Geological Survey of Canada

Current Research
2000-D2

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2000

Natural Resources Canada
Ressources naturelles Canada

Canada

Catalogue No. M44-2000/D2E-IN
ISBN 0-660-18045-6

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Stratigraphy and structure of the St. Lawrence Lowland in the Charlevoix area, Quebec: relationships to impact cratering[1]

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Lemieux, Y., Tremblay, A., and Lavoie, D., 2000: Stratigraphy and structure of the St. Lawrence Lowland in the Charlevoix area, Quebec: relationships to impact cratering; Geological Survey of Canada, Current Research 2000-D2, 7 p. (online; http://www.nrcan.gc.ca/gsc/bookstore)

Abstract: The Charlevoix area, located 100 km northeast of Quebec City, was the site of a meteoritic impact some 350 millions years ago. Few studies have documented the tectonic event sequence of this area before and after the impact. Some field observations suggest that the actual fault systems in the Charlevoix area could have been induced during the rifting of the Iapetan Ocean during Late Proterozoic and Early Cambrian. In addition, those faults could have been reactivated during the meteorite impact and even in Mesozoic time due to rifting of the Atlantic Ocean. However, relationships between the inferred impact cratering with structures left by the Iapetan rifting and/or Mesozoic reactivation have still to be documented.

Résumé : La région de Charlevoix, située à 100 km au nord-est de la ville de Québec, a été le site d'un impact météoritique il y a environ 350 millions d'années. Peu de travaux ont été concentrés sur l'évolution tectonique de la région avant et après l'impact. Certaines observations faites dans le cadre de travaux de terrain portent à croire que les systèmes de failles actuels de cette région existaient déjà lors de la période de rift de l'Océan Iapétus au Protérozoïque tardif et au Cambrien précoce. De plus, ces failles ont probablement été réactivées au cours de l'impact et auraient même rejouées au Mésozoïque, lors de l'ouverture de l'océan Atlantique. Par contre, la relation entre l'impact météoritique et les structures liées aux deux épisodes de rift reste à être documentée.

[1] Contribution to the Appalachian Foreland and St. Lawrence Platform Architectures in Quebec, New Brunswick and Newfoundland NATMAP Project

INTRODUCTION

The Charlevoix area has been a region of geological interest for several decades because it holds one of the few impact craters discovered in southern Quebec. Although detailed mapping has been done in the past (Rondot, 1989), the relationship between observed fault systems and the impact crater is uncertain. On the basis of previous work, this study, which is part of the GSC Appalachian Foreland and Platform Architectures in Quebec, New Brunswick and Newfoundland NATMAP Project initiative of the Quebec Geoscience Center, aims to unravel and specify the tectonic history of the Charlevoix area. In this paper, we present preliminary data from fieldwork that took place during the summer of 1999. The main objective of this two-year project is to characterize the brittle fault systems of the area, in order to discriminate preimpact structures from syn- and postimpact faulting episodes. The project is also aimed at studying the relationships between the Precambrian crystalline basement and younger rocks and the lithostratigraphy of the Paleozoic platform of the St. Lawrence Lowlands in the area.

GEOLOGICAL SETTING

The Charlevoix area is located 100 km northeast of Quebec City, on the north shore of the St. Lawrence River (Fig. 1). The bedrock of the area mostly consists of metamorphic rocks of the Precambrian crystalline basement. However, along large segments of the shoreline between Baie-St-Paul and La Malbaie, as well as in two river valleys (i.e.'Du Gouffre' and Malbaie rivers), Paleozoic rocks of the St. Lawrence Lowlands are well exposed and uncomformably overlie the Grenvillian basement.

The Charlevoix area has been affected by several tectonic events of regional significance. In Late Precambrian to Early Cambrian times, the opening of the Iapetus Ocean (Pinet and Tremblay, 1995) is recorded in Charlevoix by isolated and discontinuous segments of the St. Lawrence Lowlands platform. According to Rondot (1989), northeast-trending faults, such as the St. Lawrence fault that extends for more than 25 km along strike, are the result of this rifting event. Following the formation of these rift-related faults, the Iapetan ocean is inferred to have covered the Grenvillian basement, which led to the deposition of siliciclastic and calcareous sediments that form the lower part of the St. Lawrence Lowlands in the area. In the Quebec Appalachians, Iapetan oceanic units and adjacent continental margin rocks of the Humber Zone were deformed and juxtaposed during plate convergence related to the Taconian (Middle Ordovician) and Acadian (Middle Devonian) orogenies (St-Julien and Hubert, 1975; Tremblay and Pinet, 1994). In the Charlevoix area, the Taconian orogeny has been coeval with the deposition of synorogenic flyschoid units, which overlie the platformal sequence. There is no record of Acadian-related flysch deposits. According to available geochronological data (Rondot, 1968), a major

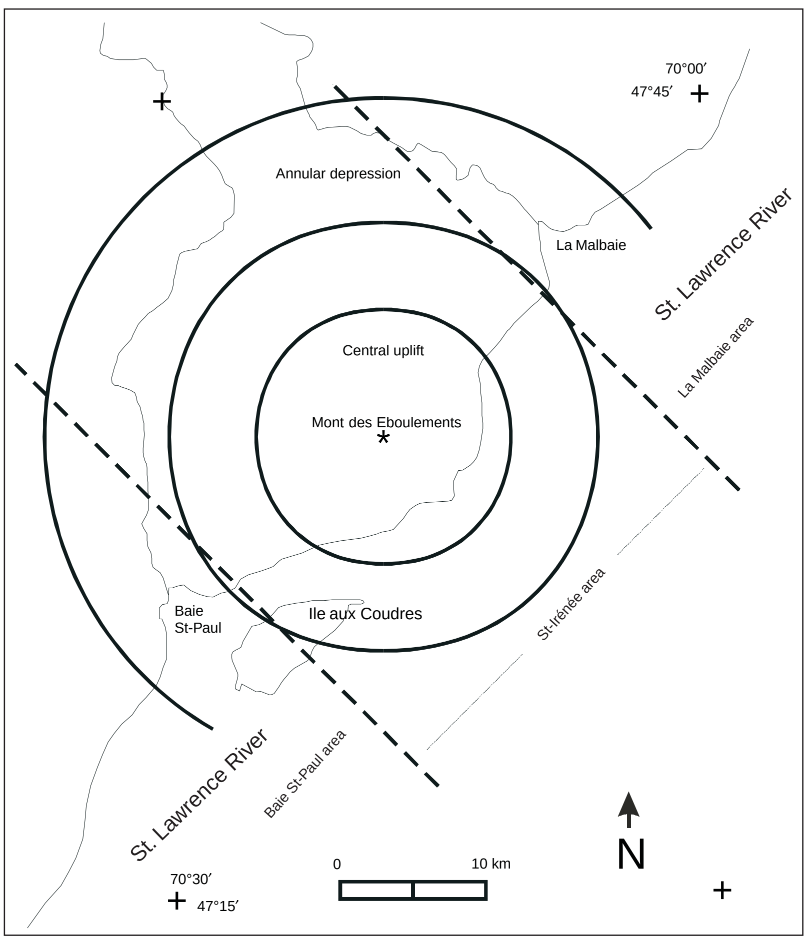

Figure 1.

Location map of the study area (dashed lines correspond to the boundary between the subzones and the circles are the structures related to the impact).

meteoritic impact occurred in the late Devonian, and is recorded by abundant shattercone localities in basement and Paleozoic rocks and by circular topographic features (?faults) that characterize the Charlevoix area (Rondot 1966). Finally, the occurence of a Mesozoic tectonic event has been suggested for the area and consisted of fault reactivation (e.g. Carignan et al., 1997) attributed to the opening of the Atlantic Ocean.

METHODOLOGY

The area covered during our fieldwork comprises the northern coast of the St. Lawrence River from Baie-St-Paul to La Malbaie, where the St. Lawrence Lowlands platform is well exposed (Fig. 1). In addition, some work inland has been done along the inferred outer rim of the crater (Fig. 1). The study consisted of a structural analysis of fault and fracture systems affecting the Paleozoic platform as well as the basement and descriptions have been done to enhance the stratigraphic framework of St. Lawrence Lowlands in the area.

Observation and measurements in the crystalline basement have been concentrated on the post-Grenvillian brittle fault systems, but Grenvillian ductile fabrics and structures were measured. However, their analysis is beyond the scope of this work. Within the St. Lawrence Lowlands, planar structures were measured, and when possible, a relative chronology of fabrics was tentatively established.

OBSERVATIONS

Lithostratigraphy

The first formal stratigraphic framework for the Charlevoix area was proposed by Rondot (1972), but was later modified by a regional study from Bussières et al. (1977). This latter framework was readdressed by D. Lavoie and others (D. Lavoie, A. Tremblay, R. Bertrand, E. Asselin, G. Chi, K. Lauzière, and C. Deblonde, unpub. confidential report to PanCanadian, 1998) in a study of the Cambrian–Ordovician successions in the Quebec re-entrant. The latter framework is used for our own study.

The Paleozoic succession in the Charlevoix consists, upward, of 1) the Cap-aux-Oies and the Cap-à-l'Aigle formations, 2) the Black River Group, 3) the Deschambault Formation, 4) the Moulin River 'facies', 5) the St-Irénée and the Lotbinière formations, and finally 6) the 'New' facies (Fig. 2). This succession can be divided into three informal intervals (Lavoie et al., 1998). The lower siliciclastic interval consists of the Cap-aux-Oies and the Cap-à-l'Aigle formations; the Ordovician limestone succession comprises the Black River Group, the Deschambault Formation, and the Moulin River 'facies'. Finally, the upper siliciclastic interval comprises the St-Irénée Formation and all the overlying units.

The Cap-aux-Oies Formation consists of about 27 m of orthoquartzite with an upper member of mixed shaly sandstone and dolomitic limestone (D. Lavoie, A. Tremblay, R. Bertrand, E. Asselin, G. Chi, K. Lauzière, and C. Deblonde, unpub. confidential report to PanCanadian, 1998). Where the contact is observed, this formation unconformably overlies the Precambrian basement. However, the Cap-aux-Oies Formation is scarcely exposed, and was only observed in the central section of the study area. Rondot (1972) first attributed this formation to the mid-Middle Ordovician period. Later, Rondot (1989) attributed this formation to the Cambrian, and proposed an unconformity between Cap-aux-Oies Formation and the overlying Cap-à-l'Aigle Formation. Some of our field observations confirm the presence of such an unconformity, but the age of the Cap-aux-Oies Formation remains uncertain (Fig. 3).

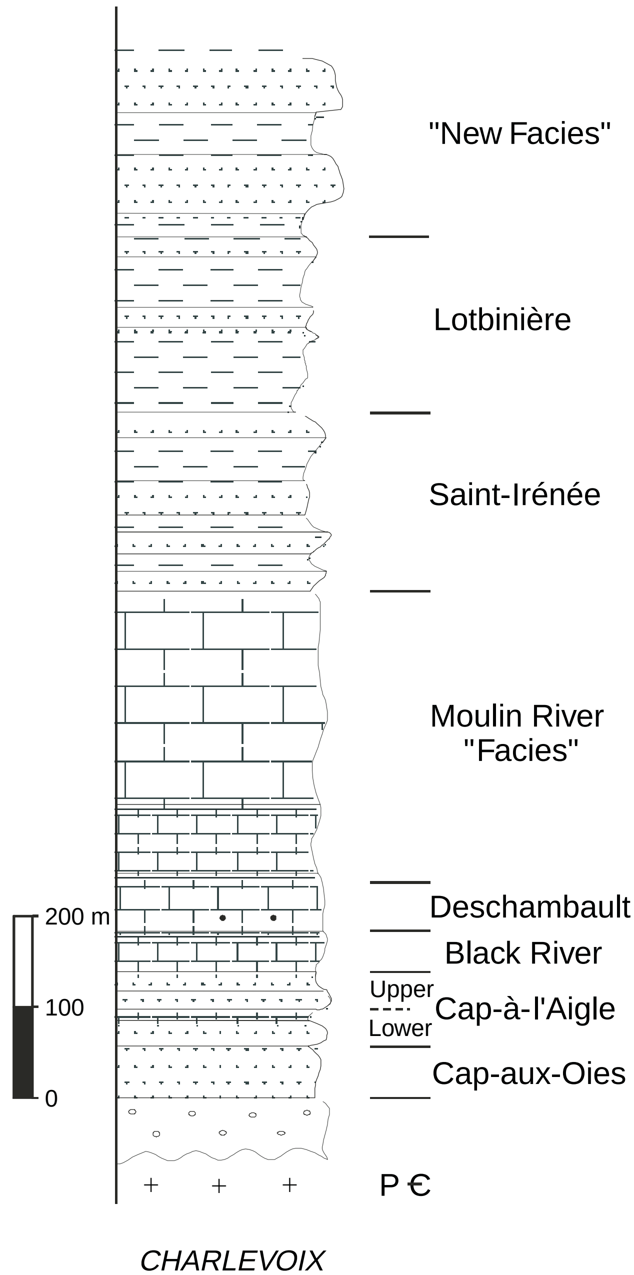

Figure 2. *Stratigraphy of Charlevoix (*modified from *D. Lavoie, A. Tremblay, R. Bertrand, E. Asselin, G. Chi, K. Lauzière, and C. Deblonde, unpub. confidential report to PanCanadian, 1998).*

Figure 3. Unconformity between the Cap-aux-Oies and the Cap-à-l'Aigle formations.

The Cap-à-l'Aigle Formation unconformably overlies the Cap-aux-Oies quartzite in the central Charlevoix area, and the Precambrian basement in the northeastern and southwestern parts. The formation is roughly 17 m thick and is divided into two units. The lower unit consists an impure arkose, which is locally conglomeratic and contains a few shaly interbeds. The upper unit consists of interbedded siliciclastic-rich bioclastic limestone and sandstone units (D. Lavoie, A. Tremblay, R. Bertrand, E. Asselin, G. Chi, K. Lauzière, and C. Deblonde, unpub. confidential report to PanCanadian, 1998). Interestingly, this formation can reach as much as 80 m thick.

The Black River Group is rarely observed in the Charlevoix area. It outcrops at only two localities where its thickness ranges between 20 cm and 50 cm thick. This unit was first proposed by Rondot (1972), but was then dropped from the stratigraphic nomenclature by Bussières et al. (1977). This term was reintroduced by Lavoie and others (D. Lavoie, A. Tremblay, R. Bertrand, E. Asselin, G. Chi, K. Lauzière, and C. Deblonde, unpub. confidential report to PanCanadian, 1998), but not exactly as first described by Rondot; the more recent study revealed a fenestral-rich, limy mudstone unit that occurs near the Cap-à-l'Aigle marina. A similar unit has been mapped in the Cap-aux-Oies area. Further studies are needed to evaluate the regional occurrence of this unit in order to warrant a formal nomenclature.

The Deschambault Formation conformably overlies the Cap-à-l'Aigle Formation, except at two localities where it overlies the Black River Group. As defined by Globensky (1987) and Lavoie (1995) in southern Quebec, this formation is represented by coarse-grained bioclastic and intraclastic grainstone and packstone with a diverse fauna. In the Charlevoix area, the Deschambault Formation reaches 35 m in a quarry in La Malbaie area. At the northeastern end of the study area, an unusual breccia can be seen affecting the Deschambault Formation (Fig. 4). This breccia mainly contains big blocks of Deschambault limestone units. Such a feature is not common in this formation, and suggests some syndepositional tectonic activity. This aspect is further discussed below.

The Moulin River 'facies' was first introduced by Belt et al. (1979), based on significant lithological differences between the Neuville Formation, used by Rondot (1972), and the equivalent limestone succession in the Charlevoix area. Further work could lead to formal designation of that unit. This facies comformably overlies the Deschambault Formation, and consists of locally wavy-bedded to more commonly planar-bedded lime mudstone and wackestone (D. Lavoie, A. Tremblay, R. Bertrand, E. Asselin, G. Chi, K. Lauzière, and C. Deblonde, unpub. confidential report to PanCanadian, 1998). A few beds are highly fossiliferous (trilobites, cephalopods, and brachiopods) and some shaly interbeds can be observed at the base of the facies. Locally, this facies displays synsedimentary deformation features (slumping) suggesting some tectonic activity during its deposition. Belt et al. (1979) have estimated that the Moulin River facies can reach a thickness of approximately 200 m. The maximum thickness of this unit observed during our work has been about 175 m, but it is noteworthy that the upper contact was not observed at this section.

The St-Irénée Formation is the lower unit of the upper siliciclastic interval and seemingly conformably overlies the limestone succession. It consists of interbedded siliciclastic rocks with planar bedded limy mudstone (D. Lavoie, A. Tremblay, R. Bertrand, E. Asselin, G. Chi, K. Lauzière, and C. Deblonde, unpub. confidential report to PanCanadian, 1998). This formation is easily recognizable in the field because of its heavily slumped and brecciated nature. Such intense synsedimentary deformation renders tentative the determination of the overall unit thickness. Still, Bussières et al. (1977) have suggested that the St-Irénée reaches 240 m. The definition of the lower contact with the Moulin River facies is still debated. However, for the purpose of this research, the contact between the Moulin River 'facies' and the St-Irénée Formation was established on the basis of the abundance of mudstone. We assume that the Moulin River facies contains less than 10% of mudstone. However, this contact remains quite equivocal, and further work is needed to clarify the ambiguity.

The St-Irénée Formation is conformably overlain by the Lotbinière Formation. This noncalcareous formation consists of alternating decametre-thick packages of coarse-grained lithic sandstone units alternating with intervals of thinly bedded

Figure 4. Synsedimentary breccia in the Deschambault Formation.

sandstone and laminae separated by thick shaly deposits (D. Lavoie, A. Tremblay, R. Bertrand, E. Asselin, G. Chi, K. Lauzière, and C. Deblonde, unpub. confidential report to PanCanadian, 1998). Although we have not observed more than about 50 m of this formation, it was interpreted to reach a maximum thickness of 250 m (Belt et al., 1979). In addition, we did not observe the upper contact with the 'New' facies, as introduced by Belt et al. (1979).

FAULTS SYSTEMS

Most faults of the Charlevoix area are brittle faults (Fig. 5). They are usually normal faults characterized by downdip motion, but strike-slip motion is locally observed. Very few faults were observed with a reverse movement. In addition, most of these faults crosscut the crystalline basement and its Paleozoic cover. Evidence for fluid circulation during faulting is scarce as quartz and/or calcite veining has been only found locally. Most fault planes are filled by fault gouge, cataclastic breccia and microbreccia, mylolisthenite (polymictic breccia dyke of Rondot (1989)) and/or pseudotachylite units that have been ascribed to the impact by Rondot (1989). The Charlevoix impact crater was first described by Rondot

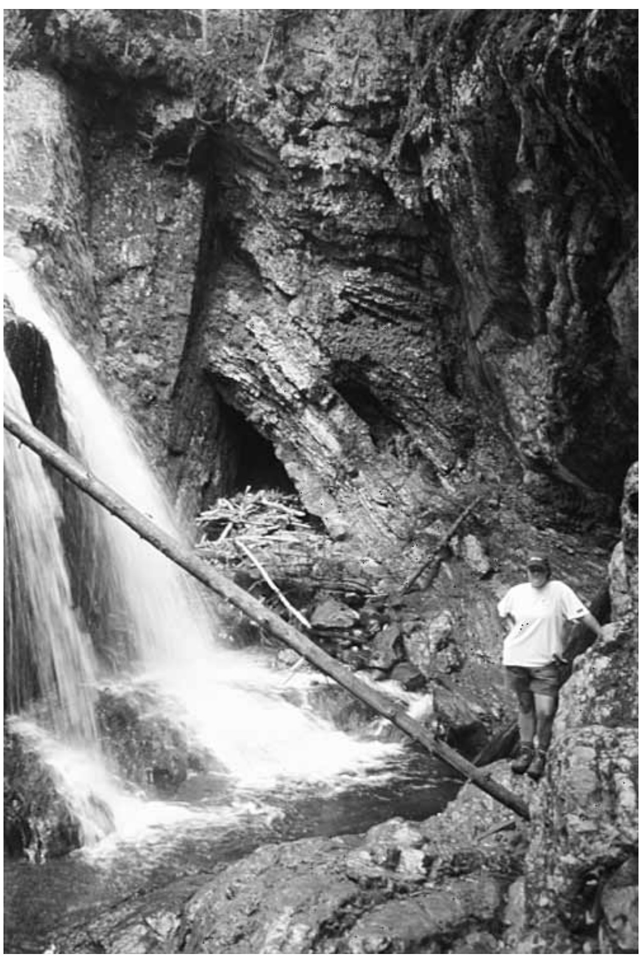

***Figure 5**. Brittle, northwest-striking fault in the Baie-St-Paul subzone.*

***Figure 6.** Shattercones in limestone.*

(1966) on the basis of shattercone occurrences (Fig. 6) which are only known in impact structures (Melosh, 1989). Rondot (1968) proposed that the impact occurred in the Devonian based on the whole-rock K/Ar dating of two samples that yielded ages ranging between 372 Ma and 335 Ma. During this study, we attempt to precisely establish the age of the inferred impact. Samples from the Mont des Éboulements (i.e. the impact centre) and from the inner parts of the structure have been collected for fission tracks dating and $^{40}Ar/^{39}Ar$ analysis.

In order to obtain more consistent fault patterns, the study area have been divided into three subzones; the Baie-St-Paul, the St-Irénée, and the La Malbaie subzones (Fig. 1). We also decided to use rose diagrams instead of stereographic projections to better illustrate consistent variations of fault trends in the Charlevoix area.

Baie-St-Paul subzone

Figure 7 shows a rose diagram of faults, fractures, and joints measured in the Baie-St-Paul subzone. The diagram reveals one major trend which varies between N300 and N330 and represents about 30% of all measurements. Field observations in this subzone suggest that faults of such orientation represent the most recent tectonic event of the area. They clearly crosscut an older fault system that varies in orientation from north-south to northeast-southwest. At a few localities, we have observed northwest-trending faults that are crosscut by younger northeast-trending faults. Although such crosscutting relationships were only locally observed, it still raises the possibility that all these faults are related to the same tectonic event. Figure 5 shows a field example of one of these major northwest-trending brittle faults.

The youngest rock formation (i.e. Middle to Late Ordovician Moulin River facies) is crosscut by faults in Baie-St-Paul subzone. We can therefore suggest that these faults were either active in pre-Ordovician time and then reactivated in post-Ordovician times, or simply occurred in post-Ordovician time. In the Baie-St-Paul subzone, there is no structural indication showing synsedimentary faulting during the Ordovician. There are, however, significant thickness

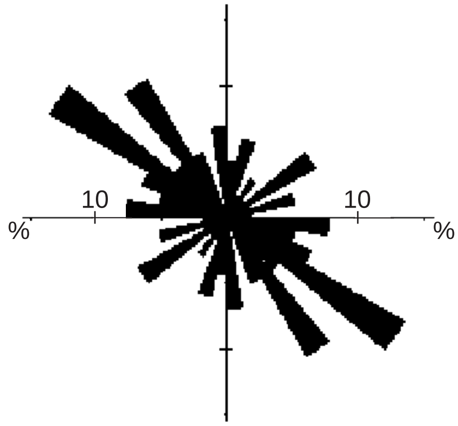

Figure 7. *Rose diagram of planar structures for the Baie-St-Paul subzone (n=116).*

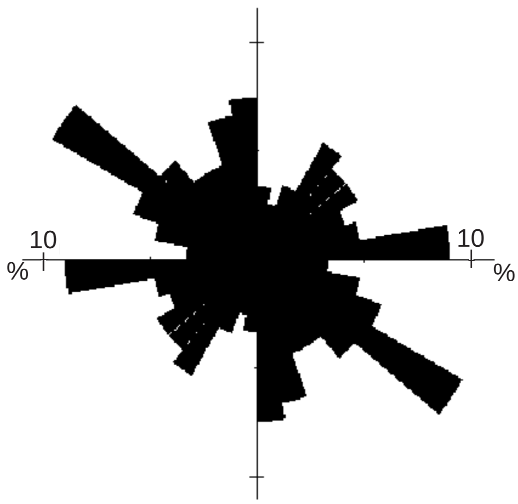

Figure 8. *Rose diagram of planar structures for the St-Irénée subzone (n=390).*

variations of some units of the St. Lawrence Lowlands platform, suggesting some tectonic activity before or during sedimentation.

St-Irénée subzone

The St-Irénée subzone represents the middle segment of the area and is located between Baie-St-Paul and La Malbaie. Figure 8 presents the orientation of fault and fracture systems that were measured in the St-Irénée subzone. It shows fault orientations that are consistent with data form the Baie-St-Paul subzone, with a major fault system striking northwest. This group of faults is slightly less common than in the Baie-St-Paul subzone, as it only represents about 20% of fault data. However, east-trending faults are well developed in the St-Irénée subzone, whereas north-and northeast-trending fault systems are more predominent than in other subzones.

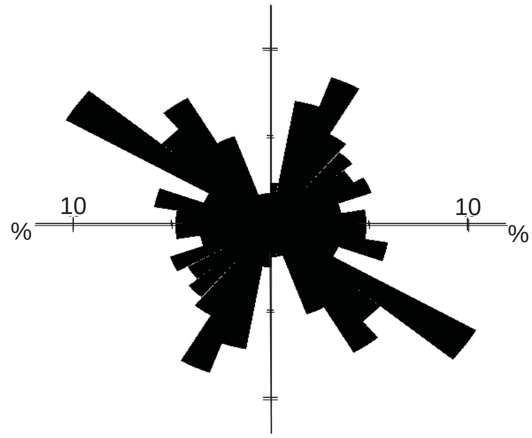

Figure 9. *Rose diagram of planar structures for the LaMalbaie subzone (n=167).*

Northwest-trending faults still form the predominant fault system, but they are, however, more commonly crosscut by northeast-trending faults than in the other subzones. This could be related to the circular structures left by the Charlevoix impact (*see* Fig. 1) being more northeasterly striking than elswhere in the St-Irénée subzone and may possibly explain the predominance of northeast-striking faults as compared to the Baie-St-Paul and St-Irénée subzones.

La Malbaie subzone

Figure 9 presents a rose diagram for the La Malbaie subzone. A predominent northwest-trending fault system is still visible and accounts for more than 30% of fault data. Except for the well developed northeast-trending fault system, the rose diagram shows fault orientations that are quite similar to the Baie-St-Paul subzone. Most faults of the La Malbaie subzone displays normal-sense motion, but reverse faults have also been observed locally. Several faults also show a component of strike-slip motion. As for the Baie-St-Paul subzone, northwest-trending faults appear to form the younger system.

The La Malbaie subzone shows a very unique feature of the St. Lawrence Lowlands in the Charlevoix area. East of Cap-à-l'Aigle, a major synsedimentary breccia occurs in the Deschambault Formation (Fig. 4). This breccia is more than 2 m thick, approximately 20 m wide, and mostly contains blocks of Deschambault limestone units. Such a breccia attests for at least local syndepositional faulting during the formation of the St. Lawrence platform.

DISCUSSION

One of the main objectives of this project is to better constrain the tectonic evolution of the Charlevoix area, and to discriminate between the fault systems related to impact cratering from those related to older or younger tectonic events. In order to obtain a coherent sequence of faulting events, we need to establish the structural framework of the area before the impact. In all three subzones, northwest-trending faults are predominant.

We think that most of these structures may have been induced during the rifting of the Iapetus Ocean and subsequently reactivated later on. Unfortunately, the only observation that support synsedimentary faulting in the Ordovician is the sedimentary breccia observed in the Deschambault Formation of the La Malbaie subzone (Fig. 4). However, we also observed significant thickness variations of the Paleozoic cover rocks in the Charlevoix area. As an example, in the Baie-St-Paul subzone, we measured four sections of the lower limestone unit (Deschambault Formation and Moulin River 'facies') that varied from 188 m, 77 m, 64 m, and 37 m. Such variations can be attributed to different subsidence rates during synsedimentary faulting. Although that no hypothesis can be excluded at this stage of the study, isotopic data presented by Carignan et al. (1997) suggest that there has been significant tectonic activity during and after the Paleozoic along the St. Lawrence and Saguenay rift valleys. It is not excluded that tectonic events of the other areas have been associated with the development of northwest-southeast structures as seen in the Charlevoix region.

The geometry and nature of faults related to impact cratering in the Charlevoix area will have to be determined in order to reconstruct and understand the regional tectonic evolution. The presence of shattercones in the St. Lawrence Lowlands Paleozoic rocks clearly indicates that the impact is younger than Ordovician. Ongoing fission-track dating in the area will allow to decipher the low-temperature thermal history of basement rocks, to obtain a more precise age of the impact structure, and to enhance Rondot's (1989) model. Mesozoic tectonism related to rifting of the Atlantic Ocean will also have to be considered in the regional tectonic sequence of the Charlevoix area. Carignan et al. (1997) have suggested that northwest-trending structures of the Charlevoix crater were reactivated in the Mesozoic. Such a hypothesis is consistent with crosscutting relations observed during our study.

Our work in the Charlevoix area also includes the stratigraphy of the St. Lawrence Lowlands. Rondot (1972) has proposed the first stratigraphic framework for the Paleozoic cover of the area. This framework was further modified by Bussières et al. (1977) and Lavoie and others (D. Lavoie, A. Tremblay, R. Bertrand, E. Asselin, G. Chi, K. Lauzière, and C. Deblonde, unpub. confidential report to PanCanadian, 1998). However, there are still uncertainties regarding, for example, the nature of the contact between the Cap-aux-Oies and the Cap-à-l'Aigle formations. It may represents an unconformity Also, the nomenclature of the Black River Group in the Charlevoix area would need to be readdressed.

CONCLUSION

The Charlevoix area is a region of significant geological interest, particularly since the discovery of the impact structure. Previous mapping and analysis have unravelled a major part of the regional tectonic history of the area but relationships between the inferred impact cratering with structures left by the Iapetan rifting or a Mesozoic reactivation have still to be determined.

ACKNOWLEDGMENTS

The authors would like to thank authorities of Eastern Canada NATMAP project for subsidizing the project. We acknowledge Sébastien Castonguay for thoughful reviews of this paper. We also thank Pascale Sergerie, field assistant for the summer survey, for her contribution and her effort to the success of this project. A. Tremblay acknowledges financial support by NSERC (operational grant #PG-105669). This is a joint project between the Geological Survey of Canada and the Institut National de Recherche Scientifique (INRS – Georessources).

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