Lineaments from Airborne SAR Images and the 1988 Saguenay Earthquake, Québec, Canada*

Abstract

Airborne SAR (synthetic aperture radar) images provided essential clues to the tectonic setting of (1) the M_bL_g 6.5 Saguenay earthquake of 25 November 1988, (2) the Charlevoix-Kamouraska seismic source zone, and (3) some of the low level seismic activity in the Eastern seismic background zone of Canada. The event occurred in the southeastern part of the Canadian Shield in an area where the boundary between the Saguenay graben and the Jacques Cartier horst is not well defined. These two tectonic blocks are both associated with the Iapetan St-Lawrence rift. These blocks exhibit several important structural breaks and distinct domains defined by the lineament orientations, densities, and habits. Outcrop observations confirm that several lineament sets correspond to Precambrian ductile shear zones reactivated as brittle faults during the Phanerozoic. In addition, the northeast and southwest limits of recent seismic activity in the Charlevoix-Kamouraska zone correspond to major elements of the fracture pattern identified on the SAR images. These fractures appear to be related to the interaction of the Charlevoix astrobleme with the tectonic features of the area.

Introduction

The M_bL_g** 6.5 Saguenay earthquake (Québec, Canada) of 25 November 1988, occurred at a depth of 29 km in an intraplate environment with no known previous seismic activity (North *et al.*, 1989; Duberger *et al.*, 1991). It was located 35 km south of the Saguenay river and well outside (more than 60 km away) of the Charlevoix-Kamouraska seismic source zone along the St-Lawrence River (Figure 1). Prior to this event, the Saguenay area has been included in the "Eastern background zone" of the seismic zoning map of Canada (Basham *et al.*, 1985).

In this paper, lineaments visible on airborne synthetic aperture radar (SAR) images are used to characterize the tectonic blocks of the area and to derive a geometric model of the Phanerozoic brittle tectonism of the area. This geometry is then used to discuss how (1) the isolated Saguenay earthquake, (2) the Charlevoix-Kamouraska seismic source zone, and (3) some other events of the Eastern background zone (the 1990 riviere Croche event and low activity in southern lac St-Jean, Figure 1) may be related to local structural features and to each other.

The area of the Saguenay earthquake is underlain by a crystalline basement that was transformed during the Grenvillian orogeny (1160-970 Ma; Rivers *et al.*, 1989). The basement was split along the St-Lawrence River by the Iapetan rift (*ca.* 600 Ma; Kumarapeli, 1985). The middle-Ordovician Taconic orogeny, marked by an island arc collision with North America (*ca.* 450 Ma; Bradley and Kidd, 1991), and a later extensional event, possibly corresponding to the opening of the central Atlantic ocean (190-170 Ma), reactivated the Iapetan rift faults and related fractures (Roy *et al.*, 1993). This Phanerozoic brittle tectonism produced the Saguenay graben and the Jacques Cartier horst, and resulted in a composite fault scarp along the northwest margin of the Iapetan St-Lawrence rift (Figure 1). The walls of the Saguenay graben are well defined only where outliers of Ordovician platform sediments are downfaulted at the base of conspicuous fault scarps. The south wall of the graben, thus defined, ends about 17 km to the north-northwest of the Saguenay earthquake epicenter. And the boundary between the Saguenay and the Jacques Cartier tectonic blocks remains undefined from Lake Kenogani to the St-Lawrence River.

A giant meteorite impact created the 54-km wide Charlevoix astrobleme along the Iapetan rift margin during the Devonian (*ca.* 350 Ma; Rondot, 1968). The astrobleme forms the southwest part of the Charlevoix-Kamouraska seismic source zone which is the most active in eastern Canada (Basham *et al.*, 1985). The current seismic activity within that zone, recorded since the early 1970s (Leblanc *et al.*, 1973; Leblanc and Buchbinder, 1977; Buchbinder *et al.*, 1988), is restricted to a smaller quadrangle elongated along the St-Lawrence River (Figure 1) where it appears controlled by old Iapetan rift faults and where it does not show any clear or simple relationship with the features of the astrobleme (Anglin, 1984; Lamontagne, 1987).

Lineament Analysis

Description

Lineaments are strikingly exhibited on the available airborne SAR images which provide a wide traverse across the Saguenay graben and the northeast part of the Jacques Cartier horst between the north wall of the graben and the Charle-

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**"M_bL_b" is the magnitude of an earthquake computed from the "Lg waves". "Lg waves" are higher mode surface waves in the continental crust which play a major role in earthquake damage.

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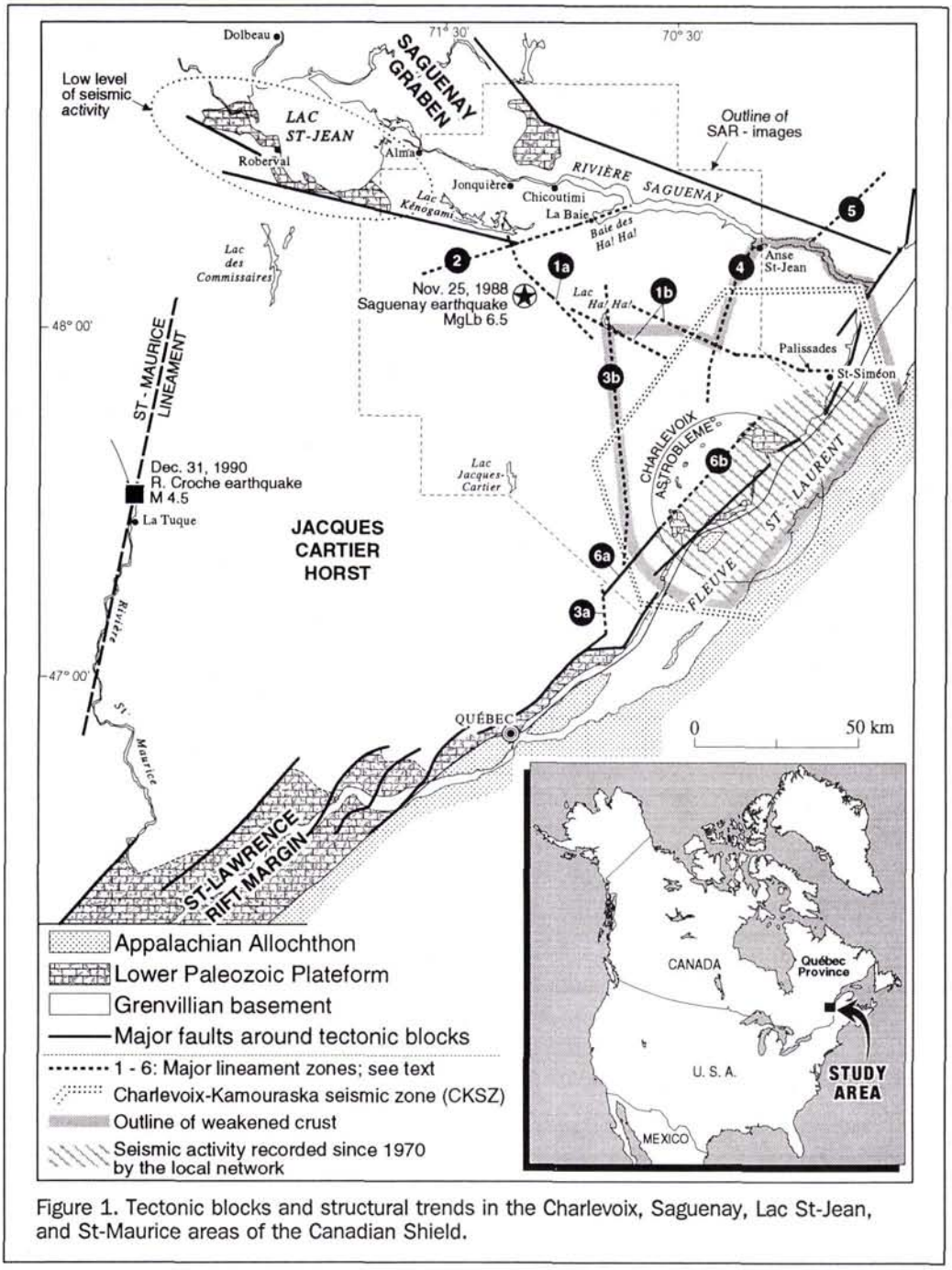

Figure 1. Tectonic blocks and structural trends in the Charlevoix, Saguenay, Lac St-Jean, and St-Maurice areas of the Canadian Shield.

voix astrobleme along the St-Lawrence rift margin (Figure 2, Table 1). These images, because of their coverage, allow a regional compilation and interpretation of the lineaments and of the structural trends that would have been impossible from field mapping alone. Most parts of the study area are covered by at least two (up to six) swaths with a different look orientation. All the available swaths were used in the present study in order to minimize the biases that may arise from a single look orientation. The C and X bands show the same lineaments.

Most lineaments on these images correspond to well defined linear topographic and hydrographic features, mainly straight narrow valleys, straight scarp lines, and large linear water bodies. The shadows, projected by the topographic features and the reflectance contrast between water and land, account for most of the sharp tonal changes in the images. Tonal changes due to vegetation are well marked only in the agricultural areas of the Saguenay and Charlevoix lowlands where man-made lines are also abundant. In the forested highlands (about 90 percent of the area), isolated power lines and roads are the only recognizable man-made features; vegetation does not give rise to appreciable tonal changes and surface topography is directly controlled by the bedrock, because glacial and post-glacial sediments are thin almost everywhere.

No lineament appears to correspond to the mapped con-

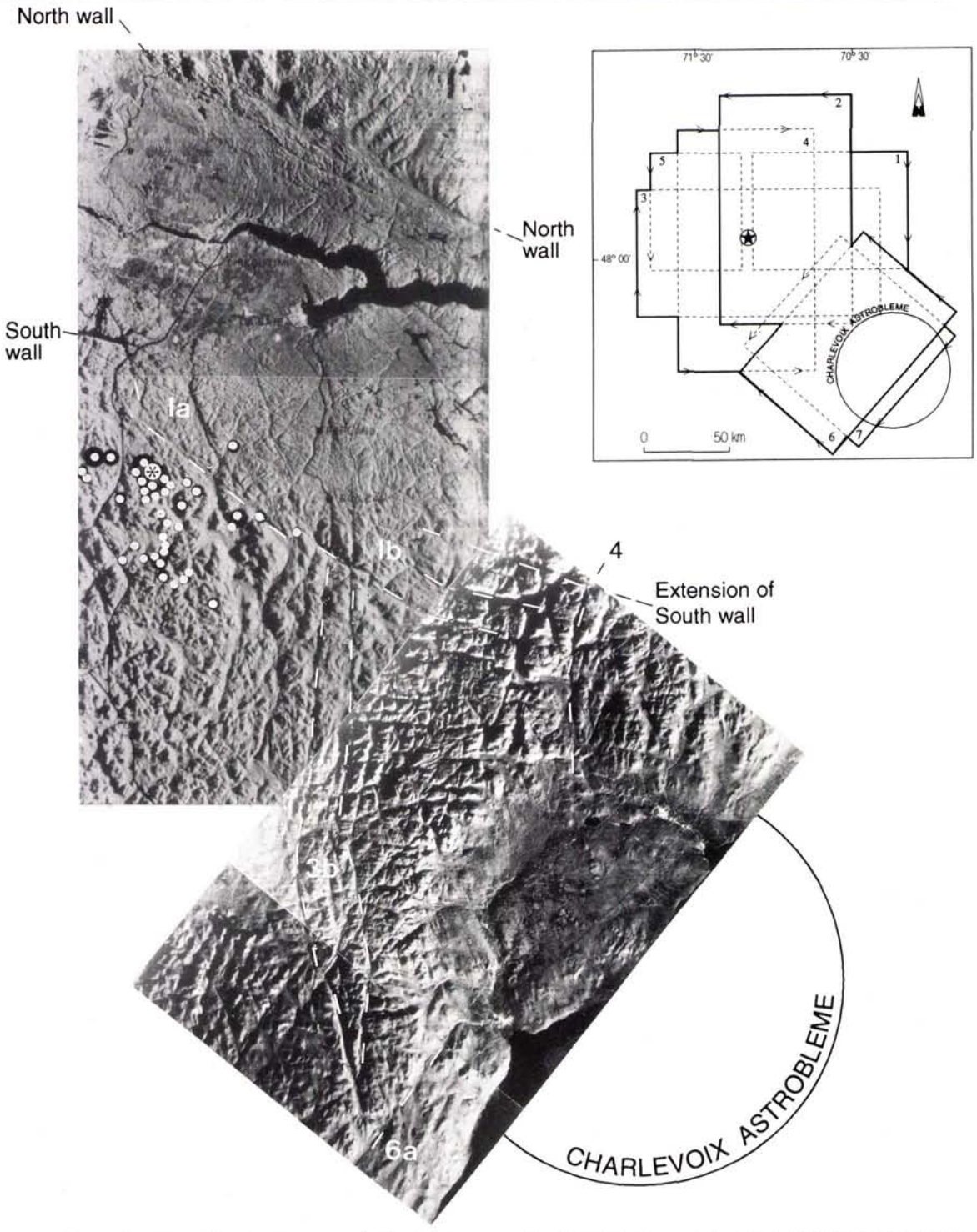

Figure 2. SAR images of the Saguenay and Charlevoix areas. The image index and the look directions are shown in the upper right corner. The Saguenay area is represented by image 2, band C, look to the west. The Charlevoix area is represented by image 6, band C, look to the northwest. Star and dots: epicenters of the main shock and of several aftershocks of the 1988 Sagueany earthquake. Dashed lines: major lineament zones discussed in the text.

tacts or to the internal structures of the large and small intrusive bodies which underlie most of the area (Laurin and Sharma, 1975; Roy *et al.*, 1986). Fine parallel curvilinear banding, a few hundred metres in width, coincides with par-

TABLE 1. AVAILABLE SAR IMAGES

Area	Swath	Radar Band	Look Dir.	Length km	Width km	Date
SAGUENAY	1	C, X	S	69	64	08 Jun 89
	2	C, X	W	114	64	07 Jun 89
	3	C, X	N	116	64	08 Jun 89
	4	C, X	E	117	64	07 Jun 89
	5	C, X	S	44	64	08 Jun 89
CHARLEVOIX	6	C	NW	83	64	28 Oct 87
	7	C	SW	75	64	28 Oct 87

Wide swath mode, HH polarization.

agneissic units. Crude, less conspicuous banding, a few kilometres in width, is developed along elongated gneissic bodies in the easternmost part of the area. The other lineaments, by far the most abundant, probably reflect individual fractures or narrow fracture zones.

Two studies were conducted with these images: (1) a systematic analysis of the lineament orientations and habits within a wide area around the epicenter of the Saguenay earthquake (Schmitt, 1990), and (2) an analysis of the lineament domains of the contiguous Saguenay and Charlevoix areas.

Lineament Sectors

Schmitt (1990) divided the area covered by the five swaths of the Saguenay area (Table 1) into 24 apparently homogeneous sectors generally bounded by deeper and wider valleys (Figure 3). He compiled all the lineaments apparently related to bedrock fractures on special "fan diagrams" in which the number of lineament sets is given by the number of lines, the azimuth of each set by the trend of the lines, and their densities by the length of the lines. The densities are computed the same way as drainage densities are: cumulative length divided by the surface area. The 887 such lineaments have a cumulative length of 3435 km over 12 000 km²; that is an average density of 0.3 Km/km² for the area covered by the five Saguenay swaths.

The lineaments form diverse patterns throughout the study area: for example, the pattern of multiple fine lineaments lightly imprinted into the fairly smooth terrain to the north of Lac Ha! Ha! contrasts with that of coarser lineaments in the rougher topography seen to the south of the same lake (Figure 2). Differences in orientation and density of the lineaments are readily visible by direct comparison of

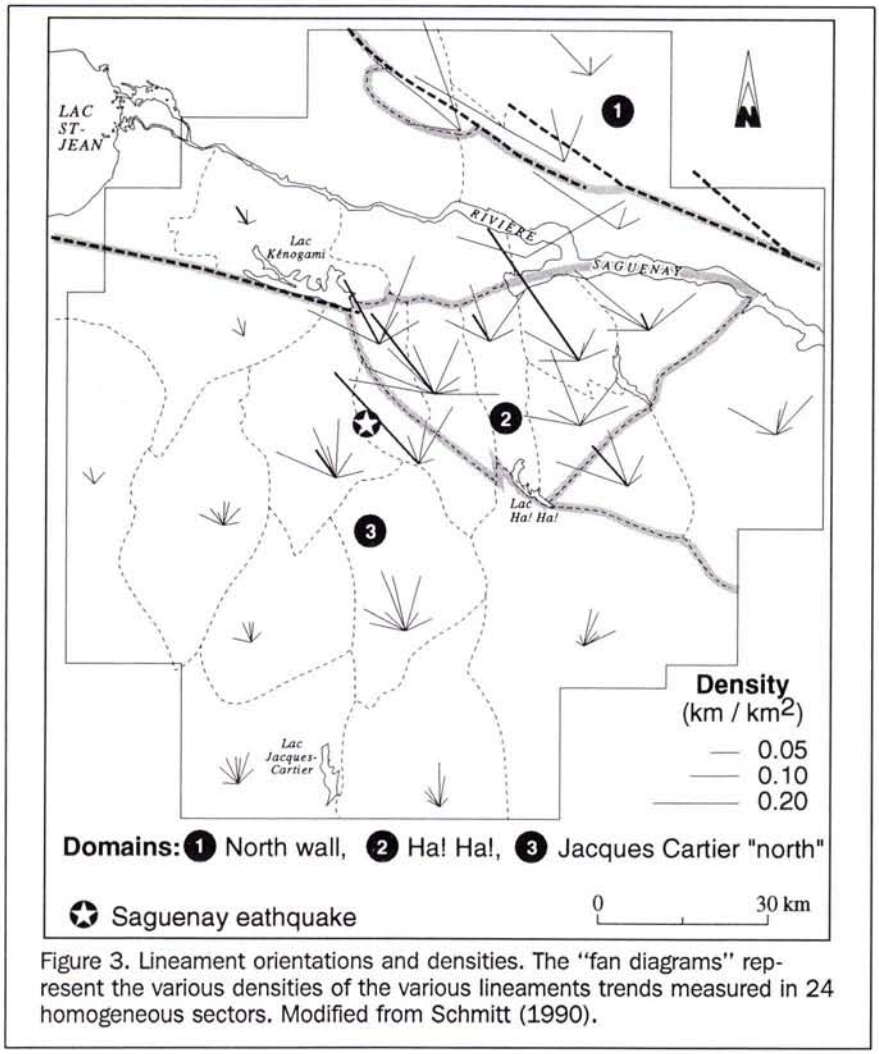

Figure 3. Lineament orientations and densities. The "fan diagrams" represent the various densities of the various lineaments trends measured in 24 homogeneous sectors. Modified from Schmitt (1990).

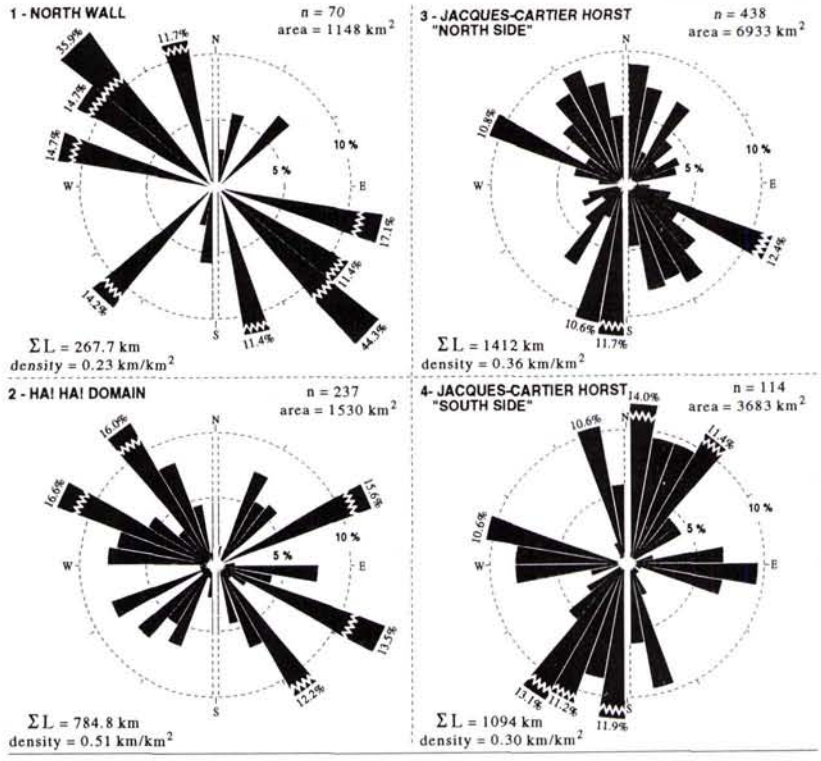

Figure 4. Cumulative length and frequency of lineaments. Rose diagrams of four structural domains: 1, 2, and 3 outlined in Figure 3; and 4 corresponding to the highland terrain seen around the Charlevoix astrobleme in images 6 (shown in Figure 2) and 7.

the fan diagrams (Figure 3). Other differences, such as the variation in the density of a given lineament trend among the various sectors, are more subtle. This is illustrated for the 140° to 150° range by a heavier line in the fan diagrams. That trend, which is parallel to one of the nodal planes of the 1988 Saguenay earthquake, is prominent in the sectors close to the epicenter of the 1988 earthquake.

Contiguous sectors exhibiting similar patterns and habits are grouped in three larger domains (domains 1, 2, and 3 in Figures 3 and 4) to facilitate comparisons and analysis. The fan diagrams of domain 2 show a much weaker development of the northerly trends than those of domain 3 (Figure 3). Moreover, the proportion of the fine lineaments is much greater in domain 2 (84 percent of the total number of lineaments and 79 percent of their cumulative length) than in domain 3 (49 percent of the number and 41 percent of the cumulative length). Such differences in lineament patterns and habits suggest that the lineament zone that separates the two domains is an important structural feature of the study area ("1a" and "1b" in Figures 1 and 2, and between Lake Kenogami and Lake Ha! Ha! in Figure 3).

Lineament Domains

A rose diagram was compiled for each of the three domains recognized above on the Saguenay swaths (Figures 4-1, 4-2, and 4-3). A fourth domain, which partly overlaps the third, represents the major lineaments in the highlands around the Charlevoix astrobleme visible on the SAR images 6 and 7 (Figure 2). A "major lineament" corresponds to a topographical feature also visible on a 1:250,000-scale map with a 60-m (200-foot) contour interval. Thus, the finer lineaments with a smaller vertical relief are not included in the fourth rose diagram (Figure 4-4) while they are in the other three; this probably accounts for most of the differences between rose diagrams 4-3 and 4-4.

These rose diagrams show five main lineament trends (Figure 4). All five trends correspond to brittle faults observed in outcrop (Woussen and Ngandee, 1991), and, with the exception of the northwest-southeast trend, to Precambrian ductile shear zones. These observations support the interpretation of the lineaments as the surface expression of small faults. These trends are also parallel to important structural features of the study area:

- The *NW-SE* trend is the main trend in domain 1, and is present in the other three domains with a progressively more NNW-SSE orientation from north to south. It is parallel (1) to the western segment of the north wall of the Saguenay graben, (2) to the preferred fault plane of the 1988 Saguenay earthquake, and (3) to the lineament zone 1a in Figure 1.
- The *WNW-ESE* trend is the second most important trend in domain 1, and is present in the other three domains with a variable spread to the southeast or the east. It is parallel (1) to the axis of the Saguenay graben, (2) to its south wall, (3) to the eastern segment of its north wall, (4) to the lineaments corresponding to lineament zone 1b in Figure 1, and (5) to

the alignment of several aftershocks between the epicenter of the main shock and Lac Ha! Ha! (Figure 2).

- The *NE-SW* trend is present in all four domains: 040° to 049° in the first two, and 030° to 039° in the other two. It is parallel (1) to the wall of the St-Lawrence rift along the south-east side of the Jacques Cartier horst, (2) to the northwest Gouffre fault (lineament zone 6a and line 6b, Figure 1; Rondot, 1979), and (3) to the lineament zone 5 in Figure 1.
- The *ENE-WSW* trend is abundant in domain 2, weak in domain 3, and absent from domains 1 and 4. It is parallel to the Baie des Ha! Ha! lineament (lineament zone 2, Figure 1) which is the north edge of domain 2.
- The *N-S* to *NNE-SSW* trend is abundant only in domains 3 and 4. It is parallel (1) to the St-Maurice lineament which constitutes the west side of the Jacques Cartier horst and (2) to the lineament zones 3a, 3b, and 4 in Figure 1.

Discussion and Conclusion

The SAR images enabled us to identify five lineament (fracture) sets that are parallel (1) to one or another of the boundaries of the tectonic blocks of the region and (2) to internal structural breaks which may control the distribution of the seismic activity in the study area. Figure 1 illustrates the major lineament zones that were identified on the SAR images, their topographical extensions outside of the SAR coverage, and faults around the tectonic blocks well established by field mapping.

The Saguenay earthquake occurred nearly below the *lineament zone 1a*; and several of its aftershocks are aligned with *lineament zone 1b* (Figure 2), which marks, at its eastern end, the northern limit of the Charlevoix seismicity recorded by the local network since 1970 (Figure 1). This and the change in lineament patterns between domains 2 and 3 (Figures 3 and 4) lead us to propose that these lineament zones are the eastward extension of the south wall of the Saguenay graben. *Lineament zone 2*, which interrupts the well-defined part of the south wall of the graben at the east end of Lac Kenogami, may be a small, north facing, normal fault that brings some slip to the trough of the lower Saguenay River in the eastern part of the graben.

Lineament zones 3a, 3b and 4 are interpreted as transfer faults between the Saguenay graben and the St-Lawrence rift margin across the Jacques Cartier horst: the first two directly to the west of the Charlevoix astrobleme and the third, through the outer wall of the astrobleme. We think that the astrobleme weakened the crust near the junction of the Saguenay graben with the St-Lawrence rift margin and that the northeast tip of the horst broke along these north-south to NNE-SSW transfer faults when the last reactivation of the rift and graben faults occurred.

The last reactivation appears to have followed two paths along the St-Lawrence rift margin (Figure 1): one, simple, along the north shore of the St-Lawrence River and across the Charlevoix astrobleme, and another, more complex and inland, that went around the astrobleme and across the Jacques Cartier horst and the Sagueany graben. *Lineament zone 6a and line 6b*, about 10 km inland, correspond to the northwesternmost Iapetan rift fault in the study area. It was an active fault scarp during the Ordovician sedimentation (Rondot, 1972) and it marks the northwest limit of the seismic activity recorded by the local network since the early 1970s. However, the present-day lack of surface expression of that fault inside the Charlevoix astrobleme (line 6b in Figure 1) indicates that that part of the fault was not reactivated during the last reactivation of the rift margin. Instead, the motion was carried by the outer wall of the astrobleme and by the transfer faults 3 and 4 to the south wall of the graben and to the trough of the Saguenay River. From there other rift faults corresponding to *lineament zone 5* carried the slips outside of the graben.

The Charlevoix-Kamouraska seismic source zone appears to coincide with the weakened parts of the Jacques Cartier horst and of the adjacent part of the Saguenay graben. The analysis presented above suggests that its limits should follow lineament zones 3b, 1b, and 4, the trough of the Saguenay River, a north-south line across the St-Lawrence River from the mouth of the Saguenay River, the south shore of the river, and an arc around the southwest edge of the Charlevoix astrobleme (Figure 1).

Lastly, the Jacques Cartier horst appears to be surrounded by seismogenic boundaries: (1) the south wall of the Saguenay graben with the 1988 Saguenay earthquake and some low level seismic activity south of Lac St-Jean, (2) the St-Maurice lineament with the 1990 rivière Croche event, and (3) the Iapetan rift margin, very active in the Charlevoix-Kamouraska zone, and with some sporadic low level activity further to the southwest.

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