometry and size of the unit block may be used to relate it to hydraulic properties; the example of the block from Fig. 5.10 is discussed in the next sections.

6.3.1 Hydraulic properties of the unit block

Hydraulic properties of the Kenogami uplands were estimated by Chesnaux (accepted) through an analysis of groundwater flow at a regional scale. Although only the southern part of the Kenogami uplands was considered, the calculated values may be extrapolated to the whole uplands, considering: (1) the relative homogeneity of its lithology; (2) the definition of a single structural domain forming the fractured rock aquifer. The properties estimated by Chesnaux (accepted) are the hydraulic conductivity \(4.3 \times 10^{-7} \text{m/s}\), the transmissivity \(2.30 \times 10^{-5} \text{m}^2/\text{s}\) and the recharge \(3.5 \text{mm/y}; \text{i.e. 0.38}\% \text{ of 930mm over a year}.\) They were calculated based on an analytical interpretation of regional hydraulic head profiles, based on a one-dimensional Dupuit-Forchheimer model in steady state conditions.

It is possible to calculate a mean joint aperture for each joint set of the unit block by applying the calculated value of hydraulic conductivity in Eq. 2.1, assuming that the joints are formed by parallel and smooth walls. Let's consider that each joint set from the unit block contributes equally to the hydraulic conductivity, so that each set presents \(K = 1.075 \times 10^{-7} \text{m/s}\) (a quarter of the total value calculated for the Kenogami uplands). Also, for this example, let's take into account a difference of hydraulic head \(dh\) of 0.1m and a value of water viscosity \(\mu\) equal to \(1.519 \times 10^{-3} \text{kg/s.m}\) (the latter corresponds to a water
temperature of 5°C, a value commonly found in the first 30m of the logged wells in the Kenogami uplands). Water density $\rho$ and gravitational acceleration $g$ are assumed to be equal to 999.96km/m$^3$ and 9.81m/s$^2$, respectively. Thus, for the joint set 044/88 as an example:

$$K = \frac{(2b)^3 \rho g}{W 12\mu}$$

$$1.075 \times 10^{-7} = \frac{(2b)^3}{1.50} \times \frac{999.96 \times 9.81}{12 \times 1.519 \times 10^{-3}}$$

$$\therefore 2b \approx 6.69 \times 10^{-5}m$$

A mean joint aperture of approximately 66.9$\mu$m is estimated for the joint set 044/88 of the unit block. This aperture value is within ranges proposed for other regions in the Canadian Shield: (1) apertures of 2-200$\mu$m, obtained by straddle-packer injection tests and ATV logging (Raven 1986); (2) apertures of 25-375$\mu$m for subvertical joints and of 62.5-187.5$\mu$m for subhorizontal joints, estimated through groundwater flow simulations (Gleeson 2009; Gleeson et al. 2009).

Another value that can be calculated from the characteristics of the unit block is the wet surface per unit volume of rock, that is, the ratio between its surface area and its volume (Pino et al. 2011; 2012b). The wet surface indicates the surface area available for water-rock geochemical interaction for the groundwater flow through the joints in that rock mass. As the unit block is a hexagonal prism, its volume may be approximately (due to inclined sides) calculated by multiplying the surface of its base (surface of the hexagon) by its height (the spacing of the subhorizontal set). Thus, its base has approximately a surface
area of 8.12m² and the block has a volume of 1.25m³. The wet surface is easily calculated as 6.47m⁻¹.

Next, both the volume of water surrounding the unit block and joint porosity are parameters that provide an estimate of the amount of water storage in the joints of the fractured rock aquifer. Considering the calculated joint aperture for the other sets of the unit block (69.5µm for set 139/84, 75.4µm for set 095/86, and 46.4µm for set 070/04), it is possible to calculate the volume of water surrounding it. Nonetheless, it must be highlighted that the water within each joint that forms the unit block is also considered for the calculi for an adjacent block; thus, it is necessary to divide the values of joint aperture by two. Following these observations, the volume of water around the unit block is estimated at 2.23x10⁻⁴ m³. This value is related to joint porosity (ratio between empty volume – the joint volume in this case – and the total volume of the block). For the unit block of the Kenogami uplands, with the previously mentioned aperture values, a joint porosity of approximately 0.02% is obtained. The joint porosity of 0.02% is comparable to values estimated for a quartzite (down to 0.06%) using both field and laboratory data (Rouleau et al. 1996).

6.3.2 Estimating flow velocity

Given a hydraulic gradient value, it is possible to calculate the water flow through each joint set that defines the unit block, combining the elements from Darcy’s law (Eq. 6.1) and Eq. 2.1. In Darcy’s law (Eq. 6.1), the flow Q [m³/s] is given by multiplying the hydraulic conductivity K [m/s] by the cross-sectional area to the flow A [m²] and the hydraulic gradient, which is equal to the ratio between the difference of hydraulic head dh [m] and the length dl [m] over which the value dh is considered (Darcy 1856).
To estimate the water flow in a single joint, assuming a parallel-plate mode, Eq. 2.2 and Darcy's law (Eq. 6.1) may be combined as the following:

\[ Q = -(2b)^2 x \frac{g}{12 \mu} x A_{joint} x \frac{dh}{dt} \]  

(Eq. 6.2)

To better assess the unit block, let's consider a system that contains a single joint from the set 044/88 (Fig. 6.6a). It is assumed that the mean joint aperture value (66.9 μm) previously calculated may be considered for each single joint. Therefore, for the system represented on Fig. 6.6a:

\[ Q = (6.69 \times 10^{-5})^2 x \frac{999.96 \times 9.81}{12 \times 1.519 \times 10^{-3}} x (1.55 \times 1.06 \times 10^{-4}) x \frac{0.1}{0.5} \]

\[ \therefore Q \approx 5.00 \times 10^{-8} \text{m}^3/\text{s} \]

A flow rate value of approximately 5.00x10^{-8} m^3/s is obtained for water flow through a joint of the set 044/88 of the unit block (Fig. 6.6a).

Then, it is also possible to estimate the hydraulic conductivity of an equivalent porous media (Fig. 6.6b), using Darcy’s law (Eq. 6.1). It is supposed that it would have the same water flow calculated for the single joint, so:

\[ Q = -K x A x \frac{\Delta h}{\Delta l} \]

\[ 5.00 \times 10^{-8} = K \times (1.55 \times 1.5) \times \frac{0.1}{0.5} \]
A hydraulic conductivity value of approximately $1.08 \times 10^{-7}$ m/s is obtained for the equivalent porous media (Fig. 6.7b) of the block diagram that comprehends a joint of the set oriented 044/88 (Fig. 6.6a). This value is in accordance with the hydraulic conductivity calculated by Chesnaux (accepted), as they have the same order of magnitude.

Fig. 6.6 (a) A rock volume that contains one joint of the set 044/88 in its center. Its dimensions are 1.5 x 0.5 m, and correspond to the spacing of this joint set and the height of the unit block, respectively. The side not shown in the sketch corresponds to the edge from the hexagonal base of the unit block formed by the set 044/88, with a width of 1.55 m (values introduced on chapter 5).

(b) Equivalent porous media representation of the previous rock volume.

The average velocity of water flow is very important for the cases of contaminant flow through fractured aquifers and to the restoration of these aquifers. Given the water flow rate through a joint, the value of the average velocity $v_{\text{joint}}$ [m/s] of water through the joint can be estimated. This parameter may be compared to the value of infiltration velocity $v_i$ [m/s] obtained for a porous media with the same water flow rate, and for which a realistic
value of effective porosity $n_{ef}$ [dimensionless] is assumed. The velocities for each media are given by the following equations:

\[ v_{joint} = \frac{Q}{A} \]

\[ v_{joint} = \frac{q}{2b \times l} \quad \text{(Eq. 6.3)} \]

\[ v_i = \frac{q}{A \times n_{ef}} \quad \text{(Eq. 6.4)} \]

Therefore, for the fractured media:

\[ v_{joint} = \frac{Q}{2b \times l} \]

\[ v_{joint} = \frac{1.08 \times 10^{-7}}{6.69 \times 10^{-5} \times 0.5} \]

\[ v_{joint} \approx 3.23 \times 10^{-3} \text{m/s} \]

For the porous media, assuming an effective porosity of 30%:

\[ v_i = \frac{Q}{A \times n_{ef}} \]

\[ v_i = \frac{1.08 \times 10^{-7}}{(1.55 \times 1.50) \times 0.30} \]

\[ v_i \approx 1.55 \times 10^{-7} \text{m/s} \]

Thus, for a volume of rock mass containing a single joint (Fig. 6.6a) and a similar volume constituted of an equivalent porous media (Fig. 6.6b), the water flow through the joint from the first system has to be about 4 orders of magnitude faster than through the
pores from the second one ($3.23 \times 10^{-3} \text{ m/s versus } 1.55 \times 10^{-7} \text{ m/s}$), in order to maintain the same flow rate.

**6.3.3 Hydraulic conductivity tensor**

The hydraulic conductivity tensor of a fractured rock mass allows the quantification of its anisotropy, considering geometrical parameters of the joints, such as their aperture, orientation and spacing (Bianchi & Snow 1968; Snow 1969; Oda 1985; Raven 1986). It is assumed that the joints are parallel and continuous conduits, interference effects at intersections are negligible and there is a single-phase, non-turbulent flow of incompressible Newtonian fluid through the joints (Raven 1986).

The hydraulic conductivity tensor $K_{ij}$ of a continuous media equivalent to a joint system is given by (Snow 1965):

$$K_{ij} = \frac{\rho g x (2b)^3}{12 x \mu x W} (\delta_{ij} - M_{ij})$$

(Eq. 6.5)

where $W$ is the effective joint spacing, $\delta_{ij}$ is the Kronecker delta, and $M_{ij}$ is a 3x3 matrix formed by the direction cosines of the normal to the conduit (that is, of the joint pole).

Matrix $M_{ij}$ is given by (Bianchi & Snow 1968; Snow 1969):

$$M_{ij} = \begin{bmatrix} Q_x \cdot Q_x & Q_x \cdot Q_y & Q_x \cdot Q_z \\ Q_y \cdot Q_x & Q_y \cdot Q_y & Q_y \cdot Q_z \\ Q_z \cdot Q_x & Q_z \cdot Q_y & Q_z \cdot Q_z \end{bmatrix}$$

(Eq. 6.6)

where $Q_x, Q_y$ and $Q_z$ are the direction cosines of the joint pole.
Next, regarding the unit block from Fig. 5.10, the input data for Eq. 6.5 is shown on Table 6.1.

**Table 6.1** Data available for calculating the hydraulic conductivity tensor for the unit block from Fig. 5.10.

<table>
<thead>
<tr>
<th>Strike</th>
<th>Dip</th>
<th>Trend</th>
<th>Plunge</th>
<th>2b (m)</th>
<th>Qx</th>
<th>Qy</th>
<th>Qz</th>
<th>μ (kg/s.m)</th>
<th>p (kg/m³)</th>
<th>g (m/s²)</th>
<th>W² (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>44</td>
<td>88</td>
<td>314</td>
<td>2</td>
<td>6.69x10⁻⁵</td>
<td>0.6942</td>
<td>-0.7189</td>
<td>0.0349</td>
<td>0.001519</td>
<td>999.96</td>
<td>9.81</td>
<td>1.5</td>
</tr>
<tr>
<td>139</td>
<td>84</td>
<td>49</td>
<td>6</td>
<td>6.95x10⁻⁵</td>
<td>0.6525</td>
<td>0.7506</td>
<td>0.1045</td>
<td>0.001519</td>
<td>999.96</td>
<td>9.81</td>
<td>1.68</td>
</tr>
<tr>
<td>95</td>
<td>86</td>
<td>5</td>
<td>4</td>
<td>7.54x10⁻⁵</td>
<td>0.9938</td>
<td>0.0869</td>
<td>0.0698</td>
<td>0.001519</td>
<td>999.96</td>
<td>9.81</td>
<td>2.15</td>
</tr>
<tr>
<td>70</td>
<td>4</td>
<td>340</td>
<td>86</td>
<td>4.64x10⁻⁵</td>
<td>0.0656</td>
<td>-0.0239</td>
<td>0.9976</td>
<td>0.001519</td>
<td>999.96</td>
<td>9.81</td>
<td>0.5</td>
</tr>
</tbody>
</table>

¹ Calculated with Eq. 2.1. An example for the joint set 044/88 was previously shown.  
² Calculated after Terzaghi’s correction.

Applying the data from Table 6.1 into Eq. 6.5 for each joint set, the following hydraulic conductivity tensors are obtained:

\[
K_{044/88} = \begin{bmatrix}
5.57 \times 10^{-8} & 5.37 \times 10^{-8} & -2.60 \times 10^{-9} \\
5.37 \times 10^{-8} & 5.19 \times 10^{-8} & 2.70 \times 10^{-9} \\
-2.60 \times 10^{-9} & 2.70 \times 10^{-9} & 1.07 \times 10^{-7}
\end{bmatrix}
\]

\[
K_{139/84} = \begin{bmatrix}
6.17 \times 10^{-8} & -5.26 \times 10^{-8} & -7.33 \times 10^{-9} \\
-5.26 \times 10^{-8} & 4.69 \times 10^{-8} & -8.43 \times 10^{-9} \\
-7.33 \times 10^{-9} & -8.43 \times 10^{-9} & 1.06 \times 10^{-7}
\end{bmatrix}
\]

\[
K_{095/86} = \begin{bmatrix}
1.34 \times 10^{-9} & -9.29 \times 10^{-9} & -7.45 \times 10^{-9} \\
-9.29 \times 10^{-9} & 1.07 \times 10^{-7} & -6.52 \times 10^{-10} \\
-7.45 \times 10^{-9} & -6.52 \times 10^{-10} & 1.07 \times 10^{-7}
\end{bmatrix}
\]

\[
K_{070/04} = \begin{bmatrix}
1.07 \times 10^{-7} & 1.68 \times 10^{-10} & -7.03 \times 10^{-9} \\
1.68 \times 10^{-10} & 1.07 \times 10^{-7} & 2.56 \times 10^{-9} \\
-7.03 \times 10^{-9} & 2.56 \times 10^{-9} & 5.23 \times 10^{-10}
\end{bmatrix}
\]

The contribution from the individual joint sets are added resulting in a symmetric tensor \( K' \). It may be later diagonalized in the tensor \( K \), in order to obtain the principal hydraulic
conductivities for the Kenogami uplands. The diagonalization of $K'$ was done with the software MATLAB\textsuperscript{15}.

$$K' = \begin{bmatrix} 2.58 \times 10^{-7} & -8.11 \times 10^{-9} & -2.44 \times 10^{-8} \\ -8.11 \times 10^{-9} & 3.13 \times 10^{-7} & -3.83 \times 10^{-9} \\ -2.44 \times 10^{-8} & -3.83 \times 10^{-9} & 3.21 \times 10^{-7} \end{bmatrix}$$

$$K = \begin{bmatrix} 2.48 \times 10^{-7} & 0 & 0 \\ 0 & 3.14 \times 10^{-7} & 0 \\ 0 & 0 & 3.29 \times 10^{-7} \end{bmatrix}$$

### 6.4 The conceptual model

A basic unit that characterizes the joint system in the Kenogami uplands was defined through the unit block. This was done at a local scale (block volume of $1.25m^3$), but the results obtained with Terzaghi's correction (the bimodal spacing distributions; Appendix 8) have allowed the definition of two unit blocks with different sizes (Figs. 5.10 and 5.13). As the two different sizes of block were observed within a same outcrop, it is reasonable to assume that its geometry could be also extrapolated to the regional context. Moreover, defining two unit blocks of different sizes is interesting for numerical modeling: it may be used, for instance, to refine the model mesh; the smaller block may be used to model lineaments related to more densely fractured zones and faults, while the larger block would constitute the rest of the fractured media. The geometry of the unit block may still be used to represent less densely fractured zones, previously discussed (Figs. 4.1f and 6.2a; section 5.3).

As previously discussed, subvertical joints are the main fracturing expression in the Kenogami uplands, and they have an important role regarding groundwater recharge.

paths. Provided the great extent of outcropping crystalline rocks in the Kenogami uplands, and even in the SLSJ region, it is reasonable to assume that the study area is better interpreted as a recharge and transit region rather than simply a water storage zone. Nonetheless, the subhorizontal joint sets should not be neglected: not only they enhance the connections between the subvertical joint sets, but also contribute to the regional groundwater flow, particularly to the lowlands to the east and the west of the Kenogami uplands.

6.5 Recommendations for future studies in the Kenogami uplands

For future works in the Kenogami uplands region, the most immediate recommendation is the development of a regional flow model — possibly based on the discrete fracture network approach, using the unit block and taking into account the present stress field.

It is also advisable to perform more ATV and flowmeter loggings, as well as hydraulic tests (pumping and packer tests) within the Kenogami uplands. The determination of hydraulic properties at several sites in the study area may provide a more definitive assessment regarding their extrapolation to the regional scale, on the basis that the Kenogami uplands can be considered as a homogeneous structural domain whose local structures are repeated at the regional scale. The realization of more ATV logs would improve the data of the subhorizontal joint set from the unit block.

The analysis of thin sections may be interesting as well, in order to verify the existence of infillings, with regard to the various joint sets, and to check the indicators of sense of movement along fault surfaces. The magmatic bedding and the kinematic indicators of shear zones in anorthosite and gabbro could be better described with the help of thin sections.
Finally, regarding lineament analysis, four main advices are given below.

1) Verification of the lineament map by another interpreter, as this is a subjective analysis;

2) A longer fieldwork campaign in order to analyze possible relationships between lineaments and more densely fractured zones, as this could not be documented during this research;

3) Plot of cumulative frequency of wells versus specific capacity for different categories of wells, e.g.: (i) wells at different distances from any type of lineaments, (ii) wells close to lineaments that bear the same trend of measured fractures in nearby outcrops, (iii) wells close to lineaments that do not correlate to any of the fracture trends that were measured in nearby outcrops, (iv) wells close to ductile shear zones, (v) wells close to brittle shear zones, (vi) lineament directions to which the wells are closest. The PACES-SLSJ gathered a large database on wells in the SLSJ region that could be useful for some of these analyses;

4) More detailed analysis of the brittle shear zones found during this research (and other possibly existing ones). Verification of the existence of wells in their surroundings and analysis of the production of wells regarding the core and the damage zone from each shear zone.
CONCLUSIONS

This project allowed the characterization of an aquifer in fractured crystalline rocks, regarding the following aspects: joint systems at different scales, past stress fields, hydraulic properties and the possible relationships between these parameters. The methodology adopted proved itself efficient and may be applied to other studies on fractured rock aquifers. The example of the Kenogami uplands has contributed to increase the knowledge on aquifers and groundwater in Quebec, particularly in fractured rock terrains, as most of the PACES (Programme d'acquisition de connaissances sur les eaux souterraines du Québec) projects include that type of aquifer.

The results obtained are summarized in the following paragraphs, in relation with the four questions proposed as the objectives (chapter 1) of this study.

In the general survey\textsuperscript{16}, five joint sets were identified in the Kenogami uplands. The study area is considered to be a single structural domain, as the five joint sets may be found all over the study area and their relative importance is the same in the different lithologies present in the area.

\textsuperscript{16} Question 1: Is there a structured joint system in the bedrock, that is, is it possible to identify preferential joint orientations and structural domains?
The lineament analyses\textsuperscript{17} at scales 1:20,000 and 1:1,000 allowed the identification of structures mainly oriented NW-SE. This coincides with the main joint set orientation from the general survey. The lineament trending WNW-ESE is also important; it is parallel to the main roads in the study area, which, in turn, are parallel to the Saguenay graben axis, as well as to another joint set identified in the field despite unfavorable bias of orientation of most observation faces. The occurrence of the same structural trends at different scales was also illustrated by the data obtained with the application of Terzaghi's correction on scanlines, as two different sizes of the unit block were defined; this suggests that the geometry of the unit block could be used at other scales as well. Therefore, there is a clear correlation between structures at local and regional scales in the Kenogami uplands.

The observations made on horizontal outcrops\textsuperscript{18} allowed the determination of conjugate pairs of joints and of the orientation of the main components of past stress fields. Four different conditions were identified on the 13 outcrops analyzed. Regarding the present stress field (oriented NE-SW), it should be remarked that it tends to close the joints of the main set in the Kenogami uplands, oriented NW-SE, as well as the sets 139/84 and 085/86 from the unit block. On the other hand, the set 044/88 considered in the unit block and the other subvertical sets from the general survey tend to remain open.

The flowmeter test\textsuperscript{19} could only be performed at one of the three wells logged in the Kenogami uplands. Nonetheless, when the results are compared to other logs done in the SLSJ during the PACES campaign, it is observed that the conductive joints usually have

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\textsuperscript{17} Question 2: Can joint systems be defined at different scales (e.g. regional and local ones)? If yes, are there any relationships between the systems observed at different scales?

\textsuperscript{18} Question 3: Can any correlation between the joint system(s) and the past and present stress fields be identified?

\textsuperscript{19} Question 4: Is there a relationship between the hydrogeological properties obtained from boreholes and the joint system(s)?
directions around 200°, 270° and 330°, and they are all mostly dipping up to 30°. As they all have northerly dip directions and low angle dip, the present day stress field will tend to open them. It may be also suggested that the most conductive joints have a preferential orientations, which could be confirmed with the logging of other wells in the region, particularly in the uplands.

A conceptual model for the fractured rock aquifer in the Kenogami uplands was developed, taking advantage of the unit block. As previously discussed, the unit block may be extrapolated to a regional scale, and the subvertical joints are the most expressive ones in the study area. These are considered as the main path for groundwater recharge, particularly the sets that tend to be open with the present stress field. Nonetheless, the subhorizontal joints should not be neglected: as previously shown, the subhorizontal joints are the most transmissive ones in the wells, particularly in the first 100m. Moreover, the subhorizontal joints enhance the connections between the subvertical joint sets and represent an important path for regional flow, particularly to the adjacent lowlands to the east and the west of the Kenogami uplands.

Finally, the other contributions from this work are: (1) the highlight of the value of constructing a unit block to characterize a fractured media for hydrogeological studies; (2) the exemplification of how to combine the structural data used for the unit block with calculated hydraulic properties; (3) the introduction of a method for applying Terzaghi's correction on computers to obtain information regarding the size and geometry of the unit block, without the need for specialized softwares; (4) the emphasis on the possible polymodal distributions of joint spacing, and the care to be taken when estimating average spacing values over a scanline; (5) the application of the analysis of structures on
subhorizontal outcrops for obtaining the orientation of the main components of past stress fields.


Chesnaux, R. (accepted). Regional recharge assessment in the crystalline bedrock aquifer of the Kenogami uplands, Canada. *Hydrogeological Sciences Journal*.


d'Acquisition de Connaissances sur les Eaux Souterraines du Québec. 86p and 30 maps.
Definitions adopted in the present work, regarding terms of current use.

- **Dip**: maximum angle from which a planar feature deviates from the horizontal. This angle is measured in a plane perpendicular to the strike.
- **Dyke**: a sheet-like or tabular igneous intrusion that cuts through a host rock.
- **Fault**: fracture across which there has been relative displacement (the movement is determined by kinematic indicators). Its two sides are known as *fault walls*.
- **Fracture**: general term to indicate a physical discontinuity in a rock mass; may refer either to a joint or a fault.
- **Groove**: a long narrow furrow or channel.
- **Joint**: *fractures that show no discernible relative displacements* (Hodgson 1961; Price 1966; Hancock 1985; Dunne & Hancock 1987; Ramsay & Huber 1987). Joints are considered as the most common result of brittle deformation (Pollard & Aydin 1988).
- **Joint set**: group of joints whose poles form a concentration on a stereonet of 20° or less in angular width; it is an analytical classification of joints.
- **Joint system**: the configuration of joints as they are seen in nature.
• **Kinematic indicator**: geological structures or features that may provide information on the direction, magnitude and mode of transport of a given rock bulk (Bull et al. 2009).

• **Lineament**: mappable recti-linear feature on the Earth surface, e.g. a straight stream or a ridge, that commonly reflects a subsurface structure (O’Leary et al. 1976).

• **Pole**: line orthogonal in space to a given planar surface.

• **Shear**: stress that slices rocks into parallel blocks that slide in opposite directions along their adjacent sides.

• **Slickenside**: striations and grooves on a fault wall parallel to the direction of movement (Tjia 1964).

• **Step**: breaks on a fault wall. They may indicate the sense of motion of the fault walls: when no infilling is observed, the motion is on contrary to the step; if there is infilling on the fault wall, the motion is on the same sense as the step (Fig. A1.1). Steps are perpendicular or strongly oblique to slickensides. Steps are often observed on joint surfaces in crystalline rocks.

• **Strike**: direction of the horizontal line on the inclined plane of a geological structure. It is measured from true north.

• **Structural domain**: defines a region in which the same joint sets were observed everywhere.

• **Vein**: mineral tabular structure, of hydrothermal origin, that fills fractures of the host rock.
Fig. A1.1 Inferred relative displacement of fault walls based on steps and slickensides. (a) The occurrence only of the steps indicates the sense of movement is contrary to this feature. (b) The presence also of the slickensides suggests the sense of movement is contrary to the steps. Source: Tjia (1964).
APPENDIX 2

STRUCTURAL SURVEY FORMS

Outcrop description forms developed during structural survey are presented on Figs. A2.1 (detailed survey) and A2.2 (general survey). Table A2.1 presents the acronyms used for filling these forms.

---

(a)

(b)

Fig. A2.1 Outcrop description form for detailed structural survey, for both (a) scanline and (b) window methods.
**Fig. A2.2 Outcrop description form for general structural survey.**
Table A2.1 Acronyms for outcrop description forms (originally attributed in French).

<table>
<thead>
<tr>
<th>Structure type</th>
<th>Water</th>
<th>Foliation</th>
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</tr>
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<td>Dyke</td>
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<td>Fault</td>
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<td>Seepage</td>
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<td>Fracture</td>
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<td>Gneissosity</td>
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<td>Joint</td>
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<tr>
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<tr>
<td>Elongated mineral</td>
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<tr>
<td>Axe</td>
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<tr>
<td>Movement indicator type</td>
<td></td>
<td></td>
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<tr>
<td>Textures</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Structure type**
- Rock contact: Cr
- Dyke: Dy
- Fault: Fa
- Fracture: Fr
- Fracture: Fr
- Gneissosity: Gn
- Stria: St
- Joint: Jt
- Vein: Vn
- Mylonite: Ml
- Elongated mineral: Am
- Axe: Ax
- Groove: Cn
- Mineral: Mn
- Shear zone: ZC
- Magmatic bedding: LM

**Water**
- Flow: Ec
- Humidity: Hm
- Rust: Ro
- Seepage: Su

**Foliation**
- Yes: O
- No: N

**General**
- No data
- Does not apply: -
- No: N

**Joint termination**
- Visible: V
- Not visible: N

**Joint aperture**
- Free: L
- Filled: R

**Shear direction**
- Sinistral: S
- Dextral: D

**Movement indicator type**
- negative (observed on the rock): neg
- positive (observed in the filling): pos

**Textures**
- Aphanitic: A
- Phaneritic: H
- Porphyritic: P
- Granoblastic: B
- Porphyroblastic: O

**Grades**
- Clear "step", visible: A
- Ok "step": B
- Uncertain "step": C
APPENDIX 3

OUTCROP DATA

In the following, summarized data on every outcrop visited during the general survey is presented. Information follows the same format as the fieldwork forms (Appendix 2): outcrop identification, UTM zone and coordinates, outcrop orientation, outcrop dimension, environment, lithology, state of weathering (fresh or weathered), main structures, other observations.
<table>
<thead>
<tr>
<th>Outcrop ID</th>
<th>UTM Zone</th>
<th>Location</th>
<th>Orientation</th>
<th>Dimension</th>
<th>Environment</th>
<th>Lithology</th>
<th>Fresh or weathered</th>
<th>Structure</th>
<th>Observations</th>
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<td>Orientation</td>
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<td>Environment</td>
<td>Lithology</td>
<td>Fresh or weathered</td>
<td>Structure</td>
<td>Observations</td>
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</table>

Environmental observations:
- Shear zone.
- Lots of vegetation.
- The top of the outcrop is rounded due to weathering.
- Occurrence of exfoliation.
- Light green weathering.
- Possible shear zone in opposite side of the road, 10m to north.
- Not easy to reach, as there is a creek to cross and there are not many places to climb the outcrop.
<table>
<thead>
<tr>
<th>Outcrop ID</th>
<th>UTM Zone</th>
<th>Location</th>
<th>Orientation</th>
<th>Dimension</th>
<th>Environment</th>
<th>Lithology</th>
<th>Fresh or weathered</th>
<th>Structure</th>
<th>Observations</th>
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<td>Environment</td>
<td>Lithology</td>
<td>Fresh or Weathered</td>
<td>Structure</td>
<td>Observations</td>
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<td>gneiss with granitic veins (K-feldspar)</td>
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<td>20m to E, there is a massif outcrop with the same lithology.</td>
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<td>Slippery surface.</td>
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<td>gneiss</td>
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<td>Lots of vegetation.</td>
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<td>poorly fractured</td>
<td>Joints on the top; slippery surface.</td>
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<td>Non-continuous outcrop, 30% covered by dirt and vegetation.</td>
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<td>165</td>
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<td>Orientation Dir.</td>
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<td>Environment</td>
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<td>gneiss with pegmatitic vein</td>
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<td>UTM Zone</td>
<td>Location</td>
<td>Orientation</td>
<td>Dimension</td>
<td>Environment</td>
<td>Lithology</td>
<td>Fresh or weathered</td>
<td>Structure</td>
<td>Observations</td>
</tr>
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<td>536500</td>
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<td>anorthosite</td>
<td>F</td>
<td>fractured; shear zone</td>
<td>S-C pair: dextral movement.</td>
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<td>3212019</td>
<td>5370507</td>
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<td>roadside</td>
<td>anorthosite and gabbro</td>
<td>F</td>
<td>fractured</td>
<td>Magmatic bedding // schistosity. Tonalitic (?) vein.</td>
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<td>DP-158</td>
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<td>5372235</td>
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<td>granite (?) with pegmatitic veins</td>
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<td>granitoide, limestone</td>
<td>W</td>
<td>fractured</td>
<td></td>
</tr>
<tr>
<td>DP-237</td>
<td>19U</td>
<td>345233</td>
<td>0</td>
<td></td>
<td>quarry</td>
<td>limestone</td>
<td>W</td>
<td>fractured</td>
<td></td>
</tr>
<tr>
<td>DP-238</td>
<td>19U</td>
<td>320648</td>
<td>110</td>
<td>150,0</td>
<td>roadside</td>
<td>anorthosite</td>
<td>W</td>
<td>fractured</td>
<td></td>
</tr>
<tr>
<td>DP-239</td>
<td>19U</td>
<td>320525</td>
<td>275</td>
<td>65</td>
<td>roadside</td>
<td>anorthosite</td>
<td>F</td>
<td>fractured</td>
<td></td>
</tr>
<tr>
<td>Outcrop ID</td>
<td>UTM Zone</td>
<td>Location X</td>
<td>Location Y</td>
<td>Orientation Dir.</td>
<td>Orientation Dip</td>
<td>Dimension X</td>
<td>Dimension Y</td>
<td>Environment</td>
<td>Lithology</td>
</tr>
<tr>
<td>------------</td>
<td>----------</td>
<td>------------</td>
<td>------------</td>
<td>------------------</td>
<td>----------------</td>
<td>-------------</td>
<td>-------------</td>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>DP-240</td>
<td>19U</td>
<td>320263</td>
<td>5367632</td>
<td>290</td>
<td>65</td>
<td>120,0</td>
<td>8,0</td>
<td>roadside</td>
<td>anorthosite</td>
</tr>
<tr>
<td>DP-241</td>
<td>19U</td>
<td>320136</td>
<td>5367757</td>
<td>115</td>
<td>60</td>
<td>100,0</td>
<td>5,0</td>
<td>roadside</td>
<td>anorthosite</td>
</tr>
<tr>
<td>DP-242</td>
<td>19U</td>
<td>319897</td>
<td>5367797</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>roadside</td>
<td>anorthosite</td>
</tr>
<tr>
<td>DP-243</td>
<td>19U</td>
<td>317104</td>
<td>5376968</td>
<td>110</td>
<td>60</td>
<td>2,0</td>
<td>1,0</td>
<td>near a lake</td>
<td>gabbro</td>
</tr>
<tr>
<td>DP-244</td>
<td>19U</td>
<td>317054</td>
<td>5379687</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>near a lake</td>
<td>anorthosite</td>
</tr>
<tr>
<td>DP-245</td>
<td>19U</td>
<td>317279</td>
<td>5379627</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>near a lake</td>
<td>gabbro</td>
</tr>
<tr>
<td>DP-246</td>
<td>19U</td>
<td>316180</td>
<td>5378343</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>cliff</td>
<td>gabbro</td>
</tr>
<tr>
<td>DP-247</td>
<td>19U</td>
<td>316209</td>
<td>5378327</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>cliff</td>
<td>gabbro</td>
</tr>
<tr>
<td>DP-248</td>
<td>19U</td>
<td>320178</td>
<td>5367859</td>
<td>185</td>
<td>60</td>
<td>2,0</td>
<td>1,0</td>
<td>transmission tower</td>
<td>anorthosite with magnetite</td>
</tr>
<tr>
<td>DP-249</td>
<td>19U</td>
<td>320191</td>
<td>5367876</td>
<td>130</td>
<td>50</td>
<td>20,0</td>
<td>1,0</td>
<td>transmission tower</td>
<td>anorthosite</td>
</tr>
<tr>
<td>DP-250</td>
<td>19U</td>
<td>320219</td>
<td>5367931</td>
<td>230</td>
<td>30</td>
<td>2,5</td>
<td>1,5</td>
<td>woods, next to transmission tower</td>
<td>anorthosite</td>
</tr>
<tr>
<td>DP-251</td>
<td>19U</td>
<td>318862</td>
<td>5368669</td>
<td>170</td>
<td>70</td>
<td>15,0</td>
<td>2,0</td>
<td>woods</td>
<td>anorthosite</td>
</tr>
<tr>
<td>DP-252</td>
<td>19U</td>
<td>319280</td>
<td>5368491</td>
<td>128</td>
<td>70</td>
<td>30,0</td>
<td>4,0</td>
<td>woods</td>
<td>granitoide with magnetite concentrations (~1cm²)</td>
</tr>
<tr>
<td>DP-253</td>
<td>19U</td>
<td>320094</td>
<td>5368943</td>
<td>240</td>
<td>70</td>
<td>100,0</td>
<td>10,0</td>
<td>woods</td>
<td>anorthosite with magnetite</td>
</tr>
</tbody>
</table>

139
<table>
<thead>
<tr>
<th>Outcrop ID</th>
<th>UTM Zone</th>
<th>Location</th>
<th>Orientation</th>
<th>Dimension</th>
<th>Environment</th>
<th>Lithology</th>
<th>Fresh or weathered</th>
<th>Structure</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP-254</td>
<td>19U</td>
<td>320468 5369122</td>
<td>200 30</td>
<td>10.0 0.8</td>
<td>roadside</td>
<td>anorthosite</td>
<td>W</td>
<td>fractured</td>
<td>Superficial white weathering.</td>
</tr>
<tr>
<td>DP-255</td>
<td>19U</td>
<td>320259 5368858</td>
<td>0 50</td>
<td>30.0 1.6</td>
<td>roadside</td>
<td>anorthosite</td>
<td>W</td>
<td>fractured</td>
<td></td>
</tr>
<tr>
<td>DP-256</td>
<td>19U</td>
<td>321164 5367548</td>
<td>104 85</td>
<td>50.0 3.0</td>
<td>roadside</td>
<td>anorthosite</td>
<td>W</td>
<td>fractured</td>
<td>Subhorizontal (dip = 07°) fractures spaced 50cm-1m. Chloritization observed in one fracture.</td>
</tr>
<tr>
<td>DP-257</td>
<td>19U</td>
<td>321201 5367874</td>
<td>311 70</td>
<td>3.0 2.0</td>
<td>roadside</td>
<td>anorthosite</td>
<td>W</td>
<td>fractured</td>
<td></td>
</tr>
<tr>
<td>DP-258</td>
<td>19U</td>
<td>321277 5368131</td>
<td>40 40</td>
<td>30.0 1.5</td>
<td>roadside</td>
<td>anorthosite</td>
<td>W</td>
<td>fractured</td>
<td></td>
</tr>
<tr>
<td>DP-259</td>
<td>19U</td>
<td>321260 5368217</td>
<td>100 75</td>
<td>60.0 3.0</td>
<td>woods</td>
<td>anorthosite</td>
<td>W</td>
<td>fractured</td>
<td></td>
</tr>
<tr>
<td>DP-260</td>
<td>19U</td>
<td>321181 5368213</td>
<td>95 65</td>
<td>2.0 1.5</td>
<td>woods</td>
<td>anorthosite</td>
<td>W</td>
<td>fractured</td>
<td>Rust.</td>
</tr>
<tr>
<td>DP-261</td>
<td>19U</td>
<td>321159 5368214</td>
<td>355 76</td>
<td></td>
<td>woods</td>
<td>anorthosite</td>
<td>W</td>
<td>fractured</td>
<td></td>
</tr>
<tr>
<td>DP-262</td>
<td>19U</td>
<td>320853 5368754</td>
<td></td>
<td></td>
<td>roadside</td>
<td>limestone</td>
<td>W</td>
<td>fractured</td>
<td></td>
</tr>
<tr>
<td>DP-263</td>
<td>19U</td>
<td>320762 5368644</td>
<td></td>
<td></td>
<td>roadside</td>
<td>limestone</td>
<td>W</td>
<td>fractured</td>
<td></td>
</tr>
<tr>
<td>DP-264</td>
<td>19U</td>
<td>257445 5386111</td>
<td></td>
<td></td>
<td>roadside</td>
<td>limestone</td>
<td>W</td>
<td>fractured</td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX 4

OTHER SUGGESTED PROCEDURES

The approaches described below were considered during the phases of fieldwork and data analysis; the first two were actually tested. They include: (1) panoramic photographs assemblages; (2) application of Terzaghi's correction over a rock face ("window"); (3) LiDAR. Nonetheless, they were considered relatively time demanding or costly, regarding the results provided, and thus were not used in the scope of this project.

A4.1 Panoramic Photographs

During the general survey, selected outcrops were submitted to series of photographs in order to generate panoramic mosaics. Good outcrops for a panoramic mosaic are wide (at least 50m long), approximately straight and, of course, with as many families of visible joints as possible.

The photographs are taken perpendicularly to the outcrop, to reduce distortion, and far enough from it to make visible the whole outcrop. The distance between photographs along an outcrop should be enough to ensure an overlap of about 50% between
photographs. The photograph mosaics (Fig. A4.1) were made using Adobe Photoshop Elements 7\textsuperscript{20}, and the joints and outcrops contours are drawn with CorelDRAW\textsuperscript{21}.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig_a4_1.png}
\caption{In both figures, red lines delineate the outcrop contour; yellow lines indicate joints. (a) Assembling of panoramic photographs. (b) Detailed view. Photos: D. S. Pino.}
\end{figure}

Photograph mosaics may be useful to better visualize the joint sets, particularly the subhorizontal ones; to identify joints that are too high on the outcrop face to be measured; and to help locate sections to be submitted to detailed survey (see section A4.2). As the photographs are taken perpendicularly to the outcrop and with scale markers, they allow the approximation to Terzaghi’s correction regarding a window survey.

A4.2 Terzaghi's correction over a window

The correction of the orientation bias over a window is similar to the one applied for a scanline. Let's consider the joint J that intersects the window W at a vector \( \mathbf{I} \) (Fig. A4.2).

![Fig. A4.2 Initial features considered in the bias correction over a window: joint plane (J), outcrop face or window (W), intersection between J and W (\( \mathbf{I} \)). The window's strike (\( \alpha \)) and dip (\( \delta \)) are also represented. Original sketch by: D. W. Roy.](image)

The angle \( \alpha \) between the joint pole and the window pole is calculated first. It allows the calculation of the direction cosine of the intersection \( \mathbf{I} \), by the vectorial product between the joint and the window poles. This direction cosine is used to calculate the angle \( \beta \) between the window strike and the intersection (Fig. A4.3).

The weight attributed to each joint in the window procedure is also given by \( 1/\sin\alpha \), although it is multiplied by the factor \( dW/Lt \) to standardize all weights, where \( dW \) is the window diagonal and \( Lt \) is the equivalent observation length of the joint (Fig. A4.3). The latter is calculated by trigonometry.
Fig. A4.3 Planar view of the window, defined by its length B and its high H. By trigonometry, the angle \( \beta \) between the intersection \( I \) and the window base B provides the value of the equivalent observation length \( L_t \). The maximum value \( L_t \) might have is equal to the window diagonal. Original sketch by: D. W. Roy.

The corrected density plot is done in the same way as for the scanline, that is, using the weight multiplied by 10 due to plotting software limitations. Similarly, a blind zone of ±20° with respect to the pole of the window plane is considered for the window\(^{22}\), and for all joints inside it, a new weight equal zero is attributed.

Finally, the corrected frequency for each joint set is calculated by the inverse of its weight and for the ensemble by the arithmetic average of the individual frequencies. The definition of a station follows the same procedure applied to the scanline; windows and scanlines may be combined in a same station.

\(^{22}\) The blind zone in the case of a scanline forms a cone, represented by a small circle on the stereoplot. In the case of a window survey, the blind zone is represented by a great circle.
It should be noted that the photograph window approach is not as precise as the scanline one. As mentioned on section 4.3.4, during a scanline study all joints are measured, so it is possible to know the location of each joint on the scanline. In the photograph window approach, though, only the reachable subhorizontal joints are measured (usually up to 1.5m high, or up to 2m when it is possible to climb on the outcrop), and by comparison of joint traces in the outcrop, the orientation values of accessible joints are attributed to the ones located on the top. At this point, it should be mentioned that printing a large photograph of the area where the window survey is planned is truly helpful to asserting the orientation values while taking the measurements. Due to a tight schedule, in the present work the photographs were taken during the same visit as the subhorizontal joints measurements, which later made it harder to make the correlations between the orientations of the measured joints on the bottom of the outcrop and the unreachable ones on the top.

**A4.3 LiDAR: Light Distance And Ranging**

A ground-based LiDAR, also referred to as a 3D laser scanning, is an instrument that rapidly sends laser pulses and calculates the three dimensional position of reflected objects (Fig. A4.4) (Kemeny *et al.* 2006; Harrap & Lato 2010).

The LiDAR uses the same principles of an ordinary radar; however, it uses a narrow pulsed beam of light instead broad radio waves (Kemeny *et al.* 2006). The speed of light and very precise time devices are used to calculate the distance between the instrument and the object reflecting the beam, as long as the position and pointing direction of the laser are known for each measurement (Harrap & Lato 2010). LiDAR may collect data from airborne or terrestrial vehicles, from fixed positions (e.g. a tripod) and from offshore
platforms (Harrap & Lato 2010). Using multiple scanning locations and orientations is always recommended (Lato et al. 2010).

The interest in the LiDAR device for rock assessments increased with its development (Lato et al. 2007, 2009, 2010; Pate & Haneberg 2011). Nowadays, there are equipments capable of collecting data at rates higher than 2000 points per second, with a position accuracy of around 5mm at distances up to 800m (Kemeny et al. 2006). It is important to notice that LiDAR’s accuracy is limited by the accuracy to which its location is known (Harrap & Lato 2010). Nonetheless, laser scan-based surveys and automated analyses may be faster, less laborious and thus cheaper than traditional surveys and analyses (Kemeny et al. 2006).

The data obtained with a laser survey is a “point cloud”, consisted of millions of reflection points representing the three dimensional surface scanned and usually coded
with the intensity of light return. With data cleaning, a triangulated face is obtained, allowing many other calculations and visualizations, such as extracting information about discontinuities (e.g. orientation, spacing and roughness) and plotting information on stereonets and histograms (Kemeny et al. 2006). Moreover, digital images may be overlaid onto the 3D surface.

Finally, two major challenges with LiDAR use may be mentioned (Harrap & Lato 2010): (1) the nonexistence of a software capable of all necessary steps from input to model creation, requiring file transfer between tools and formats; (2) the large amount of data on the point clouds, rendering its processing a very slow procedure.
Here are explained the procedures for the numerical application of Terzaghi’s correction over a scanline and the following analysis of true joint spacing.

A5.1 Terzaghi’s correction

The numerical method of Terzaghi’s correction applied on this project uses the data from the detailed survey description form. All the calculi were made on Microsoft® Excel tables. The first two lines are reserved to titles and the third to information regarding the scanline (trend and plunge); the structures are listed from the fourth line. As to the columns, they are arranged as in Table A5.1.

A5.2 Joint spacing analysis: virtual position of joints

The application of Terzaghi’s correction over a scanline usually provides one or two corrected joint poles. Only the joints whose poles that form 20° or less with a corrected pole are considered to be part of the “corrected joint set” (the joints shown on Fig. 4.5) to calculate the true joint spacing of a corrected set.

The distance $d'$ is calculated by $\sin \alpha = d'/d$, where $d$ is the total outcrop or scanline length and $d'$ is the corrected length for the joint set. Then, for each joint previously
selected, it is calculated: \( \sin \alpha_{P1} = d''/(d-x) \), where \( \alpha_{P1} \) is the solid angle \( \alpha \) from the corrected pole, \( d'' \) is the joint corrected distance and \( x \) is the distance where the joint is located on the corrected length. This calculus on Microsoft® Excel is shown on Table A5.2.

Once the corrected distance is calculated for all joints, their spacing can be easily evaluated on distance diagrams (as in Fig. 4.6), to analyze its type, or on histograms, if the interest is to identify a polymodal spacing distribution, for example.

**Table A5.1** Components of the columns used in the calculus sheet for Terzaghi’s correction over a scanline. Values are described regarding the fourth line, i. e., the first line with discontinuity information; the line 100 is here assumed as the last one with such data in order of illustration. Line 101 contains information regarding the main joint pole identified on the corrected density diagram for the scanline.

<table>
<thead>
<tr>
<th>Col.</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Number of the discontinuity (ID).</td>
<td>Taken from detailed survey form.</td>
</tr>
<tr>
<td>B</td>
<td>Type of discontinuity (see Appendix 2).</td>
<td>Taken from detailed survey form.</td>
</tr>
<tr>
<td>C</td>
<td>Discontinuity strike (right hand rule).</td>
<td>Taken from detailed survey form.</td>
</tr>
<tr>
<td>D</td>
<td>Discontinuity dip.</td>
<td>Taken from detailed survey form.</td>
</tr>
<tr>
<td>E</td>
<td>Dip quadrant.</td>
<td>Taken from detailed survey form.</td>
</tr>
<tr>
<td>F</td>
<td>Position of the discontinuity in the scanline.</td>
<td>Taken from detailed survey form.</td>
</tr>
<tr>
<td>G</td>
<td>Discontinuity pole trend.</td>
<td>=if(C4&lt;90;C3+270;C4-90)</td>
</tr>
<tr>
<td>H</td>
<td>Discontinuity pole plunge.</td>
<td>=90-C4</td>
</tr>
<tr>
<td>I</td>
<td>Element ( Q_x ) from the direction cosine.</td>
<td>=cos(H3*pi()/180)<em>cos(G3</em>pi()/180)</td>
</tr>
<tr>
<td>J</td>
<td>Element ( Q_y ) from the direction cosine.</td>
<td>=cos(H3*pi()/180)<em>sen(G3</em>pi()/180)</td>
</tr>
<tr>
<td>K</td>
<td>Element ( Q_z ) from the direction cosine.</td>
<td>=sen(H3*pi()/180)</td>
</tr>
<tr>
<td>L</td>
<td>Direction cosine ( \cos \alpha ) between the discontinuity and the scanline.</td>
<td>=I$3<em>I4+J$3</em>J4+K$3*K4</td>
</tr>
<tr>
<td>M</td>
<td>Angle ( \alpha ) in degrees between the discontinuity and the scanline.</td>
<td>=(acos(abs(L4))*180/pi())</td>
</tr>
<tr>
<td>N</td>
<td>Weight attributed to the discontinuity.</td>
<td>=if(M4&gt;=70;0;1/(cos(M4*pi()/180)))</td>
</tr>
<tr>
<td>O</td>
<td>Standard weight.</td>
<td>=N4*10</td>
</tr>
<tr>
<td>P</td>
<td>Equivalent number of fractures</td>
<td>=sum(O4:O100)</td>
</tr>
<tr>
<td>Q</td>
<td>Direction cosine ( \cos \gamma_1 ) between the discontinuity and Pole 1.</td>
<td>=I$101<em>I4+J$101</em>J4+K$101*K4</td>
</tr>
<tr>
<td>R</td>
<td>Angle ( \gamma_1 ) in degrees between the discontinuity and Pole 1.</td>
<td>=(acos(abs(Q4))*(180/pi()))</td>
</tr>
<tr>
<td>S</td>
<td>Check if ( \gamma_1 \leq 10^\circ ).</td>
<td>=if(R4&lt;=10;O4;0)</td>
</tr>
<tr>
<td>T</td>
<td>Check if ( \gamma_1 \leq 20^\circ ).</td>
<td>=if(R4&lt;=20;O4;0)</td>
</tr>
</tbody>
</table>
Table A5.2 Components of the two columns to calculate the corrected distance for each joint whose pole makes 20° or less with a corrected pole over a scanline. Like on Table A5.1, values are described regarding the fourth line, i.e., the first line with discontinuity information; the line 100 is here assumed as the last one with such data in order of illustration. Line 101 contains information regarding the main joint pole identified on the corrected density diagram for the scanline.

<table>
<thead>
<tr>
<th>Col.</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>First step to calculate the corrected distance.</td>
<td>=sin(M$101<em>PI()/180)</em>(F$100-F4)</td>
</tr>
<tr>
<td>V</td>
<td>Corrected distance.</td>
<td>=sin(M$101*PI()/180)*F$100-U4</td>
</tr>
</tbody>
</table>
APPENDIX 6

GEOPHYSICAL LOGGING

The geophysical logging profiles for the wells RM001, RM004 and PZ-S18-R are shown in the following (Figs. A6.1 to A6.3). ATV interpretations done by R. H. Morin, log displays by J. Roy.

As the only geophysical logging discussed so far is the ATV, due to its input in defining the unit block subhorizontal side, this appendix also presents commentaries on other loggings that were performed in the same boreholes in the study area. The interpretation of these logging data benefited greatly from the contributions of J. Roy (IGP, Canada) and R. H. Morin (USGS).

A8.1 Other remarks on geophysical logging

In the three wells logged within the Kenogami uplands, the caliper logging confirmed the occurrence of fractures at depth (peaks in an otherwise linear log). Particularly high peaks were observed in the log of the well RM004, for depths higher than 91m (300ft). Regarding the well PZ-S18-R, the caliper also indicated a change of drill diameter below 123m (405ft), from 6" to 5"¼.
Fig. A6.1 Logs for the well RM001. From left to right: (1) stratigraphic profile, (2) water temperature and resistivity and borehole caliper, (3) rock resistivity, (4) sonic waves and natural gamma, (5) ATV image with identified joints (black sinusoids) and (6) orientation data of joints on the ATV image.
Fig. A6.2 Logs for the well RM004. From left to right: (1) stratigraphic profile, (2) water temperature and resistivity and borehole caliper (the peaks in yellow indicate instabilities of the signal received by the probe, not joints), (3) rock resistivity, (4) sonic waves and natural gamma, (5) ATV image with identified joints (black sinusoids) and (6) orientation data of joints on the ATV image.
Fig. A6.3 Logs for the well PZ-S18-R. From left to right: (1) stratigraphic profile, (2) water temperature and resistivity and borehole caliper, (3) rock resistivity and flowmeter, (4) natural gamma, (5) ATV image with identified joints (black sinusoids) and (6) orientation data of joints on the ATV image.
The natural gamma log, combined with a rock resistivity log, allowed the identification of a few lithologies in the wells logged. Well RM001 has a still undefined stratigraphy, but it has two main lithologies (one with high values of resistivity and sonic wave velocity, and another one with lower velocity and moderate resistivity values) and four possible dykes or thinner layers. These punctual higher responses of natural gamma could also represent joints filled by clay, which normally give higher values of this parameter due to the acquisition of radioisotopes by adsorption or ion exchange. Well RM004 has a single lithology, given that the values of natural gamma and rock resistivity are relatively constant. It is probably granite, as it presents natural gamma values higher than RM001, which was supposedly in anorthosite\(^{23}\), and it is located near the contact between anorthosite and granite (Figs. 3.4 and 5.4). Finally, on well PZ-S18-R the following lithologies were identified: limestone at the interval 64.01-128.02m (210-420ft), possibly gneiss at 128.02-143.26m (420-470ft) and anorthosite at 144.78-148.74m (475-488ft), while no lithology could be assigned to other depth intervals.

Regarding water resistivity, on well RM001 two levels are identified: one down to 91m (300ft), and the other from 100m to the end of the well. Water in the first level presents a higher resistivity, around 40Ω.m, indicating good quality water (low value of total dissolved solids, TDS); the reduction of water resistivity after 100m to approximately 2Ω.m indicates lower quality water (high TDS). It is interesting to notice that most joints are located in the first 100m. Well PZ-S18-R also shows a decrease of water quality with depth: 30Ω.m down to 53m (175ft), 4Ω.m at 53-128m (175-420ft), and 2Ω.m at 128-149m (420-490m). Finally, on well RM004, an almost constant resistivity is observed (approximately 25Ω.m; medium water quality), which reinforces the hypothesis of a single lithology.

\(^{23}\) The natural gamma log from well RM001 is comparable to another well that is known to be in the anorthosite, although it is located outside the Kenogami uplands. For details, see Roy et al. (2011).
The water temperature logs indicate, in general, that water temperature tends to increase below 91m (300ft).

The sonic logging on well RM004 indicates an average velocity of the primary compressional waves (Vp) equal to 5.5km/s. More pronounced negative peaks are observed at 42m (140ft) and 82-85m (270-280ft), which could be related to the decreases in natural gamma at such depths. A positive peak is observed at 97m (320ft), with no other remarkable changes. Regarding well RM001, the average Vp is 5.5km/s down to 46m (150ft), after which it increases to 6.3km/s. More variations (peaks) are present in the log for the well RM001 than for RM004. At 38m (123ft) on well RM001, a decrease in Vp coincides with a large peak in natural gamma and rock resistivity values. This suggests that a joint located at 38m is filled with a material more active (higher response to natural gamma rays) than the surrounding rock, probably rich in potassium\(^{24}\). At 47m (155ft), another decrease in Vp is also possibly related to the presence of a joint at that depth. Lastly, the increase in average Vp observed after 91m is due to a lithology change, as also suggested by the great increase in rock resistivity and the decrease in water resistivity.

The sonic logging could not be performed on well PZ-S18-R due to probe malfunction.

The flowmeter on well PZ-S18-R allowed the identification of two productive joints: one at 53.5m (175ft), oriented 331/18, and the other at 56.5m (180ft), oriented 287/11. The deeper joint is responsible for ~86% of the water inflow in the well (1.9USG/min or 0.13L/s), while the shallower joint contributes with only ~14% of the inflow (0.3USG/min or 0.02L/s). The flowmeter logging could not be performed on wells RM001 and RM004.

\(^{24}\) Potassium-40 and the products of radioactive decay of uranium and thorium are the main radioisotopes of interest in natural gamma loggings (Cripps & McCann 2000). Potassium is suggested as the most probable radioisotope present in the material filling the interpreted joint at well RM001.
because the water level could not be stabilized during the pumping test; it decreased very quickly even after the pump level and the pumping rate were lowered.
APPENDIX 7

LINEAMENT MAP WITHIN THE TPIs (INTRAMUNICPAL PUBLIC TERRITORIES)

Lineaments were traced using a shaded digital elevation model (DEM) in the Kenogami uplands (Fig. A7.1). Attention was focused within areas called TPI, territoire publique intramunicipal (intramunicipal public territories), as explained on chapter 4.
Fig. A7.1 Lineaments (yellow) identified within TPIs in the Kenogami uplands region. Observation scales were 1:20,000 (DEM's scale) and 1:1,000.
Joint spacing distributions are represented in histograms (Figs. A8.1 to A8.5). This analysis reinforces the argument that average joint spacing values over a scanline may be misleading, as exemplified here by the recurrent occurrence of bimodal distributions in the Kenogami uplands. This topic is not treated in literature, although it is possible to find a discussion on the evolution of joint spacing (Rives et al. 1992).
Fig. A8.1 Joint spacing distribution regarding joint sets that represent the set 044/88 from the unit block. Outcrop identification and respective pole of the joint set are indicated above every histogram. Spacing measured on lines orthogonal to joint plane. Spacing classes vary in width: 0.2m for spacing sizes between 0.0 and 1.0m; 0.5m, between 1.0 and 2.0m; 1m between 2.0 and 5.0m; 5.0m between 5.0 and 10.0 m; and all sizes above 10m. Observe the bimodal distribution trend. (CONTINUES)
Fig. A8.2 Joint spacing distribution regarding joint sets that represent the set 139/84 from the unit block. Outcrop identification and respective pole of the joint set are indicated above every histogram. Spacing measured on lines orthogonal to joint plane. Spacing classes vary in width: 0.2m for spacing sizes between 0.0 and 1.0m; 0.5m, between 1.0 and 2.0m; 1m between 2.0 and 5.0m; 5.0m between 5.0 and 10.0 m; and all sizes above 10m. Polymodal distributions seem to prevail. (CONTINUES)
FIG. A8.2 (CONTINUATION)

(u=50)

DP-223 | 044/14

(u=22)

DP-157 | 042/02

(u=3)

DP-156-12 | 059/07
Fig. A8.3 Joint spacing distribution regarding joint sets that represent the set 095/86 from the unit block. Outcrop identification and respective pole of the joint set are indicated above every histogram. Spacing measured on lines orthogonal to joint plane. Spacing classes vary in width: 0.2m for spacing sizes between 0.0 and 1.0m; 0.5m, between 1.0 and 2.0m; 1m between 2.0 and 5.0m; 5.0m between 5.0 and 10.0 m; and all sizes above 10m. Although not as clear as for the two other subvertical joint sets, bimodal distributions also seem to emerge from this data.

(CONTINUES)
Fig. A8.3 (CONTINUATION)

Fig. A8.4 Joint spacing distribution regarding joint sets that represent the set 070/04 from the unit block. Outcrop identification and respective pole of the joint set are indicated above every histogram. Spacing measured on lines orthogonal to joint plane. Spacing classes vary in width: 0.2m for spacing sizes between 0.0 and 1.0m; 0.5m, between 1.0 and 2.0m; 1m between 2.0 and 5.0m; 5.0m between 5.0 and 10.0 m; and all sizes above 10m. In this case, most joints present a small spacing (unimodal distribution). (CONTINUES)
Fig. A8.4 (CONTINUATION)

Fig. A8.5 Joint spacing distribution regarding all other joint sets that do not correlate to the unit block. Outcrop identification and respective pole of the joint set are indicated above every histogram. Spacing measured on lines orthogonal to joint plane. Spacing classes vary in width: 0.2m for spacing sizes between 0.0 and 1.0m; 0.5m, between 1.0 and 2.0m; 1m between 2.0 and 5.0m; 5.0m between 5.0 and 10.0 m; and all sizes above 10m. Observe the polymodal (mostly bimodal) distribution trend. (CONTINUES)
Fig. A8.5 (CONTINUATION)
Fig. A8.5 (CONTINUATION)
APPENDIX 9

PHOTOS AND DRAWINGS REGARDING THE INTERPRETATION OF THE INTERACTION BETWEEN JOINTS AND THEIR RELATIVE AGES

This appendix brings an example of all steps of the study of the interactions between joint sets and their relative ages on an horizontal outcrop.

First, the drawing made at the site (Fig. A9.1) and respective photographs (Fig. A9.2). Notice the equivalence of markers position on both drawing and photograph.

Second, the sketch with the interpretations of joint sets (Fig. A9.3). It is possible to observe coeval joint sets (Fig. A9.3), as evidenced by the alternating cutting relationships between some joint sets (Fig. A9.3, sets in green and pink). An older set (Fig. A9.3, in blue) is also identified. This set is considered older because: (1) the two previously mentioned sets abut on it, but the contrary is not observed; (2) the same two sets are also observed crossing the main one, without interfering; (3) the portion where the set in red (Fig. A9.3) bends when approaching the main one (Fig. A9.3, in blue) suggests that this set was already present, conditioning the formation of the other one.
Fig. A9.1 Drawing of the joint sets on the horizontal outcrop DP-020.
**Fig. A9.2** Joint sets for the horizontal outcrop DP-020. Photos: D. S. Pino.

**Fig. A9.3** Sketch of joint sets on the horizontal outcrop DP-020. Observe the alternating crosscutting relationship between the sets indicated in the colors pink and green. The blue set is the oldest one.
APPENDIX 10

RECENT STRESS FIELD IN EASTERN CANADA

The primary development of joint networks and their permeability are highly influenced by paleo-stress regimes during events of crustal deformation. Recent stress fields might superimpose a secondary influence on the pre-existing joint networks, altering joint apertures especially through relaxation at shallow to near-surface depths (Mortimer et al. 2011a, b). Other phenomena that may increase the spatial heterogeneity of a fracture network in shallow fractured aquifers (depths shallower than 200m) are the surface processes, e.g. weathering, erosion and unloading (Mortimer et al. 2011b).

The stress field may be considerably influent over the fluid control patterns, especially in fractured rocks with low matrix permeability (Mortimer et al. 2011b), as the regional stress state controls joint apertures and the potential reactivation of existing fractures (Henriksen & Braathen 2006). Therefore, the conductivity of a particular joint varies with its orientation in the in situ stress field (Henriksen & Braathen 2006): the flow occurs preferentially along joints that are normal to the minimum principal stress ($\sigma_3$) direction, due to low normal stress (Mortimer et al. 2011b), or inclined (around 30°) to the maximum principal stress ($\sigma_1$) direction, due to dilatation (Mortimer et al. 2011b). Moreover, joint permeability might be expected to be more stress-dependent at shallow depths (up to 200m), at which groundwater is usually extracted (Mortimer et al. 2011b).
In eastern Canada, the stress field components have a certain consistency regarding their directions, preferably NE-SW for the major compressional component ($\sigma_1$) (Arjang 1991; Hasegawa 1991; Zoback 1992, Assameur & Mareschal 1995) (Table 10.1). This relatively uniform regional stress field is believed to be related to plate-driving stresses (Zoback 1992). The dominant phenomenon, and that better explains this pattern, is the spreading at the mid-Atlantic Ridge (Hasegawa 1991, Assameur & Maréchal 1995). Those structures are reactivated under the present-day stress field as thrust or strike-slip faults (Mazzotti & Townend 2010).

Table A10.1 Information on in situ measurements of the stress field in eastern Canada.

<table>
<thead>
<tr>
<th>Stress field component</th>
<th>Intensity (MPa)</th>
<th>Direction</th>
<th>Region</th>
<th>Reference</th>
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<tr>
<td>$\sigma_1$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.18 ± 0.0422</td>
<td>E-W</td>
<td>Canadian Shield</td>
<td>Arjang (1991)</td>
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<td>8.18 ± 0.0422</td>
<td>N055-N065</td>
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<td>Zoback (1992)</td>
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<td>13.58 ± 0.0422</td>
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<td>Sept-îles</td>
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<td>14.23 ± 0.0422</td>
<td>N093-N133</td>
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<td>Haimson et al. (1996)</td>
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<td>17.7 (± 3.1)</td>
<td>NE-SW</td>
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<tr>
<td>29.5</td>
<td>N45</td>
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<td>Corthésy (2000)</td>
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<tr>
<td>22.5</td>
<td>N055-N104</td>
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<td>Mazzotti &amp; Townend (2010)</td>
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<tr>
<td>$\sigma_2$</td>
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<td>3.64 ± 0.0276</td>
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<td>8.70 ± 0.0276</td>
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<td>Arjang (1986)</td>
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<td>8.94 ± 0.0276</td>
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<td>9.77</td>
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<td>Sept-îles</td>
<td>Haimson et al. (1996)</td>
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<td>11.0 (± 1.4)</td>
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<td>Haimson et al. (1996)</td>
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<tr>
<td>14.5</td>
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<td>Niobec Mine</td>
<td>Corthésy (2000)</td>
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<tr>
<td>$\sigma_3$</td>
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<td>6.75 ± 0.0276</td>
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<td>7.08 ± 0.0276</td>
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<td>Haimson et al. (1996)</td>
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* Average value regarding data presented in the respective reference.