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Southern continuation of the Wakeham Group and Robe-Noire mafic suite (eastern Grenville Province) from hydrocarbon-targeted seismic reflection data on Anticosti Island, Quebec, Canada.

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**Southern continuation of the Wakeham Group and Robe-Noire mafic suite (eastern
Grenville Province) from hydrocarbon-targeted seismic reflection data on Anticosti
Island, Quebec, Canada.**

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Abstract: Hydrocarbon-targeted seismic reflection profiles acquired on eastern Anticosti
Island (Quebec) image sub-parallel reflections with significant continuity below the
Paleozoic St. Lawrence Platform. These intra-basement reflections define a seismic unit
with a relatively simple geometry characterized by broad open folds, an array of sub-
parallel markers and ENE-dipping faults. The reflective seismic unit likely corresponds to
the southern extension of the Mesoproterozoic Wakeham Group and Robe-Noire mafic
sills that are exposed on the nearby north shore of the Gulf of St. Lawrence, in the eastern
Grenville Province of Quebec.

Key words: Grenville; Wakeham Group; mafic sills; seismic reflection.

40

41 **Introduction**

42 In metamorphic/igneous terranes commonly referred to as 'basement' by
43 petroleum geologists, seismic reflection data may provide useful information at scales
44 varying from that of the crust to that of the mining prospect (White et al. 2000; Eaton et
45 al. 2010; Malehmir et al. 2012; Reeve et al. 2014). However, in most such 'hard
46 rock' settings in which seismic velocities and impedance contrasts may differ
47 significantly from those encountered in sedimentary basins, special acquisition and
48 processing protocols may be required to fully resolve complex 3D geometries typical of
49 crystalline basement. As a result, in most cases the non-optimal design and processing of
50 2D hydrocarbon exploration seismic reflection surveys result in low-quality images of the
51 crystalline basement that are characterized by discontinuous short reflections of variable
52 amplitudes or regions of low reflectivity. Interpretation of such seismic patterns is
53 challenging and the subsurface geometry of the basement remains poorly defined in most
54 cases.

55 The inherent seismic complexity of crystalline rocks in basement terranes may
56 arise from a number of factors, including: 1) the common small scale petrologic
57 heterogeneities associated with significant (> 0.5 km/s) seismic velocity variations over
58 short distances (Holliger et al. 1996) which reduce the signal-to-noise ratio of the major
59 reflections; 2) the common steep dip of geological contacts which may generate
60 reflections away from the receiver array and enhance out of plane effects; and 3) the
61 superimposition of tectonic and magmatic events which commonly result in a

geometrical complexity at meter to kilometer scales. In such instances, only lithologic, tectonic or intrusive contacts that are characterized by large impedance contrasts, significant continuity and relatively simple geometry are expected to be imaged by the seismic reflection method.

On account of specific parameters commonly used for seismic experiments, most hydrocarbon-targeted seismic profiles acquired in the St. Lawrence Platform including those of southern Quebec, Gulf of St. Lawrence and Anticosti Island clearly depict the contact between the Proterozoic Grenvillian metamorphic and intrusive rocks composing the crystalline basement and the overlying Paleozoic sedimentary cover, but they generally fail to image the internal geometry of the basement.

In western and central Anticosti Island, publicly available seismic data collected by the petroleum industry image some reflections below the Paleozoic cover but due to their limited continuity and the sparse seismic coverage, their interpretation remains ambiguous. This contrasts with the situation in eastern Anticosti Island where continuous high-amplitude reflections are imaged at depths of 1-6 km. This contribution discusses the origin and significance of these intra-basement reflections on the basis of the geology of the Grenville Province documented on the north shore of the Gulf of St. Lawrence.

Geological framework

The St. Lawrence Platform corresponds to the autochthonous sedimentary cover of the North American shield in Canada. On Anticosti Island, in the northern part of the Gulf of St. Lawrence, Lower Ordovician to lower Silurian strata form a 1 to 4 km thick

sedimentary succession that dips shallowly (approximately 3°) toward the southwest (Sanford 1993). The exposed sedimentary succession on Anticosti Island is weakly deformed and hosts only minor structural features (joints, minor faults) that record the distal foreland strain associated with Appalachian orogenesis and younger events (Bordet et al. 2010; Pinet et al. 2015).

The Paleozoic sedimentary cover unconformably overlies Proterozoic rocks of the Grenville Province that are exposed on the north shore of the Gulf of St. Lawrence. In this paper, these rocks are referred to as the 'basement'. Rocks of the Grenville Province have ages ranging from Archean to latest Mesoproterozoic with much of the Grenville hinterland being composed of polydeformed mid-crustal Mesoproterozoic rocks with uppermost amphibolite- to granulite-facies assemblages that formed at about 30 km depth during the Ottawa phase of the Grenvillian orogeny at ca 1090-1020 Ma (Rivers 1997). However, the Wakeham terrane of the Quebec North Shore facing Anticosti Island is an exception, being composed of a gently folded and in part almost unmetamorphosed sequence known as the Wakeham Group (Martignole et al. 1994; Gobeil et al. 2003). These rocks are interpreted to be part of the down-dropped orogenic superstructure, and Rivers (2012 and 2015) and Rivers et al. (2012) attribute the term 'orogenic lid' for these supracrustal rocks in the Grenville hinterland that lack evidence for penetrative deformation and that were not heated above ~500°C during the Grenvillian Orogeny. The juxtaposition of the Ottawa orogenic lid with higher metamorphic grade rocks of surrounding domains is interpreted to have been achieved mainly by orogen-scale normal faulting (Rivers 2012; Rivers et al. 2012).

106 In the Grenville Province of the Quebec North shore immediately north of
107 Anticosti Island, Proterozoic rocks have been divided into three tectonostratigraphic
108 domains bounded by major shear zones (Fig. 1; Gobeil et al. 2003). To the west of the
109 town of Havre-Saint-Pierre (Fig. 1), the Lac-à-l'Aigle and Saint-Jean domains are
110 composed of gneiss and abundant intrusions of various types (granitoid, gabbro,
111 gabbro-norite, anorthosite). East of Havre Saint-Pierre, the Natashquan domain consists of
112 the relatively low-metamorphic grade Wakeham Group characterized by greenschist
113 facies assemblages, with possible subgreenschist facies locally, rising to amphibolite
114 facies near its margins and surrounded both to the west and east by high grade
115 metamorphic complexes composed mainly of Pinwarian (1.53-1.45 Ga) orthogneiss
116 exhibiting more complex ductile deformation (Gobeil et al. 2003; Gervais et al. 2004).
117 The contact between the Saint-Jean and Natashquan domains corresponds to the Abbé
118 Huard shear zone, a deformation corridor more than 1 km in width and including several
119 ductile faults. The Abbé Huard shear zone recorded early NW-directed thrusting and late
120 SE-directed transtensional motions (Martignole et al. 1994; Gobeil et al. 2003). The
121 Wakeham Group is several kilometers in thickness and is composed of mainly
122 arenaceous sedimentary rocks deposited at ca 1.5 Ga (van Breemen and Corriveau 2005)
123 with minor conglomerate, mudrock, marble and volcanic flows (Gobeil et al., 2003;
124 Corriveau and Bonnet 2005). At 1.17 Ga the supracrustal sequence was intruded by a
125 series of tholeiitic gabbroic sills up to several hundreds of meters in thickness and tens of
126 kilometers in length (Robe noire mafic suite) that form about 30% of the outcrop area of
127 the Davy Trough (Fig. 1; Martignole et al. 1994). This trough corresponds to a regional
128 N-S trending synform with a subvertical axial plane and deforms both the supracrustal

rocks and the mafic sills. Metamorphic grade observed at the surface varies from greenschist facies in the core of the the Davy Trough to amphibolite facies towards the margin of the Wakeham Group, where it is largely in fault contact with the surrounding gneisses of the Natashquan domain (Camion 1990; Martignole et al. 1994; Gobeil et al. 2003; Gervais et al. 2004). The Natashquan domain is cut by several plutonic bodies of 1.50 Ga felsic orthogneisses (Wodicka et al. 2003), and includes minor scattered paragneiss units and numerous scattered and discontinuous mafic dikes less than 10 m thick (Gobeil et al. 2003). East of the Wakeham Group the amphibolite-facies gneisses have been pervasively deformed into series of dome structures (Gervais et al. 2004). Geochronological constraints (Wodicka et al. 2003; van Breemen and Corriveau 2005) suggest that the Saint-Jean domain recorded early Ottawa high-grade metamorphism between ~1080 and 1045 Ma, whereas the Natashquan domain underwent an early period of Ottawa metamorphism between 1060 and 1020 Ma, followed by a more widespread metamorphic event at ~1010-995 Ma and a subsequent protracted cooling episode.

Available seismic reflection data

Seismic profiles acquired during the initial phase of petroleum exploration on Anticosti Island in the late 1960's were sparse, low-resolution and of poor quality in comparison to modern standards. A second period of exploration started in 1996 with the acquisition of over 800 line-km of 2 D seismic data and the drilling of eight wells. Seismic profiles discussed in this paper (Fig. 2) were shot in 1998 for Shell Canada. Acquisition parameters as well as images of the seismic lines are available in the report

of Lynch (2000). These public-domain seismic images extend to a depth of 2 s (two-way-time). Digital data was not available for this study and, for that reason, reprocessing was not considered. No direct velocity information is available for the pre-Paleozoic basement. Consequently, a velocity of 6000 m s^{-1} (two-way travel time) is used to estimate the depth and dip of the intra-basement reflections. This velocity is greater than the average for the Paleozoic sedimentary succession, and is in agreement with the velocity model used for the Grenville Orogen in southern Ontario and western Quebec that includes an upper crust (0-15 km) characterized by seismic velocities between 5.6 and 6.4 km s^{-1} (White et al. 2000).

Intra-basement reflections

Seismic reflection profiles acquired by Shell in eastern Anticosti show well-defined subparallel continuous reflections below the Paleozoic unconformity.

On the N-S striking, 15 km long, seismic profile A0071-210, subparallel high-amplitude reflections define a ca. 2.7 km thick seismic unit (subparallel reflection seismic unit, SRSU; Fig. 3). In the central part of the profile, the SRSU lies below the Paleozoic unconformity and exhibits an apparent dip of $\sim 20^\circ$ toward the north. Reflections include some high-amplitude segments up to $\sim 6 \text{ km}$ in length. Near the southern end of the same profile, a reflection located at a depth of ca 1.5 s ($\sim 2.2 \text{ km}$ below the Paleozoic unconformity) with an apparent shallow (4°) dip toward the north is well imaged, but it remains unclear if it is isolated or if it marks the top of a seismic unit including parallel reflections.

The geometry of the seismic unit(s) characterized by subparallel reflections is well illustrated on the ENE-striking, ~ 29 km long seismic line AT0071-203 (Fig. 4). In the eastern part of the line, a seismic unit including high amplitude subparallel reflections defines a broad antiform, with the hinge zone lying immediately below the Paleozoic unconformity. A seismic unit with similar characteristics exhibits an apparent dip of ~ 21° toward the ENE in the western part of the profile, except at its WSW end where poorly defined reflections dip in the opposite direction. Whether, the seismic units on both sides of the profile are correlated or not, the reflections are sharply truncated on the west side of the antiform suggesting that a fault limits them toward the west.

Other available seismic reflection profiles in eastern Anticosti (Fig. 2) image subparallel reflections at various depths and allow the mapping of the SRSU immediately below the Paleozoic unconformity (Fig. 2). The axial trace of the antiform imaged on seismic line AT0071-203 strikes NNW and plunges to the SSE (Fig. 2) resulting in the deepening of the SRSU in this direction. The geometry inferred from seismic data is in agreement with images of a confidential aeromagnetic dataset available in the report of Lynch (2000). On these images (maps of the second vertical derivative and of three depth slices), magnetic anomalies form a NNE-trending fold and are truncated along the inferred fault trace (Fig. 2). Taking into account the strike inferred from magnetic data, the 'true' dip of the SRSU can be calculated and is reported on Figures 3 and 4B. West of the fault, the geometry of the SRSU is less constrained and its ~ E-W strike on Figure 2 is mainly based on the orientation of magnetic anomalies.

Interpretation

The sub-parallel and continuous character of the seismic reflections below the Paleozoic sedimentary cover in eastern Anticosti is an uncommon characteristic of metamorphic and igneous basement units and indicates a relatively simple geometry at the 100 m – 10 km scale. Moreover, some reflections have relatively high amplitudes suggesting high impedance contrasts.

In the Precambrian basement exposed on the north shore of the Gulf of St. Lawrence, the physical property contrasts between sedimentary rocks of the Wakeham Group and the mafic sills of the Robe noire mafic suite provide the most viable explanation for the origin of ‘coherent’ reflections. The contrast in acoustic impedance between mafic sills and metasedimentary rocks should be sufficient to generate observable reflections. Moreover, the thickness (10 - 100s m) and lateral extent of the sills meet the geometrical criteria necessary to generate continuous reflections. Finally, mafic sills are very broadly folded along the Davy Trough, in a structural style consistent with the geometry imaged on profile AT0071-203 and with aeromagnetic images. 1-D waveform modelling of seismic data with velocity and density contrasts of 500 m s^{-1} and 350 kg m^{-3} respectively indicates that ~100 m thick mafic sills intruding into gneissic rocks may explain continuous reflections within the crystalline basement, an interpretation that has been applied to northwestern Alberta (Welford and Clowes 2006). On a qualitative basis, an alternative interpretation in which reflections are related to intrasedimentary impedance contrasts seems less probable and remains difficult to test without a better understanding of the succession and of its physical properties.

217 The seismic unit characterized by subparallel reflections is several kilometers
218 thick, which is in agreement with field-based thickness estimates for the Wakeham Group
219 on the St. Lawrence north shore (Martignole et al. 1994). The southern part of the profile
220 AT0071-199 illustrates a characteristic of the SRSU which is not obvious on other
221 seismic lines. On this profile, the most continuous reflections are slightly divergent
222 toward the NNE (Fig. 5). The fanning of reflections bears similarities to seismic images
223 of clastic units characterized by significant syn-tectonic thickness changes and raises the
224 possibility that mafic sills followed stratigraphic contacts and thereby provide an
225 enhanced seismic image of the slight changes in dip of the bedding.

226 On most seismic profiles, the SRSU is overlain, beneath the Paleozoic
227 unconformity, by a seismically transparent unit. Without additional data, the
228 interpretation of this unit remains undetermined; it may correlate with the upper part of
229 the Wakeham Group, which northeast of Natashquan (Musquaro Lake area) is devoid of
230 large mafic sills, or to a geological unit that is not exposed onshore.

231 The inferred presence of the Wakeham Group and Robe-Noire mafic sills, some
232 80 km south of their closest exposure on the north shore of the Gulf of St. Lawrence (Fig.
233 6) enlarges the regional extent of these units characterized by shallow dips and simple
234 open folding. Moreover, the strong contrast between the structural style imaged on
235 seismic and documented both in the Saint-Jean domain to the west (Gobeil et al. 2003)
236 and in gneiss complexes to the east (Gervais et al. 2004) indicate that the sedimentary
237 succession of the Wakeham Group is most probably detached from its underlying high-
238 grade basement (Fig. 6). Seismic data do not provide evidence for the kinematics of the
239 detachment at the base Wakeham Group. However, the superposition of low grade rocks

on top of high grade rocks, field evidence indicating that latest displacement on the Abbé Huard shear zone (Fig. 2) was transtensional (Martignole et al. 1994) and the increasing recognition of an orogen-scale episode of collapse (Rivers 2008, 2012, 2015; Rivers et al. 2012; Schwerdtner et al. 2014; Soucy La Roche et al. 2014) all point toward a major normal-sense fault at the base of the Wakeham Group (Fig. 6B), in agreement with the interpretation proposed by Rivers et al. (2012) for the Havre Saint-Pierre area.

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336 **Figure caption:**

337 Figure 1: Geological map of Anticosti Island-Havre-Saint-Pierre area. Geology of the
338 north shore of the Gulf of St. Lawrence is simplified from Gobeil et al. (2003). AHSZ,
339 Abbé Huard shear zone; See the web for a color version of this figure.

340

341 Figure 2: Map of eastern Anticosti Island showing the location of available seismic lines,
342 magnetic anomalies (interpreted from images in Lynch 2000) and the distribution of the
343 highly reflective seismic unit immediately below the Paleozoic unconformity. Location
344 on Figure 1. See the web for a color version of this figure.

345

346 Figure 3: Seismic line AT71-210 illustrating the intra-basement sub-parallel reflections.
347 Location on Figure 2. SRSU, subparallel reflection seismic unit. The intersection with the
348 seismic line AT71-203 is indicated. The red line marks the Paleozoic unconformity. The
349 blue line is a seismic marker within the Paleozoic succession. The red arrow indicates a
350 shallow dipping high amplitude reflection discussed in the text. See the web for a color
351 version of this figure.

352

353 Figure 4: Interpretation of seismic line AT71-203 (A) and uninterpreted segment of the
354 same line (B) illustrating the geometry of the seismic unit characterized by subparallel
355 reflections. Location on Figure 2. SRSU, subparallel reflection seismic unit. The
356 intersections with seismic lines AT71-193, -198, -209 and -210 are indicated. The red

line marks the Paleozoic unconformity. The blue line is a seismic marker within the Paleozoic succession. Dotted green lines and green double arrows indicate the fold axes and fold traces respectively. The two red arrows in (B) illustrate the different dips of reflections close to the inferred fault contact. See the web for a color version of this figure.

Figure 5: Interpretation of the southern part of the seismic line AT71-199 (A) and uninterpreted segment of the same line (B) illustrating the fanning of reflections. Location on Figure 2. The red line marks the Paleozoic unconformity. The blue line is a seismic marker within the Paleozoic succession. Orange arrows illustrate the apparent thickness changes between two reflections. The green dashed line marks the southern boundary of a seismically transparent unit and the trace of a possible fault. See the web for a color version of this figure.

Figure 6: A- Map showing the possible extent of the Wakeham Group and Robe-Noire mafic sills below the Paleozoic sedimentary cover. B- Highly schematic cross-section showing an interpretation in which the Wakeham Group and Robe-Noire mafic sills are detached from their relative basement. This cross-section shows the main lithotectonic elements illustrated in the cross-section of Rivers et al. (2012). SZ, shear zone equivalent to the Abbé Huard shear zone. Colors same as Figure 1.

Pinet, Figure 1

Pinet, Figure 2

Pinet, Figure 3

Pinet, Figure 4

Pinet, Figure 5

Pinet, Figure 6