Quaternary Geochronology xxx (2015) 1–6

Contents lists available at ScienceDirect

Quaternary Geochronology

journal homepage: www.elsevier.com/locate/quageo

Quartz OSL dating of late Holocene beach ridges from the Magdalen Islands (Quebec, Canada)

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A R T I C L E I N F O

Article history:
Received 24 October 2014
Received in revised form
25 March 2015
Accepted 30 March 2015
Available online xxx

Keywords:
Quartz OSL dating
Beach ridges
Sea level rise
Late Holocene
Magdalen Islands

A B S T R A C T

Quartz optically stimulated luminescence (OSL) dating has been applied to sandy beach ridge systems from the Magdalen Islands in the center of the Gulf of St. Lawrence (Quebec, Canada) to provide the first chronological framework for these features. Nineteen beach ridges (22 samples) from four different sites throughout the archipelago were investigated. At one of the sites, samples were taken at 9 m and 7.5 m depth using a vibracore. The quartz is dominated by the fast OSL component and a single-aliquot regenerative-dose (SAR) protocol was used to measure the equivalent doses; a low preheat (180°C/10 s) was chosen to avoid the influence of thermal transfer. The average dose recovery ratio of all samples is 1.02 ± 0.02 (n = 130) suggesting that the SAR protocol works satisfactorily on this material. The OSL ages are internally consistent and supported by independent age control (radiocarbon). The OSL ages indicate that the ridges were built between 2.6 ± 0.2 ka and 0.40 ± 0.10 ka, i.e. during a period of sea level rise. This rise eroded adjacent sandstone cliffs, which contributed a significant sediment supply to the littoral drift and beaches. Some low-lying coasts in the archipelago are still prograding, despite a relative sea level increase of ~1.6 mm/a over the last 600 years. The late Holocene ages obtained in this study indicate that these processes have been active for at least the past two thousand years. This study demonstrates for the first time that OSL dating using quartz has great potential in this area, and is an appropriate method for establishing precise chronologies for coastal sediments in this region of the Gulf of St. Lawrence.

1. Introduction

The Magdalen Islands lie in shallow water (<100 m) near the center of the Gulf of St. Lawrence, halfway between Prince Edward Island and Newfoundland in eastern Canada (Fig. 1A). Sandy beach ridges are found at five locations on the sandy causeway connecting the bedrock islands. Such beach ridge systems are regarded as providing a promising record of Holocene paleo-coastlines (*e.g.,* Otvos, 2000; Scheffers et al., 2012). Here we use 'beach ridge systems' in the terminology of Scheffers et al. (2012) to describe the different complexes of beach ridges, which can be of various morphodynamic origins (Taylor and Stone, 1996). These geomorphic features contain archives of the processes involved in the evolution of low-lying coasts, including records of sea-level, sediment supply, climate (including storm events and paleo-wind direction regime), wave energy and related littoral drift, *etc.* (*e.g.,* Otvos, 2000, 2012; Bristow and Pucillo, 2006; Stutz and Pilkey, 2011).

On the Magdalen Islands, despite the presence of indicators of Holocene sea level changes, no local relative sea level (RSL) curve is available. Nevertheless, a RSL rise of 3 m over the last 2 ka has been suggested using an analysis of terrestrial environments and trees in living position, but now located in the intertidal zone (Juneau, 2012). This rise corresponds to an average of 15–20 cm/century in the last two millennia, with a peak of 34 cm/century during the last century. One consequence of this recent acceleration in sea level rise is that 70% of the coastline is currently at risk of erosion

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http://dx.doi.org/10.1016/j.quageo.2015.03.013
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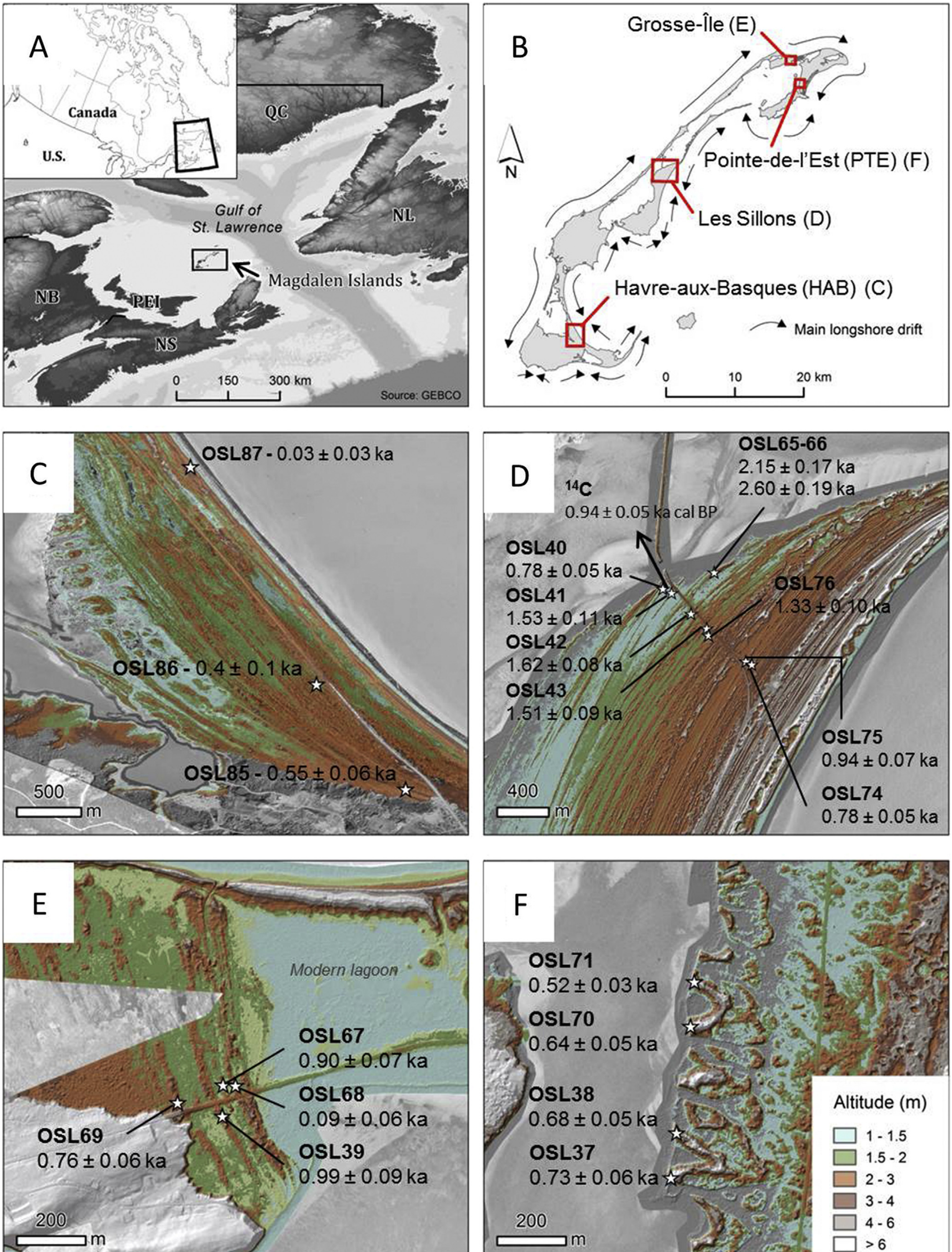
A
Canada
U.S.
QC
NL
Gulf of
St. Lawrence
Magdalen Islands
NB
PEI
NS
0 150 300 km
Source: GEBCO
B
Grosse-Île (E)
N
Pointe-de-l'Est (PTE) (F)
Les Sillons (D)
Havre-aux-Basques (HAB) (C)
Main longshore drift
0 10 20 km
C
OSL87 - 0.03 ± 0.03 ka
OSL86 - 0.4 ± 0.1 ka
OSL85 - 0.55 ± 0.06 ka
500 m
D
OSL65-66
2.15 ± 0.17 ka
2.60 ± 0.19 ka
^{14}C
0.94 ± 0.05 ka cal BP
OSL40
0.78 ± 0.05 ka
OSL41
1.53 ± 0.11 ka
OSL42
1.62 ± 0.08 ka
OSL43
1.51 ± 0.09 ka
OSL76
1.33 ± 0.10 ka
OSL75
0.94 ± 0.07 ka
OSL74
0.78 ± 0.05 ka
400 m
E
Modern lagoon
OSL67
0.90 ± 0.07 ka
OSL68
0.09 ± 0.06 ka
OSL39
0.99 ± 0.09 ka
OSL69
0.76 ± 0.06 ka
200 m
F
OSL71
0.52 ± 0.03 ka
OSL70
0.64 ± 0.05 ka
OSL38
0.68 ± 0.05 ka
OSL37
0.73 ± 0.06 ka
200 m
Altitude (m)
1 - 1.5
1.5 - 2
2 - 3
3 - 4
4 - 6
> 6

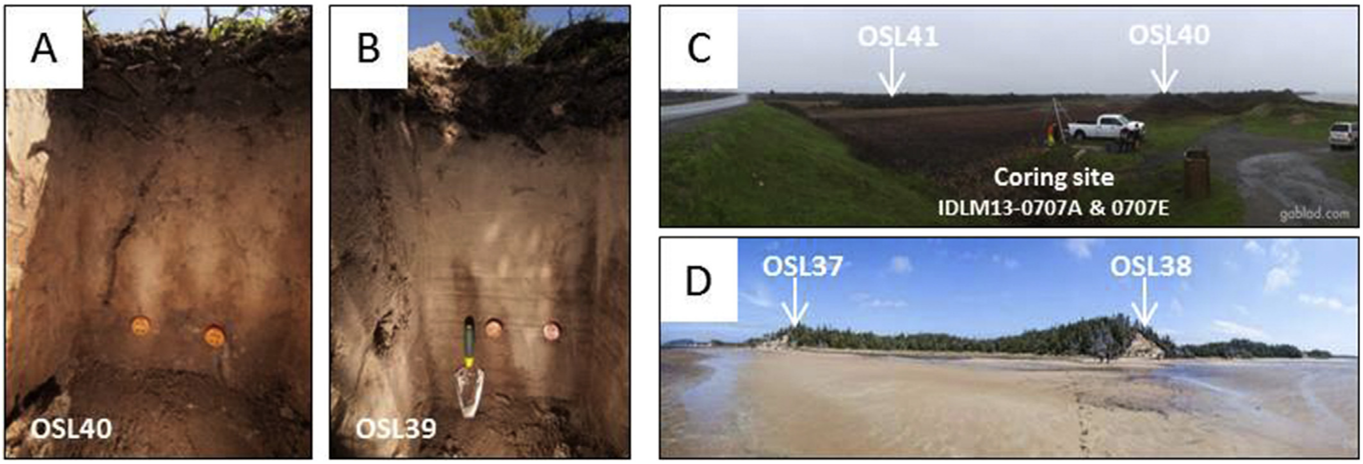

Fig. 2. Examples of sample location and sampling. A) Les Sillons site (OSL40 and its backup). B) Grosse-Île site (OSL39 and its backup). C) Les Sillons site (OSL40, OSL41, and the coring site IDLM13-0707A and 0707E). D) PTE site (OSL37 and OSL38). The backup samples were not used.

and submersion (Bernatchez et al., 2008, 2012). It is thus very important to understand past and present RSL in order to generate accurate projections and develop appropriate adaptation strategies against these hazards. Dating of the beach ridge systems located on the Magdalen Islands has previously not been undertaken; the development of such a chronology would enable: (1) a spatio-temporal reconstruction of the coastline at the local scale, and (2) an understanding of geomorphological responses to Holocene RSL changes, allowing accurate predictions of future responses.

OSL dating of features such as beach ridges has been the subject of numerous studies in the last decade and have shown that standard multi-grain quartz SAR OSL dating can yield accurate results (*e.g.*, Murray-Wallace et al., 2002; Argyilan et al., 2005; Clemmensen et al., 2012). In eastern Canada, however, such analyses have not been carried out as a consequence of the observed low yield of sensitive quartz in sediment from mainland glaciated Quebec (Lamothe, 2015).

In this pilot study, we investigate the feasibility of developing the first numerical chronology for the beach ridge systems of the Magdalen Islands, and so derive new insights into late Holocene sea level change on the northeastern coast of North America. We begin by documenting the luminescence characteristics of quartz grains extracted from beach ridges on the Magdalen Islands and present a luminescence chronology for these geomorphological features. This new dataset is the first major contribution to a detailed chronology of the beach ridge systems on the Magdalen Islands.

2. Samples, methodology and luminescence characteristics

Twenty two OSL samples were collected from 19 beach ridges at five different sites throughout the archipelago: Havre-aux-Basques (HAB), Les Sillons, Grosse-Île, Pointe-de-l'Est (PTE), and Plaisance (Fig. 1B–F). Except for the Grosse-Île site that is isolated from current coastal dynamics, these sites are located in convergence zones of the main longshore drift (Fig. 1B). All samples were collected by hammering opaque 5-cm diameter plastic tubes 30 cm into both outcrops and pits. At HAB, Les Sillons and Grosse-Île (Fig. 1C–E), samples were collected from 60 to 100-cm depth in pits dug on top of two, seven and four ridges, respectively (Fig. 2A and B). At PTE (Fig. 1F), the four ridges sampled were exposed in outcrops (Fig. 2D). At Les Sillons (Fig. 1D), one ridge was exposed in an outcrop; the base and the top of the outcrop were sampled to investigate the feasibility of dating the formation of the ridge at the outcrop scale. At Les Sillons, a vibracore (WINK) was used to obtain samples at 9 m and 7.5 m depth (Fig. 2C) using a light-proof liner. At Plaisance (Fig. 1C), one sample was taken from a recently-deposited beach ridge to test the degree of bleaching in this type of environment on the Magdalen Islands.

All OSL samples were prepared under subdued orange light. The outer ~5 cm ends of all tubes were used for water content determination and dose rate analysis. Samples were wet-sieved and the 180–250 μm fraction was etched with 10% H_2O_2, 10% HCl, and 10% HF in the usual manner. Heavy liquid separation (2.58 g/ml) was used to isolate quartz grains. Finally, the quartz-rich extract was etched using concentrated HF (40%) for 1 h to remove any remaining feldspar and to remove the outer alpha irradiated layer from the quartz grains.

All measurements were carried out using a Risø TL/OSL reader (model DA-20) equipped with blue LEDs (~80 mW/cm^2) and infrared (IR) LEDs (~135 mW/cm^2) (Thomsen et al., 2006). The sand-sized quartz grains were mounted on 8 mm diameter stainless steel discs using silicone oil. The single-aliquot regenerative-dose (SAR) protocol (Murray and Wintle 2000, 2003) was used for all equivalent doses (D_e) determination. Quartz aliquots were stimulated using blue light at 125 °C (90% power) for 40 s. The D_e values were calculated using the first 0.32 s of OSL and a background of 0.32–0.64 s (Cunningham and Wallinga, 2010) to minimize any possible contribution of non-fast components. However, because our samples are dominated by the fast component (see Fig. 3A), dose estimates are relatively insensitive to the background interval chosen. Prior to OSL measurement, the purity of the quartz subsamples was confirmed by an OSL IR depletion test (Duller, 2003); all samples had OSL IR depletion ratios within 10% of unity, indicating that there was no significant contribution from feldspar or other IR-responsive components to the blue-stimulated OSL signal.

Fig. 1. A) Location of the Magdalen Islands in the Gulf of St. Lawrence and Eastern Canada. QC = Québec, NB = New Brunswick, PEI = Prince Edward Island, and NL = Newfoundland B) Location of the sampling sites on the Magdalen Islands. Arrows correspond to the direction of the main longshore drift. C–F correspond to LiDAR imagery where white stars represent sampling locations; legend in 1F is valid for all of them. C) HAB site. The black star represents sampling location of a recently deposited beach ridge (Plaisance site; OSL87). D) Les Sillons site. E) Grosse-Île site. F) PTE site.

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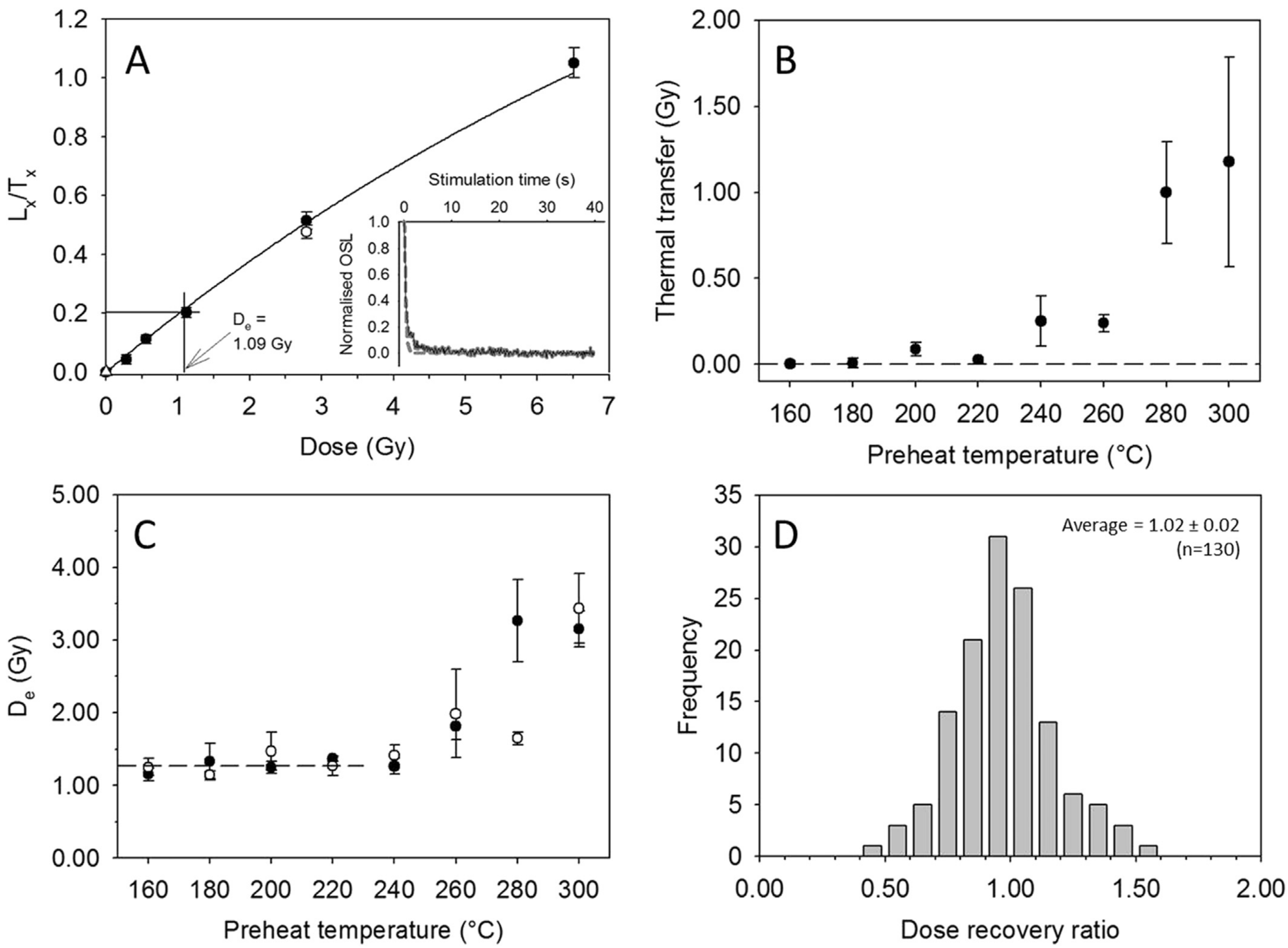

Fig. 3. A) SAR growth curve from sample OSL43 (Les Sillons site). Regenerated signals are shown as filled circle, opened circle represents recycling ratio and open triangle recuperation. Inset shows a typical natural OSL decay curve from the same sample together with a decay curve of an aliquot of calibration quartz (dashed); a background signal from the end of the stimulation curve has been subtracted before normalisation. The sensitivity corrected natural OSL signal is interpolated onto the growth curve to give the equivalent dose (in this case D_e = 1.09 Gy). B) Thermal transfer (sample OSL43); equivalent dose is plotted against increasing preheat temperature for a set of aliquots that had first been bleached by blue light at room temperature. C) Preheat plateau (sample OSL43); equivalent dose is plotted against eight different preheat temperature. Closed circles represent blue-light stimulation and open circles post-IR blue stimulation. The dashed line is guide showing the average 160–220 °C. D) Summary of dose recovery data for the 22 samples measured with preheat of 200 °C for 10 s and cut-heat of 160 °C (n = 130).

A typical sensitivity corrected growth curve is given in Fig. 3A, with a natural OSL stimulation curve shown inset, together with a curve from a quartz calibration standard (Hansen et al., in press). The strong fast-component dominated signal is in marked contrast to the insensitive quartz often found in other eastern Canadian sediments. The effects of thermal pre-treatment were tested using a thermal transfer plateau (on laboratory bleached sample) and a preheat plateau (Fig. 3B and C). These data suggest that preheat temperatures of ≤200 °C will avoid significant thermal transfer. The preheat plateau was also measured using a post-IR blue protocol (opened symbols); the results further confirm that feldspar contamination does not affect our D_e estimates.

The average recycling ratio is 1.02 ± 0.01 (n = 550) and the recuperation is always less than 10% of the test dose (see also Fig. 3A for a typical example). A dose recovery test was carried out on 6 aliquots of each sample by blue-light bleaching for two periods of 40 s at room temperature, separated by 10 ks pause, giving a laboratory dose, and then measuring this dose using a preheat of 200 °C for 10 s, and a cut-heat of 160 °C. The given dose was of 5.1 Gy and the mean dose recovery ratio is 1.02 ± 0.02 (n = 130) (Fig. 3D), confirming that the chosen SAR protocol is suitable for these samples.

For dose rate determination, approximately 250–300 g of the light-exposed material was dried, ground and ignited (24 h at 450 °C) and subsequently cast in wax in a fixed cup geometry. After three weeks of storage, the cups were counted on a high-resolution gamma spectrometer for at least 24 h, following Murray et al. (1987). The cosmic ray contribution is derived following Prescott and Hutton (1994), and the burial depths given in Table S2.

Finally, an AMS ^{14}C age obtained on plant fragments from a basal swale peat provides some independent age control; this was calibrated using the CALIB 7.0 program with the INTCAL13 calibration dataset (Reimer et al., 2013).

3. Results

3.1. Dosimetry

Radionuclide activity concentrations, water contents, dry dose rates and total dose rates are given in Table S1. The water contents used for the dose rates calculation are based on laboratory measurements of saturation water contents. The PTE and Plaisance samples were well-drained at the time of sampling and are confidently expected to have been well above the water table throughout their burial history; for these samples we have assumed a life-time water content of 20% of saturation. The remaining samples were poorly drained and are confidently expected to have always been close to the water table; for these samples we have assumed a life-time water content of 80% of saturation. In both cases an uncertainty of ±4% water content by weight was assumed. Resulting dose rates vary between 0.55 ± 0.03 and 1.96 ± 0.07 Gy/ka, typical of sandy sediments (Table S1). Because some of these dose rates are low and most samples lie with 2 m of the surface, the cosmic ray contribution to the total varies between 6 and 26%.

The uncertainties on individual ^{238}U analyses are too large to allow a discussion of the state of equilibrium on a sample by sample basis. Nevertheless, on average the $^{226}Ra/^{238}U$ activity ratio is 0.63 ± 0.17 ($n = 21$) indicating that there has probably been some loss of ^{226}Ra as a result of exposure of terrestrial sediment to saline water before deposition (*e.g.* Webster et al., 1995). This implies that the ^{226}Ra concentrations measured today may not be representative of the life time average. However, this is not of concern because ^{226}Ra and its daughters contribute <5% to the total dose rate in these sediments; the effect of variations in ^{226}Ra on a time scale of a few ka will be much less than this.

3.2. Reliability of OSL dates

Equivalent doses and the resulting ages are summarized in Table S2. In order to confirm that the quartz from the beach ridges of the Magdalen Islands was well bleached at the time of deposition, a sample was taken at the Plaisance site from a recent deposit analogous to the relic beach ridge sediments (OSL87; Fig. 1C). The resulting dose is 60 ± 40 mGy, corresponding to an age 0.03 ± 0.03 ka (Table S2), consistent with the expected time since deposition. In addition, the basal swale peat between two ridges at Les Sillons site gave a radiocarbon age of 0.94 ± 0.05 ka cal BP (UCIAMS-52770), while the OSL ages from the two adjacent ridges are 0.78 ± 0.05 ka (OSL 40) and 1.53 ± 0.11 ka (OSL 41). These OSL ages are again consistent with the independent age control and confirm that the chosen SAR protocol is suitable for this material.

3.3. Chronology of the beach ridge systems

The beach ridge systems observed on the Magdalen Islands started developing before approximately 2.6 ka ago. The oldest site is Les Sillons with samples OSL65 and OSL66 dated to 2.15 ± 0.17 ka and 2.60 ± 0.19 ka respectively. This ridge was exposed in an outcrop; OSL65 is from the bottom and OSL66 the top of the exposure. These two ages are indistinguishable at a 95% confidence interval; as a result they do not allow us to discuss the internal chronology of this ridge at the outcrop scale. The age of the Les Sillons system becomes younger on both sides of the ridge containing OSL65 and OSL66 (Fig. 1D; Table S2). Westward, the ridges give ages of 1.53 ± 0.11 ka (OSL41) and 0.78 ± 0.05 ka (OSL40). A core was taken adjacent to OSL40 and ages of 1.30 ± 0.05 ka (0707A) and 1.14 ± 0.04 ka (0707E) were measured at 9 m and 7.5 m depth, respectively. These ages suggest an approximate net accumulation rate of ~10 mm/a, indicating a high rate of sediment supply. The OSL ages suggest that the Les Sillons system grew each side of OSL65-66 ridge and a new major ridge was built every ~100–300 years.

The same pattern is present at the Grosse-Île site, where the oldest ridge is 0.99 ± 0.09 ka (OSL39) (Fig. 1E; Table S2). On each site, adjacent ridges were dated to 0.90 ± 0.06 ka (OSL67) and 0.76 ± 0.06 ka (OSL69). The ridge located the closest to the modern lagoon gives a recent age of 0.09 ± 0.06 ka (OSL68). This ridge is currently vegetated by shrubs and small trees (mainly white spruce) with shallow soil development; it is likely that the sediment was reworked by wind before the vegetation cover was established. At the PTE site, the ridges give ages between 0.73 ± 0.06 ka (OSL37) and 0.52 ± 0.05 ka (OSL71) (Fig. 1F; Table S2); the ages decrease northwards with ~50–100 years between each ridge. Finally, the same pattern was observed at the HAB site where two sampled ridges gave ages of 0.55 ± 0.06 ka (OSL85) and the more seaward 0.40 ± 0.10 ka (OSL86).

4. Discussion

Beach ridge strandplains are often preserved where the sea level is dropping or has dropped in the past (*e.g.*, Blum et al., 2002; Otvos, 2004; Scheffers et al., 2012). However, in the Saint-Pierre-et-Miquelon Islands, southwest of Newfoundland, prograding beach ridge systems were formed during a deceleration in relative sea level rise (induced by glacial isostatic adjustment) over the last 3000 years (Billy et al., 2014). On the Magdalen Islands, analysis of paleo-forest horizons and submerged trees stumps found currently in the intertidal zone, and the succession of freshwater peat overlain by intertidal marsh facies, leads to the deduction of a relative sea level rise of 3 m over the two last millennia. These measures imply a mean rise of 15 cm–20 cm per century with a recent acceleration of 24.4 and 34.4 cm/century during the 19th and the 20th centuries, respectively (Juneau, 2012). These sea level rise values are similar to those measured in the southern Gulf of St. Lawrence, especially in the provinces of Prince Edward Island and Nova Scotia (*e.g.*, Scott et al., 1981, 1995; Gehrels et al., 2004; Koohzare et al., 2008). From the 22 OSL ages obtained in this study, it appears that the Magdalen Islands beach ridge systems were built while the sea level was rising. For a coastline to prograde in such circumstances requires a large sediment supply together with a gradual sea level rise (Giles and King, 2001; Stutz and Pilkey, 2011). With a mean erosion rate of −0.3 m/year between 1963 and 2008, and reaching up to −1.5 m/year in some places (Bernatchez et al., 2012), the cliffs of the Magdalen Islands have the highest rocky coastal-cliff erosion rates in the Estuary and Gulf of St. Lawrence (Bernatchez and Dubois, 2004). Since there are no rivers capable of transporting sediment on the Magdalen Islands and offshore currents do not appear to be significant sources (Drapeau and Mercier, 1990), it is likely that sandstone cliff erosion due to rising sea level is the main source of sediment to the longshore drift and the building of prograding beaches. Indeed, some low-lying coasts on the archipelago are still prograding, despite a relative sea level increase of ~1.6 mm/a over the last 0.6 ka (Bernatchez et al., 2012; Juneau, 2012). The new late Holocene OSL ages of this study suggest that this progradation and sediment transfer have been active for at least the last two thousand years.

5. Conclusions

This study demonstrates that it is possible to build an OSL chronology using quartz grains for the beach ridge systems of the Magdalen Islands. The 22 OSL ages measured here have shown that the beach ridges began to develop about 2500 years ago while the sea level was rising. The data suggest the building of a new ridge every ~100–300 years, and such a progradation in the presence of a rising sea level requires a high rate of sediment supply. This study also suggests that quartz OSL dating has considerable potential and that it is an appropriate method for establishing precise chronologies in coastal sediments in this region of the Gulf of St. Lawrence. This dataset is the first step towards the development of a late Holocene RSL curve and the understanding of the

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geomorphological response of the local coastal systems to sea level rise.

Acknowledgments

Gabriel Ladouceur, David Noël, Sylvain Leblanc, Tarik Toubal, Louis Cormier, Robert Barnett and Francis Bonnier-Roy are thanked for their valuable help in the field, as well as Marie-Pier St-Onge and Jacques Labrie for their help in the laboratory. The authors wish to acknowledge the support of the Nordic Laboratory for Luminescence Dating (NLL) team. The Natural Sciences and Engineering Research Council of Canada (NSERC) (312343-2012), Fonds de recherche du Québec Nature et Technologies (FQRNT), the Coastal Geoscience Chair, and the Canada Research Chair in Marine Geology provided financial support for the project.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quageo.2015.03.013.

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