19 Landforms and Landscapes of the Magdalen Islands: The Role of Geology and Climate

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Abstract

The landscape and landforms of the Magdalen Islands are uniquely varied for such a small archipelago. Geomorphologically they are a part of the Maritime Plain which is located near the center of the Maritime Basin (375–325 Ma). The Magdalen Islands were pushed to the surface by salt-diapirs ($\sim$300 Ma). Formed by volcanic hills (basalt) surrounded by a low sandstone platform, the main islands are interconnected by late Holocene sand spits and tombolos. Located in the southern part of the Gulf of St. Lawrence, the Laurentide Ice Sheet (LIS) did not reach the Magdalen Islands during the last glaciation, but possibly much earlier ($\geq$170 ka). Three different sets of geomorphological processes have impacted the landscape: structural, periglacial, and coastal. Sandstone platforms adjacent to volcanic hills are the structural controls. Superimposed on the sandstone platforms, cryopediments, ice-wedge pseudomorphs and dry valleys are the dominant periglacial landforms. Coastal landforms are dominated by cliffs, tombolos, and littoral spits. Perhaps the single most surprising fact is that eight islands with a cumulative area of 202 km^2 can demonstrate such a remarkable variety of landscapes and landforms. The glacial record remains contentious.

Keywords

Maritime plain • Volcanics, sandstone • Karstic foothills • Cryopediments • Ice-wedge pseudomorphs • Tombolos • Relative sea level

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19.1 Introduction

Located in the center of the Gulf of St. Lawrence (Fig. 19.1), the Magdalen Islands offer original landscapes typical of the Maritime Plain (Brisebois 1981; Barr et al. 1985; Dubois 1992; Giles 2008) (Fig. 1.10; this volume). Geomorphology of the islands is the result of a long geological evolution marked by the development of several salt-diapirs, and, since at least 170 ka, by alternating glacial and periglacial periods resulted in inherent large scale relative sea-level (RSL) variations (Rémillard et al. 2016). These RSL changes were produced by the combined effect of global sea-level fluctuations (glaci-eustatic) and vertical adjustments of the Earth's crust (glaci-isostatic). This part of the Gulf of St. Lawrence is currently subsiding owing to the migration and collapse of the peripheral glacial forebulge (Dubois 1992; Koohzare et al. 2008). The resulting exacerbated marine transgression induces rapid coastal submergence and erosion, which represent a major challenge for coastal communities and infrastructures (Bernatchez et al. 2008, 2012).

19.2 Study Area

19.2.1 Geology and Landscapes

The archipelago is 80 km in length measured from the SW of the Havre Aubert Island to the NE of Brion Island and comprises eight rocky islands, six of which are connected to each other by sandy barrier beaches (tombolos) (Figs. 19.1 and 19.2) (e.g., Dubois and Grenier 1993; Bernatchez et al.

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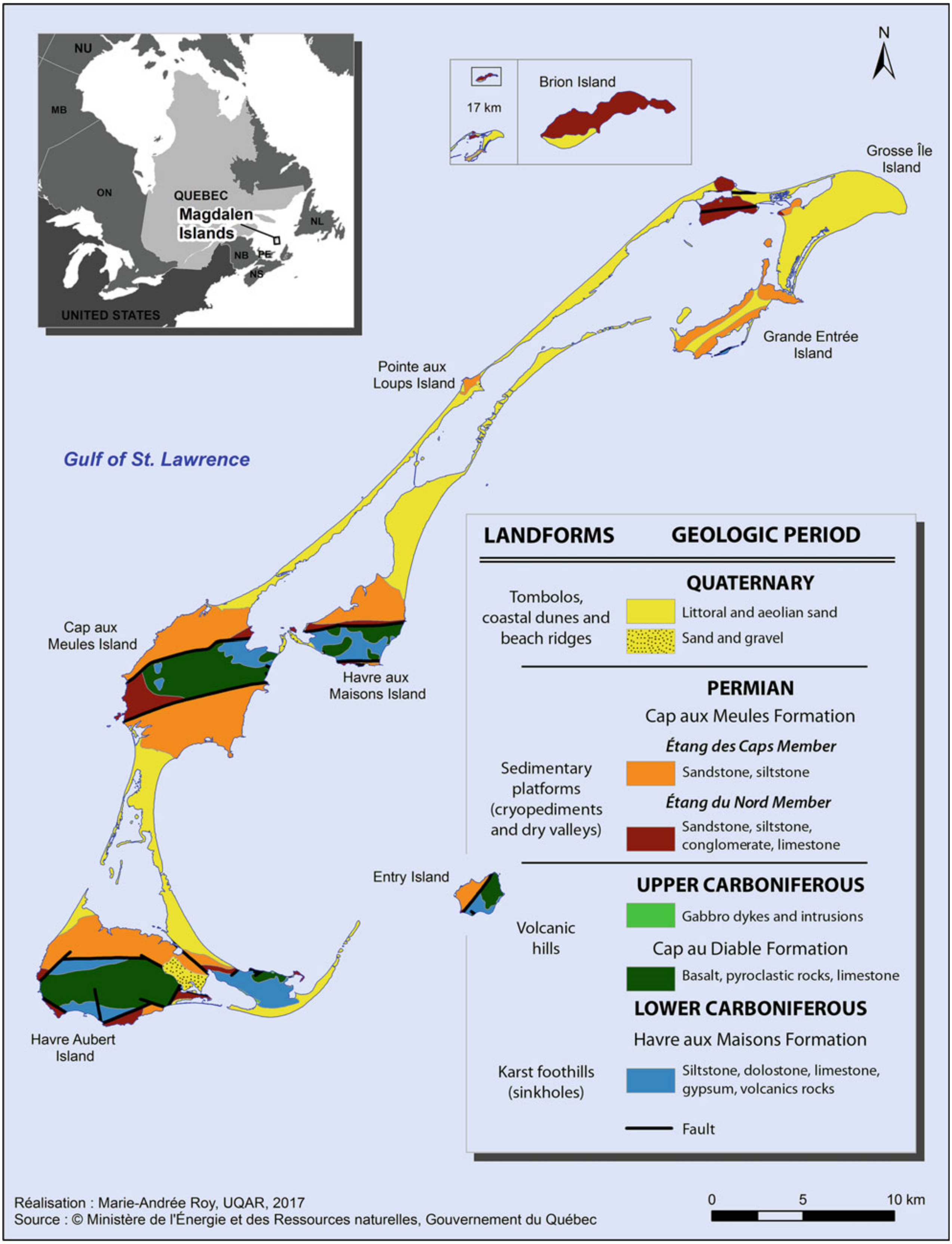

Fig. 19.1 Geology and landforms of Magdalen Islands (modified from Brisebois 1981)

Fig. 19.2 The diverse landscapes of the Magdalen Islands. **a** Double tombolo connecting the Havre Aubert Island to the Cap aux Meules Island. **b** Buttes des Demoiselles (volcanic hills) and the Sandy Hook littoral spit (background) on the Havre Aubert Island. **c** Entry Island: volcanic hills (Big Hill) and the cryopediment that truncates the sandstone platform. **d** Sandstone platform of the Cap aux Meules Island. **e** A volcanic hill of the Havre aux Maisons Island. **f** Relict nivation hollows in the volcanic hills (Butte du Vent, Cap aux Meules Island). **g** Sinkholes group on the Havre Aubert Island. *Photographs* a and g © Antoine Morissette

2012). The terrestrial area is 202 km^2 and reaches 363 km^2 including lagoons and emerged or slightly submerged sandy zones (Quirion 1988). The Magdalen Islands are part of the low relief Maritime Plain (geomorphically) and Maritime Basin (geologically), which corresponds to a wide (approximately 150,000 km^2) system of grabens that appeared just after the Acadian orogeny (375–325 Ma) under the influence of extensional tectonics whose origin is still uncertain (Brisebois 1981; Barr et al. 1985; La Flèche et al. 1998; Giles 2008). Between the end of the Devonian

(~360 Ma) and the beginning of the Permian (~300 Ma), this wide subsiding basin was filled by a thick (~9,000 m) sequence of diverse material including shallow water marine sediments (e.g., salt, gypsum, limestone), volcanic rocks (basalt, andesite, rhyolite), and, finally, terrestrial sediments (sandstone, mudstone) that indicate a semi-arid environment (fluvial sand, playas, petrified dunes) (Brisebois 1981; Barr et al. 1985; Giles 2008).

The present forms of the Magdalen Islands, subdivided into four distinct geomorphological groups (Dubois 1992), are controlled by geology (Figs. 19.3 and 19.4): the volcanic hills, karstic foothills, sandstone platform and Late Holocene barrier beaches. The highest hills on Entry Island (Big Hill: 174 m asl), Havre Aubert Island (140 m asl), Cap aux Meules Island (Butte du Vent: 168 m asl) and Havre aux Maisons Island (105 m asl) are composed of volcanic rocks (basalt, andesite, rhyolite) belonging to the Cap au Diable Formation of Mississippian age (355–325 Ma). More than 4,000 m of volcanic rocks lie above the marine sediments and evaporites of the Windsor Group. These volcanic rocks were diapirically pushed to the surface through the terrigenous sediments of the Cap aux Meules Formation. According to Brisebois (1981), each of the rocky islands composing the archipelago is located at the summit of a salt diapir. The diapirs have also dragged to the surface masses of mixed rocks (mudstone, limestone, gypsum, sandstone), which are intensively deformed, faulted, and brecciated, and some of which are soluble. Brisebois (1981), who interpreted these mixed rocks as collapsed breccia associated with salt dissolution, named the group Havre aux Maisons Formation. After a long period of dissolution that produced numerous sinkholes, the soluble rocks of the Havre aux Maisons Formation form the karstic foothills (Figs. 19.2 and 19.3) between the volcanic hills and the sandstone platforms which extend below (Figs. 19.2, 19.3 and 19.4). The large dunified barrier beaches (double tombolos) (Figs. 19.1 and 19.2), of late Holocene age (Rémillard et al. 2015a), composed the fourth geomorphological group on the Magdalen Islands.

19.2.2 Climate and Vegetation

Located in the center of the Gulf of St. Lawrence and near the Atlantic Ocean, the Magdalen Islands have a boreal climate with a strong maritime influence. Winters are relatively mild (mean temperature in January: −6.4 °C) while summers are relatively cool (mean temperature in July: 17.1 °C). Total precipitation is 1037.3 mm and is well distributed throughout the year; 23% of total precipitations are falling as snow (Environment Canada 2017, Magdalen Islands station, Climate Normals 1981–2010). An analysis undertaken on data collected between 1985 and 2008 reveals an increase of the mean winter temperatures of more than 3 °C (Bernatchez et al. 2008). The archipelago is affected almost continuously by sustained winds from all directions. The wind, particularly strong during winter, blows at an average speed of 31 km/h with peaks that exceed 100 km/h (Agglomération des Îles-de-la-Madeleine 2010). The Magdalen Islands belong to the ecozone of the Acadian Forest of Rowe, but with the exception of the uninhabited Brion Island, there is not much left of the primitive forest. Residual forests occupy only 26% of the total area, concentrated in the hills and a few zones of the tombolos (Roy-Bolduc 2010). These forests are almost exclusively coniferous, including *Abies balsamea*, which accounts for more than 50% of mature trees, 24% *Picea mariana* (black spruce) and 24% *Picea glauca* (white spruce) (Roy-Bolduc 2010). Deforestation started as early as the 16th century and reached its peak around the middle of the twentieth century with wood used for fish smokehouses, shipbuilding, and the manufacture of fishing tackle (Fortin and Larocque 2003).

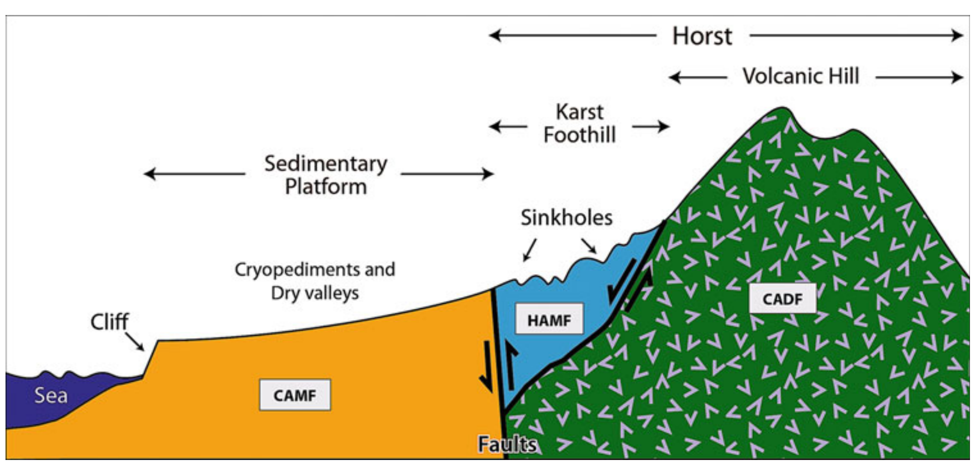

Fig. 19.3 Schematic model showing the relations between the geology and the landforms of the Magdalen Islands. CAMF = Cap aux Meules Formation; HAMF = Havre aux Maisons Formation; CADF = Cap au Diable Formation

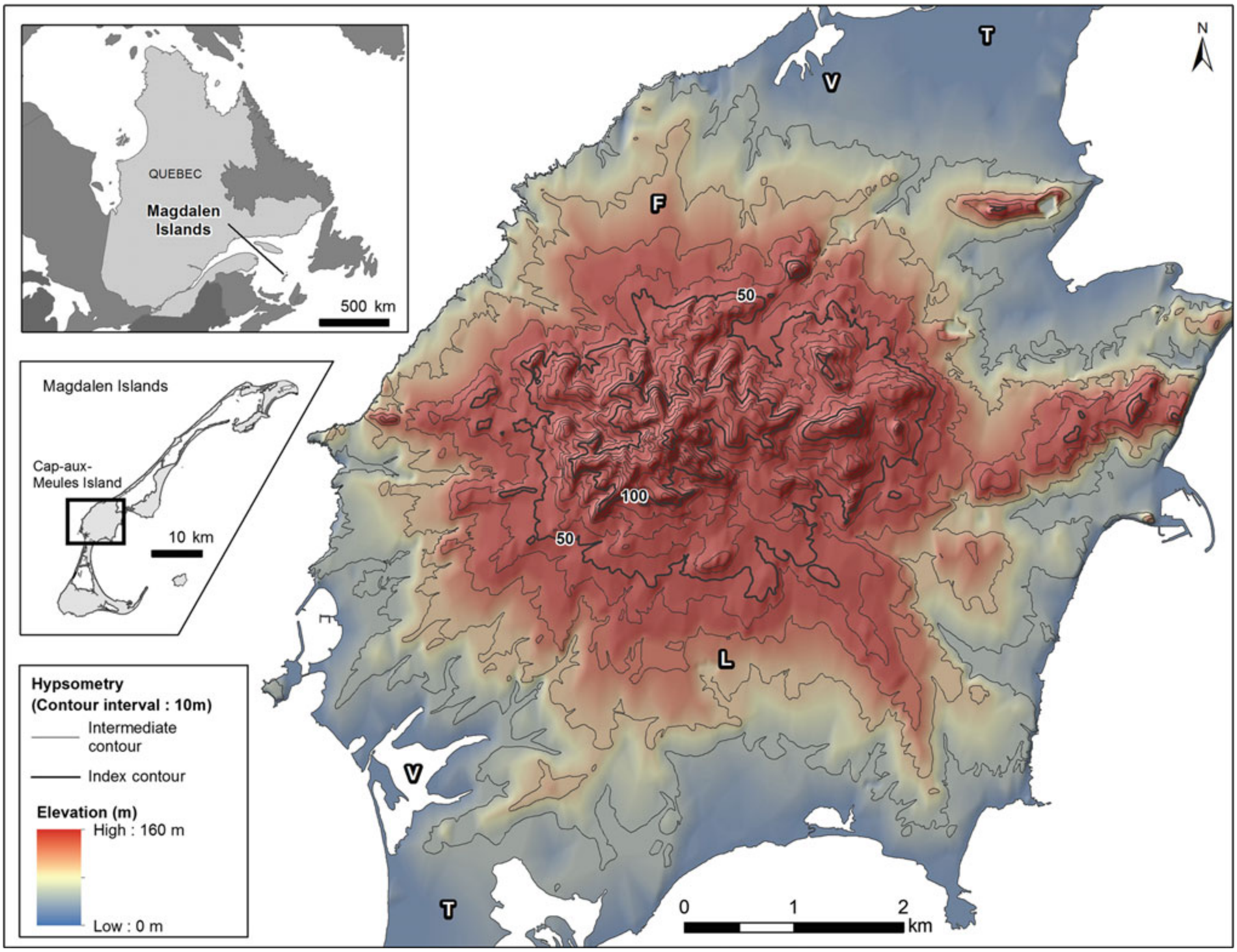

Fig. 19.4 The relief of the Cap aux Meules Island. The volcanic hill correspond to the centre of the island (>50 m). Numerous nivation hollows which were occupied by névé during non-glacial cold periods are observable. Below 50 m, the major part of the island is occupied by cryopediments; the most beautiful are located near Fatima (F) and La Vernière (L). In the lagoons, there are several valleys partially invaded by the sea (rias) (V). To the north and south, we note the beginning of tombolos (T)

19.3 Glaciation and Sea-Level History

19.3.1 Glaciation

Located in the center of the Gulf of St. Lawrence, the Magdalen Islands are a key area to the understanding of the glacial history of the Maritime Provinces (Stea et al. 1998, 2011; Shaw et al. 2006). The glacial history of the archipelago has been the subject of a long debate that started at the end of the 19th century and that persisted until recently. From the first publications of Richardson (1881), Chalmers (1895), and Goldthwait (1915) until the papers of Prest et al. (1976) and Dredge et al. (1992), the subjects of controversy were as numerous as varied (e.g., Stea et al. 2011; Rémillard et al. 2013, 2015b, 2016): origin and age of some deposits (e.g., till or glacimarine), the relative chronology of glacial and periglacial periods, the question of whether the islands were glaciated during the last glacial maximum (LGM) and if so, the origin and nature of the glaciers that reached the archipelago (Laurentide Ice Sheet or regional ice-caps). Using a detailed analysis of the sedimentological units exposed in more than 30 outcrops throughout the islands (Fig. 19.5), added to an extensive chronological dataset including 82 luminescence and 22 radiocarbon ages, Rémillard et al. (2013, 2015b, 2016) reconstructed the principal events of the glacial history since 65 ka. After an ice-free period during the MIS 3 (between approximately 65 and 40 ka), the Magdalen Islands were glaciated during the MIS 2 by two different ice-caps: the southern islands were glaciated by the Escuminac ice-cap located in the western Gulf of St. Lawrence, while the northern archipelago was glaciated at the end of the LGM by an ice flow from Newfoundland. Although it is not possible to make any

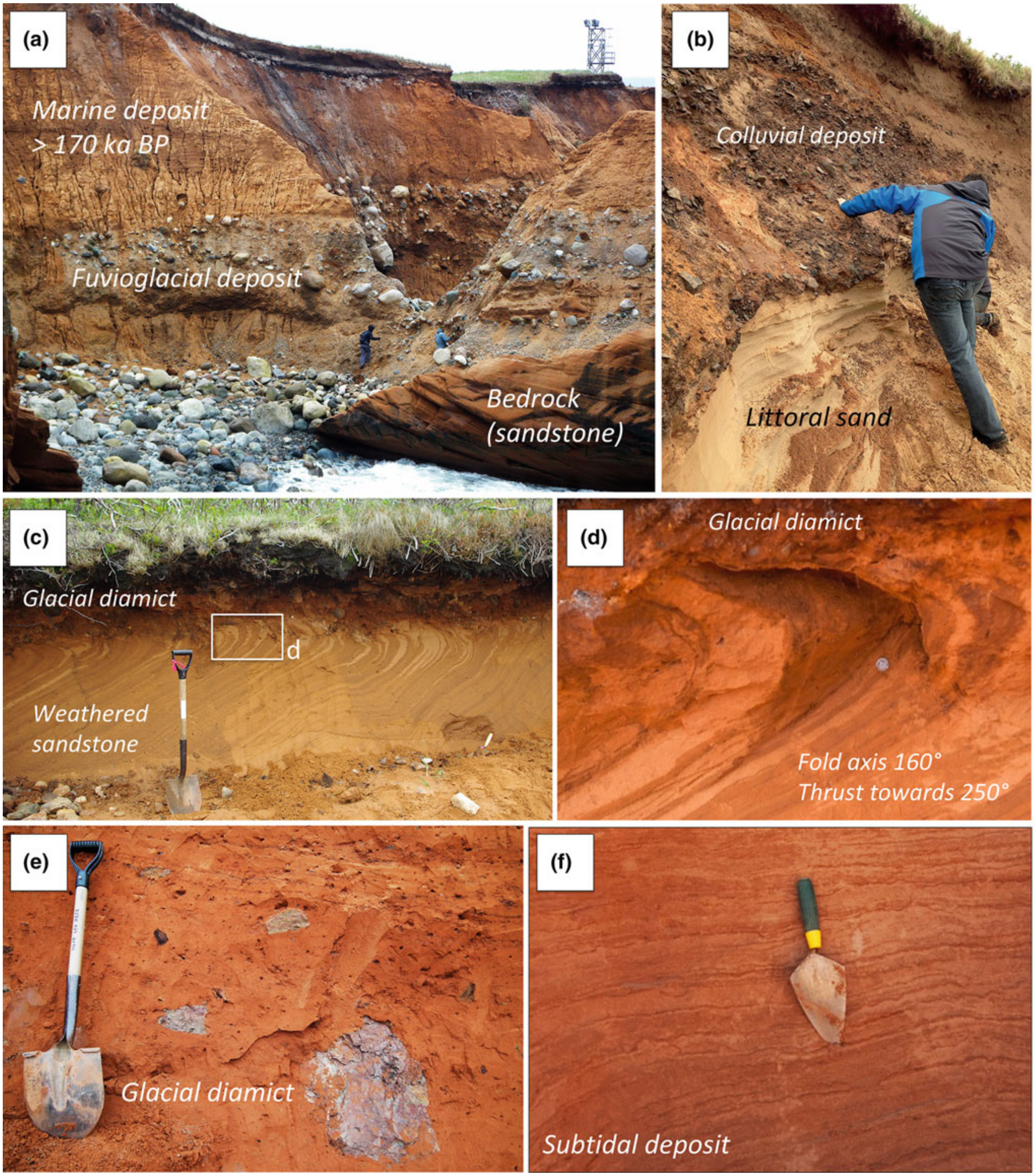

Fig. 19.5 The Quaternary deposits of the Magdalen Islands. **a** The Pointe aux Loups sequence of more than 170 kyr deposited by the LIS. The fluviglacial deposit at the bottom of the sequence contains erratic blocks from the Canadian Shield. **b** Entry Island: the colluvial deposit (cryopediment) overlying the littoral and marine sequence dated between 65 and 51 kyr. **c** and **d** Glacitectonic deformations associated with the ice movement from the Newfoundland ice-cap. **e** Havre Aubert Island: red till of the Escuminac ice-cap that flowed towards south-east. **f** Havre Aubert Island: subtidal deposit located at +24 m and dated to 11.5 kyr

assumptions about whether these ice-caps were synchronous, the observations put forward by Dredge et al. (1992), and more recently Rémillard et al. (2016), suggest that both ice movements from the Escuminac and Newfoundland ice-caps touched the Cap aux Meules Island.

Numerous dates between ~23 and 17 ka from periglacial and coastal deposits located on the southern and central islands indicate that this part of the archipelago was deglaciated early, i.e., immediately after the LGM (~25 ± 2 ka) (Rémillard et al. 2017). Once deglaciated, the southern archipelago was affected by periglacial conditions and a high RSL with different elevations on each island. The northern archipelago, i.e., Pointe aux Loups (PAL) and Grande Entrée islands, was deglaciated later, a little before 15 ka (Rémillard et al. 2016). During the MIS 2, the Magdalen Islands were thus affected by regional ice-caps that were part of the Appalachian Glacier Complex (Stea et al. 1998, 2011; Shaw et al. 2006). The Appalachian glaciers were coalescing with the Laurentian Channel ice stream (Shaw et al. 2006; Rémillard et al. 2016). The Laurentide Ice Sheet (LIS) did not reach the Magdalen Islands since at least the MIS 6. Throughout the archipelago, the only deposit that can be reliably linked to the LIS is located on the west coast of PAL is a proximal fluviglacial unit with varied erratics from the Canadian Shield and Anticosti Island. The fluviglacial unit is overlain by a marine deposit from which luminescence dating produced minimum ages of ≥ 170 ka (Fig. 19.5; Rémillard et al. 2016). The same deposit was observed elsewhere on the Grande Entrée Island (Sandcove, Bluff east, Old Harry) and all exposures gave minimum ages of 170 ka. These sedimentary bodies of marine origin are the thickest of the entire archipelago and are located only on PAL and Grande Entrée islands (Fig. 19.5).

19.3.2 Sea-Level History

The evolution of the RSL in the Gulf of St. Lawrence during the Quaternary was controlled by the combined sea-level effects of the growth and decay of ice sheets (glaci-eustatic) and the inherent dynamic response of the Earth's crust to the related changes of surface loading (glaci-isostatic). On this basis, Quinlan and Beaumont (1981) subdivided the Gulf of St. Lawrence and the adjacent regions into four zones characterized by distinct types of post-glacial RSL variations (Fig. 19.6). The Magdalen Islands lie within zone B. The latter corresponds to the area affected by an initial high RSL followed by an emergence due to the glaci-isostatic rebound and the migration of the peripheral forebulge, and finally, a submergence that is still ongoing today, caused partly by the collapse of the forebulge. In detail, however, there are important differences between the different areas of the archipelago depending on their respective glacial history. The south of the archipelago, glaciated by the Escuminac ice-cap, was deglaciated much earlier (as early as ~25 ± 2 ka) than the north (~15 ka). The observed marine limit is also much higher on the southern part: >+40 m on Entry Island and >+20 m on Grande Entrée Island (Rémillard et al. 2016). Around 15 ka, the entire archipelago was affected by the post-glacial transgression and the RSL reached minimum elevations between +10 and +20 m asl. Around 10 ka, the RSL passed below the modern level (Fig. 19.7) as indicated by the terrestrial peat dated to 10.7 ± 0.1 cal ka located at modern mean high tide and the organic horizon found by the Canadian Salt Company Seleine Mines at a depth of −17 m asl (Rémillard et al. 2016). Several geomorphological indicators observed between −35 and −200 m asl around the Magdalen Islands in the Gulf of St. Lawrence also attest to a low RSL (e.g., Sanschagrin 1964; Loring and Nota 1973; Josenhans and Lehman 1999; Shaw 2005). The timing of their formation remains unclear and therefore, they do not provide precise information required for RSL reconstructions. However, studies on the western coast of Newfoundland suggest a lowstand that would have reached −25 to −30 m asl (Forbes et al. 1995). After the evidence of a lowstand at ~9.8 ka cal around the Magdalen Islands, there is a lack of data until ~2 ka cal. The late Holocene submergence period is much better documented (Fig. 19.7). Based on multi-proxy analyses (salt-marsh foraminifera, testate amoebae and plant macrofossils; Fig. 19.8), Barnett et al. (2017) demonstrated that the RSL trend rose between 2 mm/yr and 1.3 mm/yr since the two last millennia with an acceleration during the 20th century. According to the tide gauge data, this rate would have doubled between 1964 and 2013 to reach 4.3 mm/yr (Barnett et al. 2016), as the result of the recent acceleration of the global sea-level rise and the still subsiding Earth's crust. This submergence rate, the highest along the Québec coastline, is close to the values measured on adjacent Prince Edward Island and Nova Scotia (Koohzare et al. 2008; Han et al. 2015).

The luminescence and ^{14}C ages obtained on the littoral and subtidal deposits on Entry and Havre Aubert islands report for the first time in the region of the Gulf of St. Lawrence an older transgression-regression cycle, i.e., between 65 and 40 ka (Fig. 19.7). During this period that corresponds to the interval between the end of the MIS 4 and the MIS 3, the RSL changed from >+40 m to ~+15 m asl. At that time, the global sea-level stood between −100 and −50 m below current level (Caputo 2007) which indicates a crustal depression between at least 85 and 135 m (Rémillard et al. 2017). Although there is no evidence of a glaciation on the Magdalen Islands during the MIS 4, such a crustal depression is likely due to the glaci-isostatic adjustment of the Earth's crust. However evidences of a glaciation during the MIS 4 were observed in the adjacent areas (Nova Scotia, New Brunswick) and according to Stea et al. (2011) an

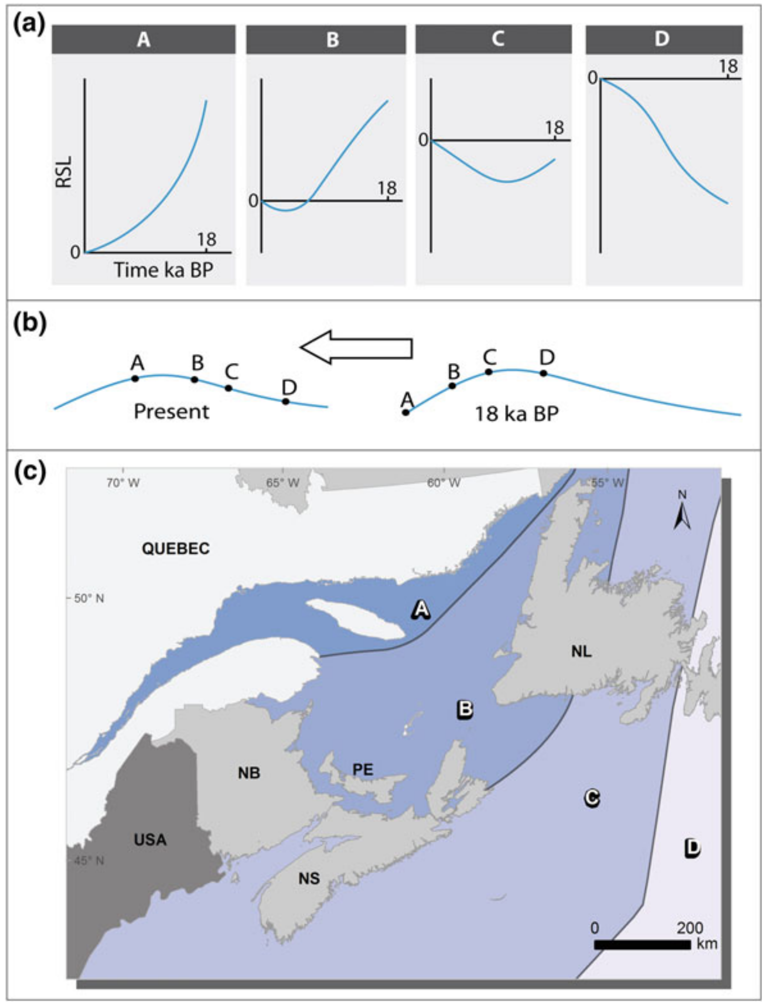

Fig. 19.6 (a) The four scenarios (A, B, C, and D) representing the history of the RSL variations for Atlantic Canada and the northeastern coast of the United States, from 18 kyr BP (∼21.7 kyr cal BP) until today. (b) Schematic representation of the position of the peripheral forebulge for 18 18 kyr BP (∼21.7 kyr cal BP) and today. The arrow indicates the direction of the forebulge migration and the points correspond to the position of the different scenarios and the influence of the forebulge on the RSL variations. (c) Hypothetical boundaries of the zones affected by each scenario (modified from Quinlan and Beaumont (1981) according to the recent data of Roy and Peltier (2015)

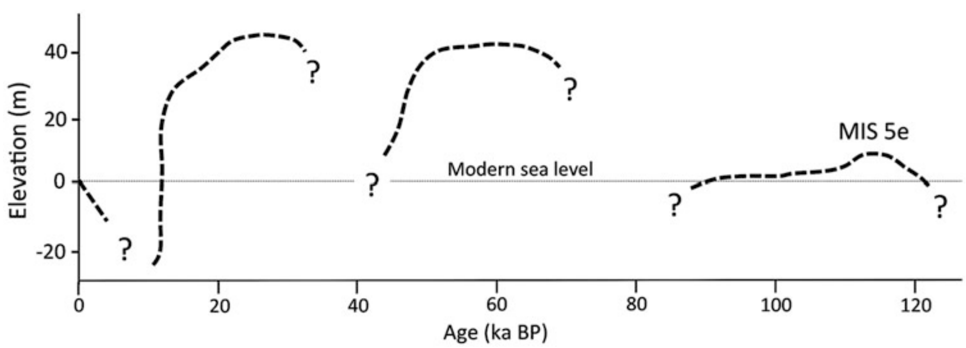

Fig. 19.7 Relative sea level variations on the Magdalen Islands since ∼130 kyr based on the luminescence and radiocarbon ages acquired by Rémillard et al. (2017)

extensive Appalachian glacier flowing towards the south-east would have covered the entire Gulf of St. Lawrence up to the edge of the Atlantic continental shelf (Caledonian Phase, 75–50 ka; Stea et al. 2011).

On the Magdalen Islands, evidences of RSL close to the modern level and dated to the MIS 5 were also observed (Fig. 19.7). The stratigraphical context, the luminescence and U/Th ages acquired from sediments and woody remains, and the fossils of thermophilic species (e.g., *Quercus, Corylus, Ostrea virginica*) present in the sediments, indicate that this RSL could correspond to the interglacial climax of the MIS 5.5 (Dredge et al. 1992; Rémillard et al. 2017). Rémillard et al. (2017) also obtained an age of 115 ± 8 ka on a littoral deposit located at +15 m asl on Cap aux Meules Island. This deposit located well above the global sea-level highstand values of +2 up to +9 m asl between 132 and 116 ka (e.g., Caputo 2007; Rohling et al. 2008) suggests a glaci-isostatic depression of ∼10 m, presumably associated

Fig. 19.8 Evidence of the recent RSL rise on the Magdalen Islands. In situ tree trunks in submersion or burial were observed at several locations throughout the archipelago (Juneau 2012)

with the MIS 6 glaciation that occurred in eastern Canada (e.g., Stea et al. 2011). However, the hypothesis of a local tectonic uplift as suggested by Paquet (1989) should also be taken into consideration. Other evidence of high RSL during the MIS 5 was observed around the Gulf of St. Lawrence (Grant 1980; Stea et al. 1998).

19.4 Periglacial Landforms

Because of their uniqueness, the periglacial landscape and landforms of the Magdalen Islands, have attracted scientific attention since the mid-20th century (Hamelin 1959). Some researchers even believed that these periglacial features were evidence that the archipelago has not been glaciated throughout MIS 4 to MIS 2 (Hamelin 1959; Ritchot 1968; Laverdière and Guimont 1974). Today, it is known that they developed into two phases, during the deglaciation period of MIS 3 (between 60 and 40 ka), and after the LGM (MIS 2) whereas the deglaciation occurred relatively early (between ~25 and 15 ka) compared to the Maritime Provinces (Shaw et al. 2006; Seaman et al. 2011).

19.4.1 Permafrost Features

Ice-wedge pseudomorphs, composite-wedge casts, and cryoturbations have been observed on the Magdalen Islands since the 1970s (Poirier 1970; Laverdière and Guimont 1974; Dredge et al. 1992). Different ages from MIS 3 to MIS 2 were proposed for these features according to the assumptions made regarding the chronology of glacial events (Laverdière and Guimont 1974; Dredge et al. 1992). Rémillard et al. (2015b) were the first to obtain absolute ages on these features. Generally, the ice-wedge pseudomorphs or composite-wedge casts truncate either a thin subtidal deposit overlying a glacimarine deposit (Havre Aubert Island) or a thin pebbly coastal deposit overlying the highly weathered sandstone (Cap aux Meules Island) (Fig. 19.9). The 10 ages (^{14}C and OSL) acquired from both the infillings and the host material of the ice-wedge pseudomorphs or composite-wedge casts show that they developed between ~12.9 and 11.5 kyr, well after the LGM. This period corresponds to the Younger Dryas, which is a period of climatic cooling well-documented in eastern Canada (e.g., Mott et al. 1986; Mayle and Cwynar 1995; Liverman et al. 2000; Hétu et al. 2003). Since the 1960s (e.g., Lachenbruch 1962), it is generally accepted that ice-wedges form in coarse-grained sediment when the mean annual air temperature (MAAT) is lower than −6 to −8 °C (French 2007). From the temperature thresholds used in the literature, ice-wedges formation would require a ~12 °C cooling relative to present (+5 °C) (See the discussion by Liverman et al. 2000 for an alternative perspective) Although they do not provide an accurate indicator of paleotemperature, the most convincing geomorphic indicator of perennially frozen ground is both ice-wedge pseudomorphs and sand-wedge casts (e.g., French 2007). Rémillard et al. (2015b) also observed involutions interpreted as cryoturbations deforming the highly weathered sandstone and the overlying coastal and colluvial deposits (Fig. 19.9a). The combined depth of the ice-wedge pseudomorphs and composite-wedge casts and cryoturbations suggest a palaeo-active layer thickness ≤1 m.

19.4.2 Cryopediments

The term 'cryopediment' is "a gently inclined erosional surface at the foot of valley sides or marginal slopes of geomorphological units developed by cryogenic processes in periglacial conditions" (Czudek and Demek 1970, p. 101).

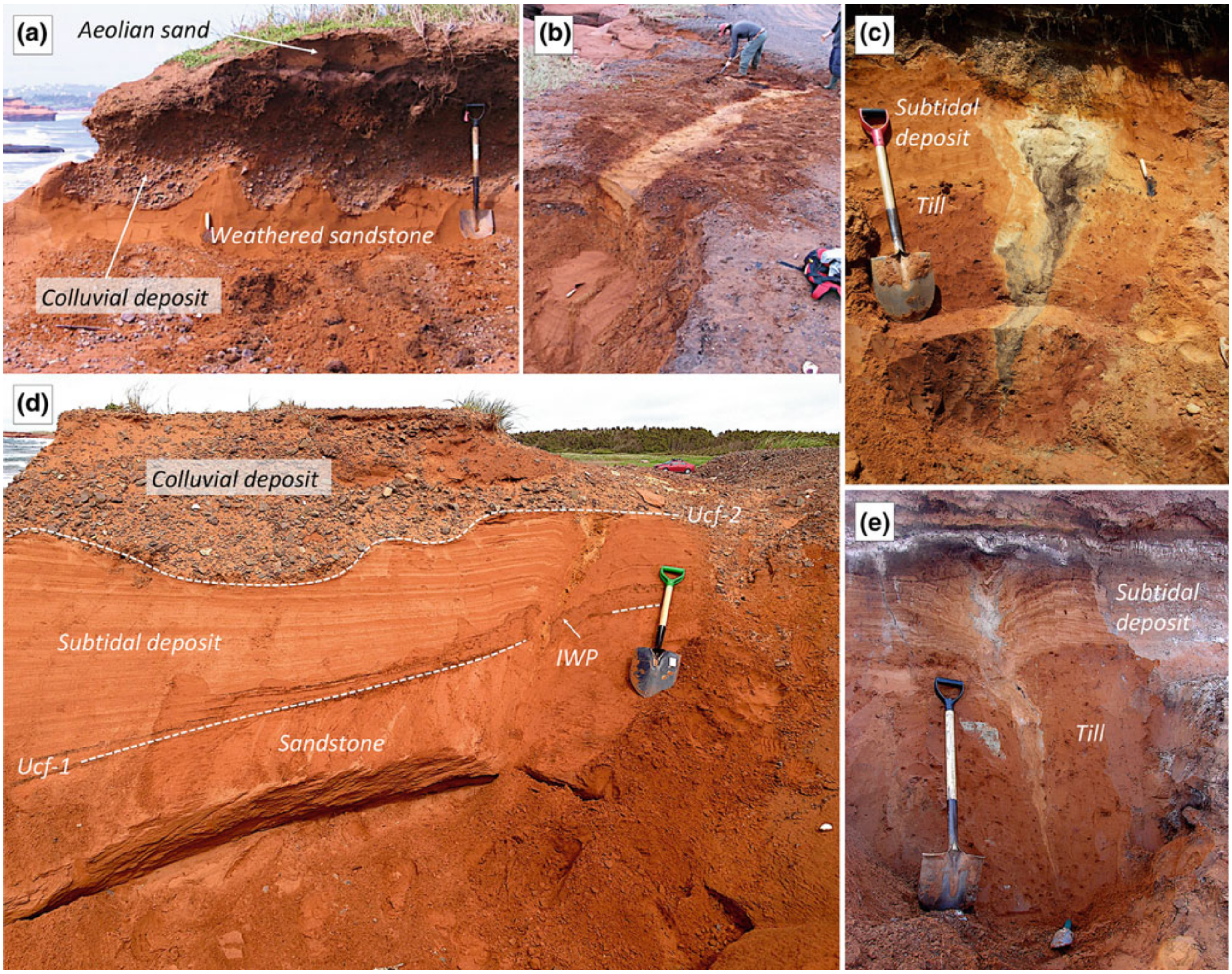

Fig. 19.9 Permafrost features on the Magdalen Islands. **a** Cryoturbations on the Cap aux Meules Island. **b** and **d** Ice-wedge pseudomorphs (IWP) on the Cap aux Meules Island. **c** and **e** Composite-wedge cast dated to the Younger Dryas on the Havre Aubert Island. Ucf-1 and Ucf-2 = unconformities

While they are prevalent in Europe and Asia (French 1973, 2007; Vandenberghe and Czudek 2008), cryopediments are rather scarce in Canada, the Yukon (Lauriol and Godbout 1988; French and Harry 1992) and the Magdalen Islands (Hamelin 1959; Ritchot 1968) being the only Canadian regions where such landforms have been recognized. On the Magdalen Islands, the cryopediments represent the dominant form on the sandstone platforms (Figs. 19.2 and 19.10). On the Cap aux Meules Island, where they are particularly extensive (Fig. 19.4), they cover approximately 75% of the territory, i.e. ~36 km^2 (Paquet 1989). It is also possible to observe cryopediments on Havre Aubert, Havre aux Maisons and Entry islands where they cover between 10 and 30% of the land.

On the Magdalen Islands, Paquet (1989) produced a detailed geomorphological and statistical study of these original landforms. On Cap aux Meules Island, two levels of cryopediments were determined. The upper (and older) level is observable only in two small areas of the Cap aux Meules Island. The lower level, which generally extends from the foothill to the coast, corresponds to the majority of the cryopediments. The cryopediment gradients of the Magdalen Islands range around 1° while the gradients of the backslope range from 6°–8° (Fig. 19.10). They have the typical profile of the cryopediments described in the literature (Czudek and Demek 1970; Vandenberghe and Czudek 2008). Where the coasts have considerably retreated since their formation (by coastal erosion), the cryopediments are truncated downslope by coastal cliff that reach up to 25 m high (Fig. 19.2). Where the coasts are protected from strong waves (e.g., lagoons), the cryopediments disappear under the Holocene coastal ridges. As they intersect both the inclined strata of the sandstone platform and the faults which delimit the volcanic rocks, cryopediments are clearly erosional landforms.

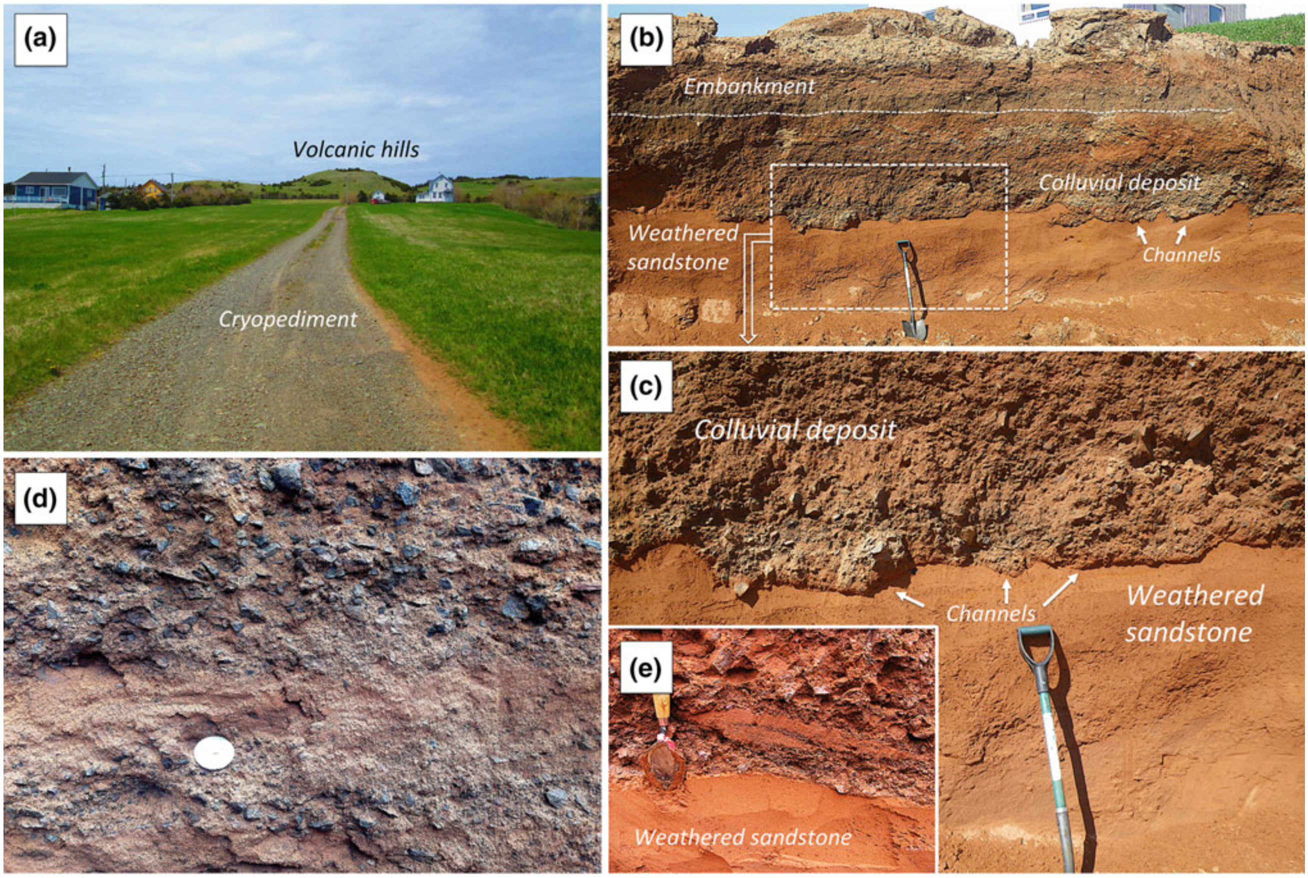

Fig. 19.10 Cryopediments on the Magdalen Islands. **a** Regular and slightly inclined topography of a cryopediment on the Havre Aubert Island. **b** and **c** Perpendicular outcrop into a cryopediment of the Cap aux Meules Island. Note the channels in the weathered sandstone at the bottom of the colluvial deposit. **d** Colluvial facies: imbricated angular basaltic pebbles from volcanic hills frost-shattering with a reddish sandy matrix that comes from the erosion of the underlying sandstone. The deposit is slightly stratified and comprises lenses of well-sorted sand (**e**)

Moreover, underlying the thin colluvial deposits (±1 m), the outcrops exposing a vertical section of the cryopediments exhibit several channels formed in the weathered sandstone (Fig. 19.10). Colluvial deposits are very similar in different outcrops. They are composed of imbricated angular basaltic pebbles with a reddish sandy matrix that comes from the erosion of the underlying sandstone. They are slightly stratified and comprise lenses composed of well-sorted sand (Fig. 19.10). The colluvial facies implies widespread areal erosion characterized by a dynamics of very mobile divagating channels similar to the pediments of the arid zones (Dylik 1957; Vandenberghe and Czudek 2008). The fact that the colluvial deposits are mainly composed of volcanic pebbles involves intense frost-shattering of the central hills and very efficient transport processes from the slope to the channels. The flows required to the transport of such pebbles over considerable distances (up to 2 km) along the low-angle cryopediments were probably caused by the summer melting of the persistent snow and névé located in the sub-basins of the central hills (Fig. 19.2f), and possibly also by strong summer rains. For such runoffs to occur over very porous sandstone, the presence of perennially frozen ground was needed to block the infiltration of water (Laverdière and Guimont 1974; Vandenberghe and Czudek 2008). The divagating channels also imply a minimal or even absent vegetation cover (Dylik 1957). This entire interpretation scenario is consistent with the absolute ages obtained on the colluvial deposits and the underlying coastal sediment. These ages, added to the stratigraphic context, highlighted two periods of periglacial (colluvial) activity, both contemporaneous of high RSL. A first colluvial period occurred between 65 and 40 ka, while the colluvial deposits are intercalated in coastal deposits located between 15 and 38 m high (Rémillard et al. 2017). A second colluvial period occurred after the deglaciation of the LGM according to the luminescence ages acquired from colluvial deposit at three different sites (19.9, 17.6, and 19.5 ka) on the Cap aux Meules Island (Rémillard et al. 2016). This second period is contemporaneous with a RSL of more than +20 m asl. These ages and the stratigraphic data are consistent with the geomorphological observations of Paquet (1989) regarding the occurrence of two different periods of cryopedimentation on the Magdalen Islands. When the high RSL retreated (owing to the glaci-isostatic rebound), the cryoplanation activity ceased and a dynamic of incision started.

19.4.3 Dry Valleys

The cryopediments of the Magdalen Islands are incised by a system of flat-floored valleys and asymmetrical small valleys extending from the central hills to the coast. They are invaded either by trees or herbaceous plants and are mostly dry; they now drain only thin intermittent water streams fed by snowmelt. Obviously, these dry valleys are relic landforms (Figs. 19.11 and 19.12). Near the coasts, these valleys truncate first glacial and littoral sediments deposited by the last glacial cycle, and secondly, the underlying bedrock (Fig. 19.12). Because of the recent RSL rise, the cliff retreated several tens of meters, transforming the periglacial valleys into perched valleys (Fig. 19.13d). In the lagoons, however, the downstream parts of the valleys, invaded by the RSL rise (rias), extend below modern sea level on the Magdalen Shelf where hydrographic networks have been identified to a depth of −30 to −50 m asl (Shaw et al. 2002; Shaw 2005). These submerged hydrographic networks illustrate that a significant part of the Gulf of St. Lawrence was emerged during early Holocene,

The bottom of the valleys is covered by coarse alluvial deposits which are essentially composed of basaltic pebbles from the central hills (Fig. 19.11). These alluvial deposits are 0.5–1.5 m thick and suggest pervasive frost-shattering activity in the central hills and competent flows sustained by the snowmelt. By blocking water infiltrations, permafrost has certainly supported superficial runoffs (Laverdière and Guimont 1974). These observations indicate that periglacial conditions persisted during the marine regression (between 13 and 10 ka), consistent with the development in littoral deposits of ice-wedge pseudomorphs and composite-wedge casts in littoral deposits dated to the Younger Dryas.

19.5 The Coastal Landscape

The beauty and diversity of the Magdalen Islands coasts, with their succession of vertiginous cliffs, arches, stacks, infinite beaches, and coastal dunes, support a remarkable biological diversity (Hamilton 2002; Attention FragÎles 2009a, b, 2010; Roy-Bolduc 2010), and enchant the 50,000 tourists who visit the archipelago annually.

19.5.1 Wave Regime, Tides, Currents, and Sea Ice

On the Magdalen Islands, the fetch length exceeds more than 300 km in all directions except to the south and south-east where it is approximately 80–90 km. Located 50 km from a amphidromic point, the archipelago has a diurnal mixed tide regime in the north and semi-diurnal in the south, with mean tides of 0.7 m and high tides of 1.1 m. (Service hydrographique du Canada 2017). The waves that form in the Gulf of St. Lawrence generally have greater amplitude than ocean waves. The average height of the waves on the western side of the archipelago is 0.49 m in summer and 1.19 m in winter, whereas it reaches 0.35 and 0.98 m on the east side, respectively (Owens 1977). Between January 1978 and December 2007, Bernatchez et al. (2008) reported 48 storm events with winds with a maximum speed exceeding 60 km/h. Although storm surges originate sometimes from the east or north-east (Bernatchez et al. 2008), storms from the northwest are the most frequent (63% of storms recorded between 1961 and 1990); they also produce the strongest waves, some of which can exceed 4 m (Savard 2008). Historically, sea ice and ice foot form around the archipelago for a period varying generally between 70 and 110 days during winter time.

19.5.2 Cliffs and Beach Environments

On the Magdalen Islands, the shoreline exposed to the offshore waves is 235 km long (Bernatchez et al. 2012). The rocky cliffs, littoral spits, beach ridges, and tombolos account for approximately 99% of the coastline (Fig. 19.2). Luminescence ages acquired by Rémillard et al. (2015a) from different sites of beach ridges suggest that these systems developed recently, i.e. between 2.6 and 0.4 ka, during a period of RSL rise (Fig. 19.14). With a mean erosion rate of −0.3 m/yr between 1963 and 2008 for rocky cliffs, and reaching 1.5 m/yr 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). 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 RSL increase of ∼4.3 mm/yr over the last few decades (Bernatchez et al. 2012; Barnett et al. 2017).

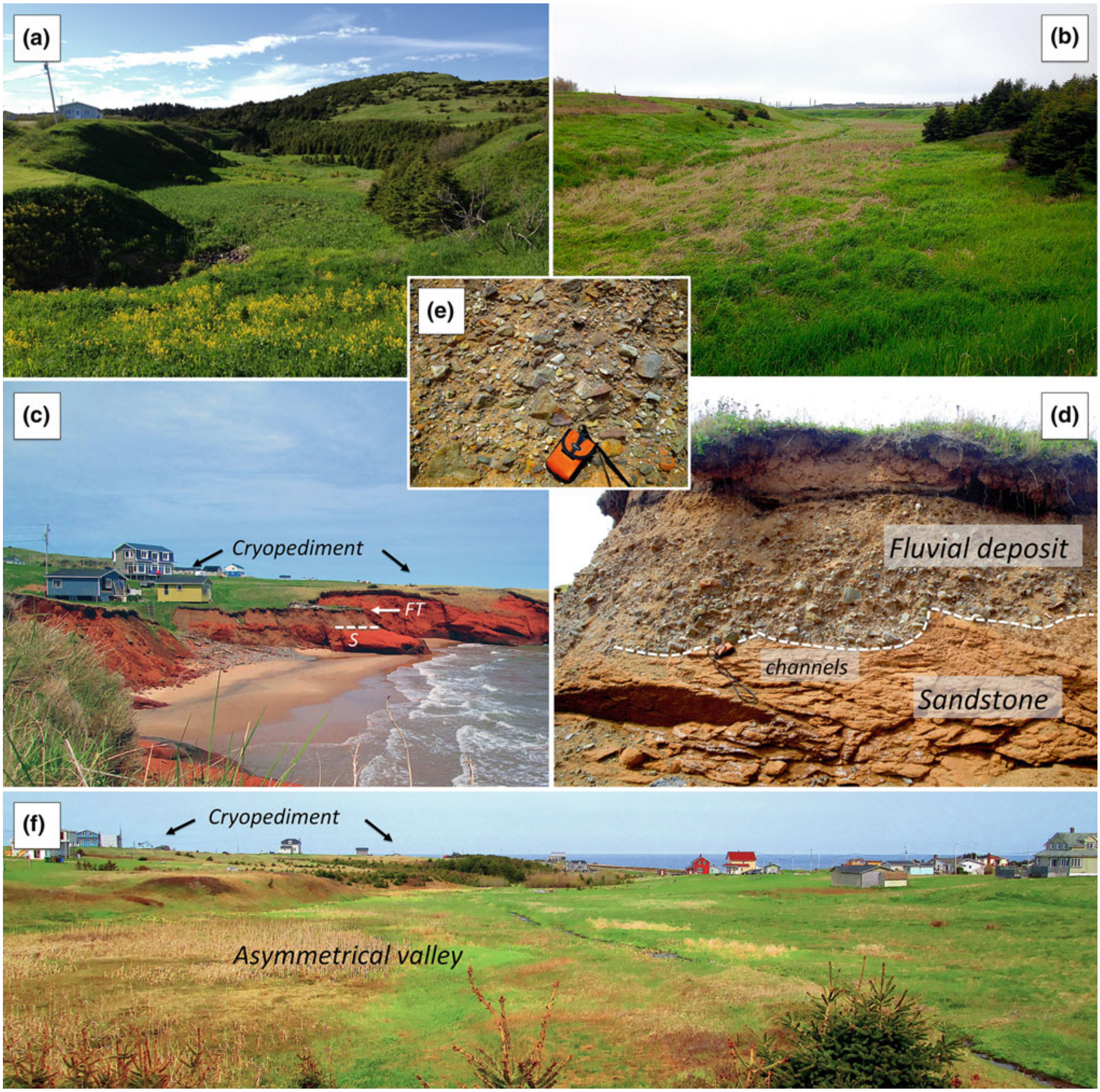

Fig. 19.11 Periglacial valleys of the Magdalen Islands. **a** Flat-floored valley on Havre Aubert and **b** Cap aux Meules islands. **c** Perched flat-floored valley asl S = sandstone; Ft = fluvial terrace. **d** Cross-section in a fluvial terrace. **e** Zoom on the fluvial deposit of the terrace. **f** Asymmetrical vallon on Cap aux Meules Island

19.5.3 Coastal Erosion and Submergence

Coastal erosion and submergence present a real challenge for the Magdalen Islands community. Shoreline retreat between 1963 and 2008 were measured on vertical aerial photographs using the methodology described by Bernatchez et al. (2012). The erosion rates are presented on Fig. 19.15 for each hydrosedimentary cell. Globally, nearly 70% of the coastline of the archipelago is currently at risk of erosion and this proportion is expected to reach 80% by 2060 (Bernatchez et al. 2012). The average migration rate for the entire archipelago's coastline between 1963 and 2008 was −0.25 m/yr (including prograding and retreating coasts). However, this average hides a great spatial variability especially for the sandy coasts for which accumulation values can reach more than 8 m/yr and erosion values more than 5 m/yr (Fig. 19.15). Erosion is prevalent on the western coast (−0.77 m/yr on average) while on the eastern coast,

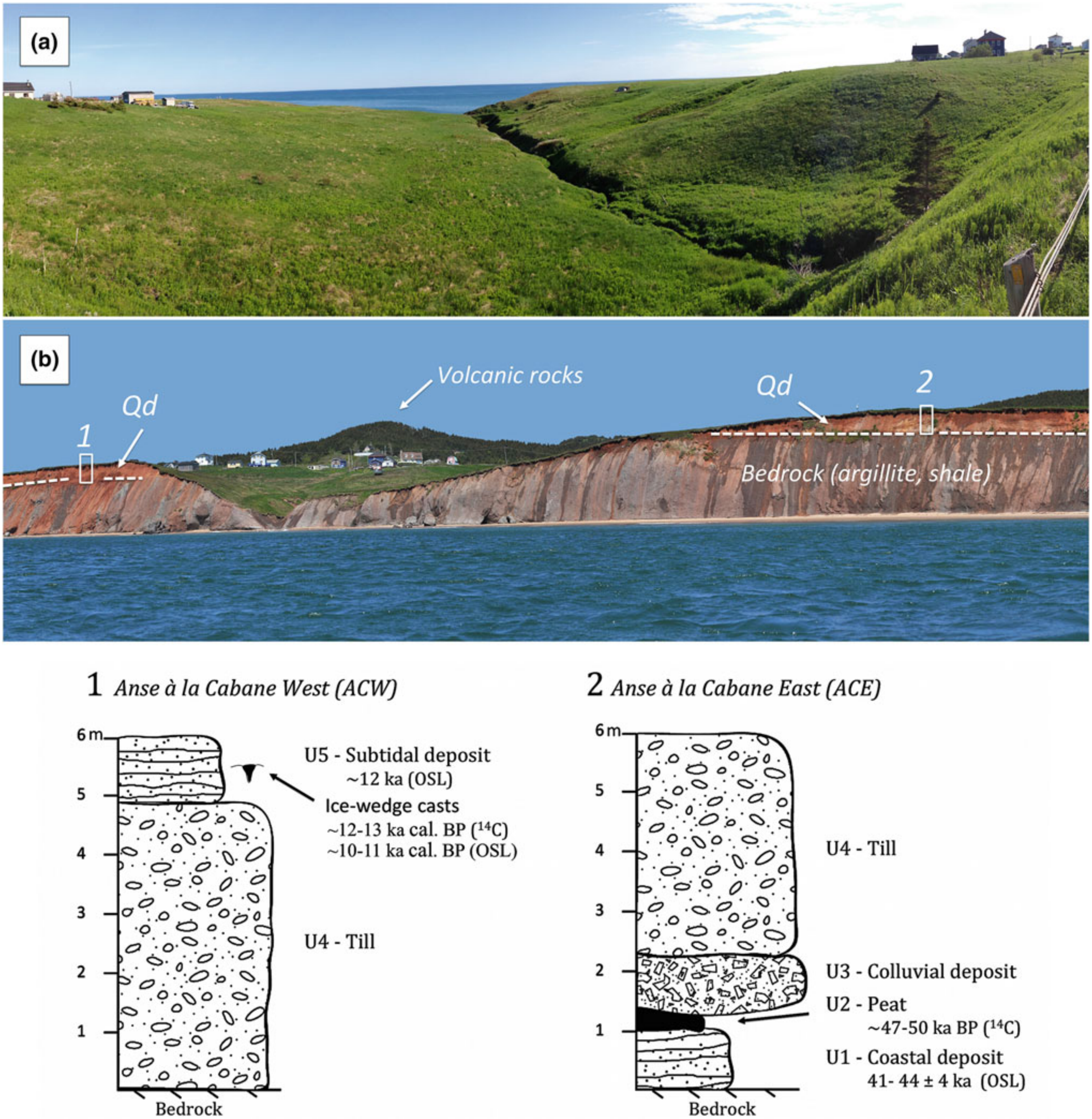

Fig. 19.12 Asymmetrical vallon on the Havre Aubert Island. This vallon truncated the Quaternary deposits exposed in the cliff (see Sect. 1 and 2) during the retreating phase of the RSL at the end of the MIS 2. Outcrops are detailed in Rémillard et al. (2013)

there are some sectors where the balance is positive (in green on Fig. 19.15). This disparity is due to the high exposure of the western coast to the storm surges. More recently, based on the Québec Maritime Coastal Erosion Monitoring Network (Bernatchez and Drejza 2015), that representing 1029 erosion stations on the Magdalen Islands coasts, the average migration rate between 2005 and 2013 was −0.75 m/yr.

Sea ice and ice foot development around the archipelago protect the coasts from the action of waves during the strongest storm surges. However, with climate warming, which especially affects winters, the freezing period is shortened and the ice cover has decreased more and more (Bernatchez et al. 2008). Results from ice foot cover modeling for the 2055 horizon suggest for the Magdalen Islands a reduction of about 40–53 days where the ice foot will no

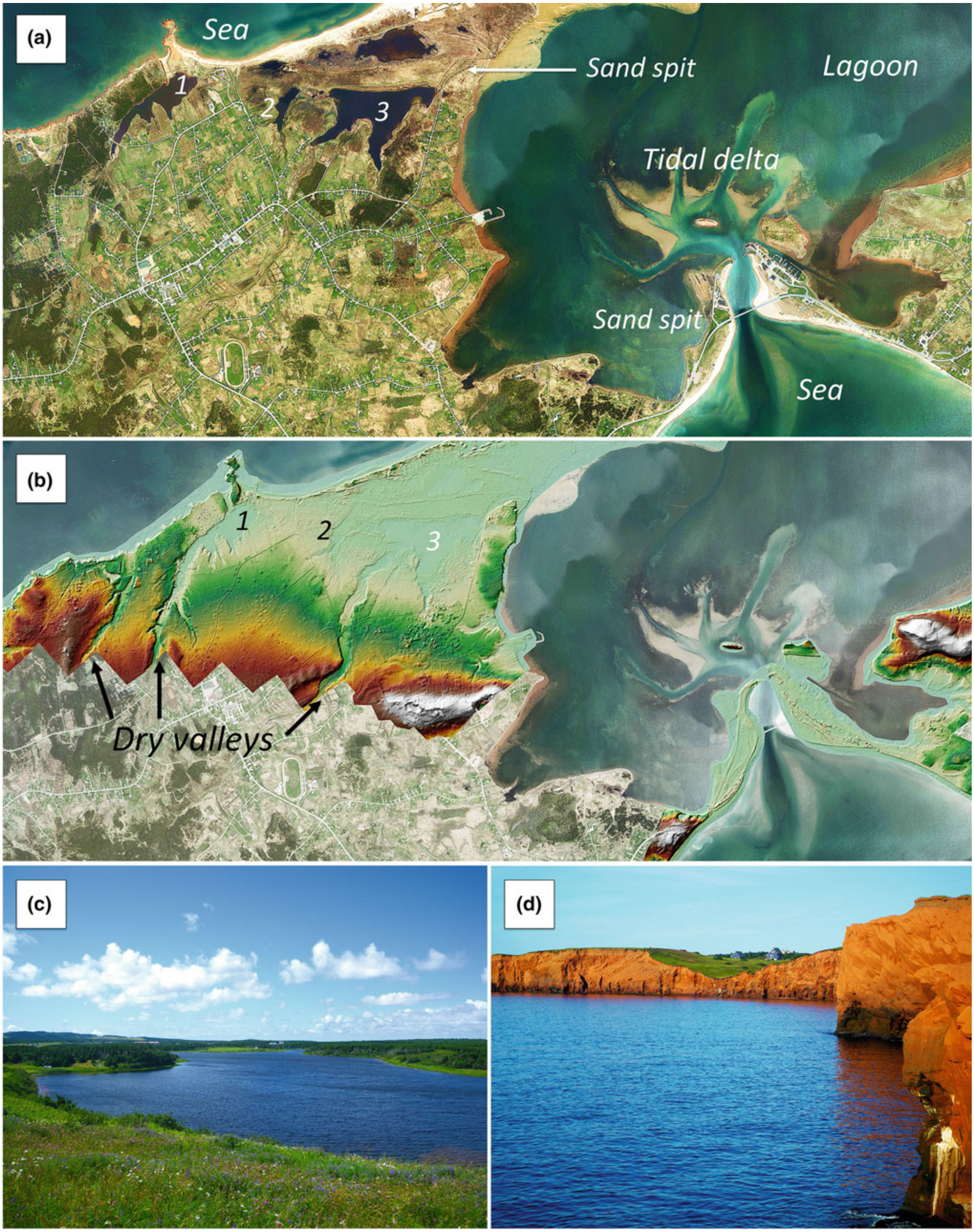

Fig. 19.13 Rias on the Magdalen Island. **a** Aerial photograph of the northwestern part of the Cap aux Meules Island showing three brackish (1, 2, and 3) representing the downstream part of periglacial valleys that were submerged during the late Holocene RSL rise. These submerged valleys were isolated from the sea by the tombolos and sand spits development during the last two millennia. **b** LiDAR imagery of the same location emphasizing the dry valleys. **c** A valley whose downstream part has been submerged on the Havre Aubert Island. **d** Perched asymmetrical vallon on Havre Aubert Island

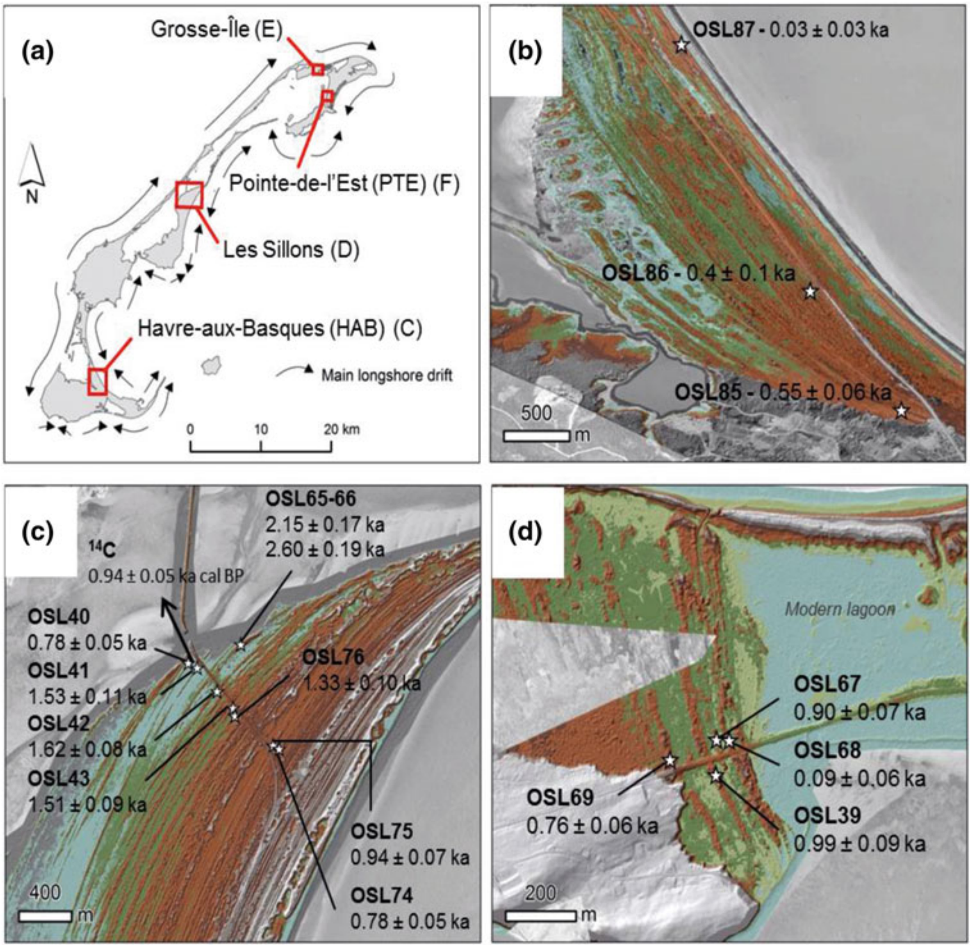

Fig. 19.14 Beach ridges, littoral spits and tombolos of the Magdalen Islands are recent forms that developed during the last two millennia as indicated by the luminescence ages obtained by Rémillard et al. (2015a). **a** Location of the beach ridges sampling sites on the Magdalen Islands. Figures 19.1c–e correspond to LiDAR imagery where white stars represent sampling locations. **b** Les Sillons site. **c** Havre aux Basques (HAB) site. The black star represents sampling location of a modern beach ridge. **d** Grosse-Île site

longer provide coastal protection from storm surges (Senneville et al. 2014). If the warming trend continues, the decrease in ice cover will accelerate coastal erosion. There have been two periods of marked decrease in ice cover, between 1977–1983 and 2001–2007, the latter corresponding to an important reduction of beach width (Bernatchez et al. 2012). The lack of sea ice and ice foot is becoming the norm since the early 2000s. The decrease in sea ice and the global sea-level rise also increase also the risk of submergence. The low coasts, which represent 70% of the total coastline length, are particularly exposed.

By 2065, the number of buildings that may be exposed to coastal erosion if no new adaptation measures are implemented and those already in place are not maintained will be 262 representing value of more than $29 million ($Can) (Bernatchez et al. 2015). There are also 18 km of roads that can be exposed by 2065, representing a value of $ 77.6 million (Bernatchez et al. 2015).

19.6 Conclusions

Figure 19.16 summarizes the major stages of the Magdalen Islands landscape evolution since the MIS 5. Located in the center of the Gulf of St. Lawrence at approximately equal distance from the main ice-caps of the Appalachian Glacier Complex, the Magdalen Islands were deglaciated early ($\sim 25 \pm 2$ ka), at least for the southern part, which has allowed long periods of periglacial processes (MIS 3 and end of MIS 2). Located at the far margins of the Escuminac ice-cap and a lobe of the Newfoundland ice-cap, the archipelago has a complex glaci-isostatic history with marked nuances between the north, the center and the south (Rémillard et al. 2017). However, from roughly 11 ka, the entire archipelago was affected by the migration of the peripheral forebulge that formed by the growth of the regional ice-caps that extended to the continental shelf and

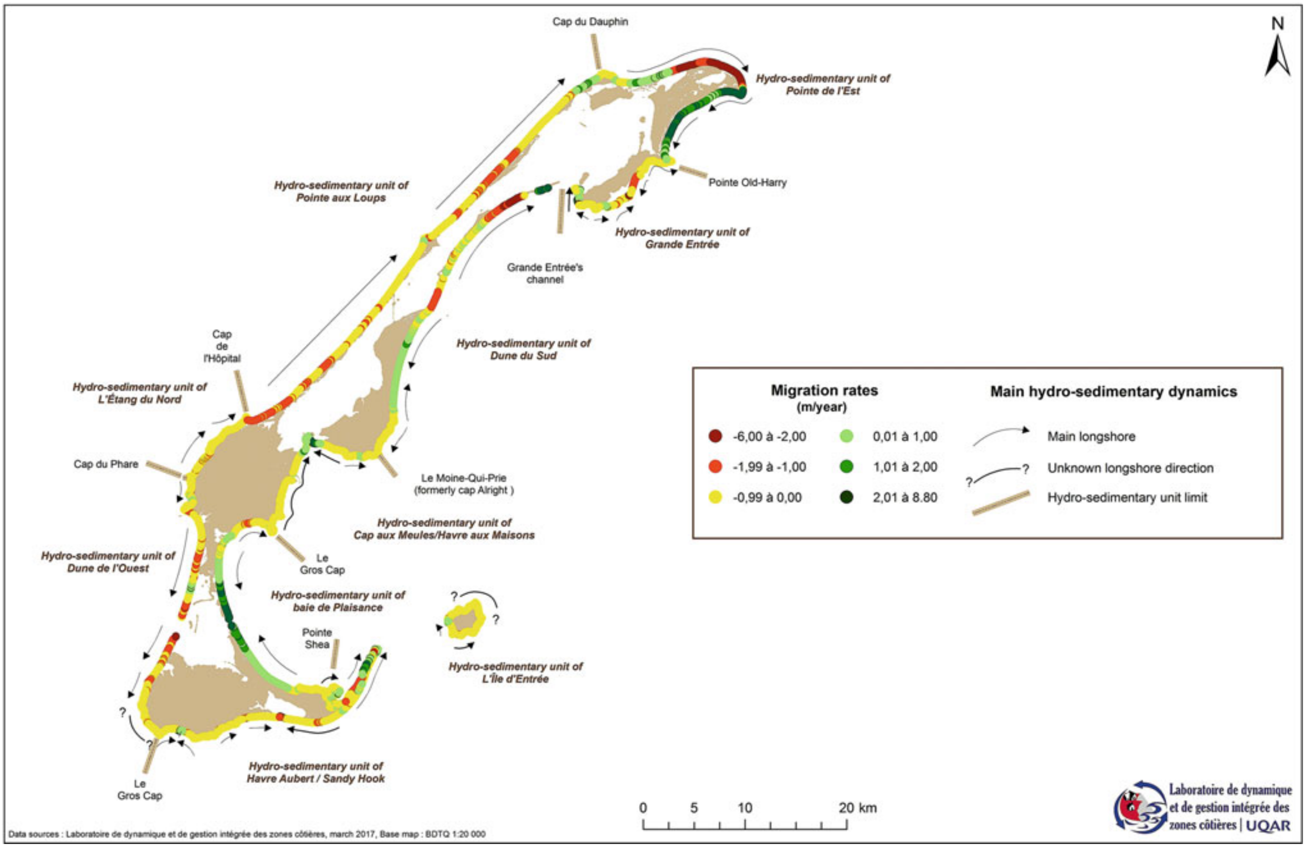

Fig. 19.15 Major hydrosedimentary cells on the Magdalen Islands and coastline migration from 1963 to 2008 measured on vertical aerial photographs using the methodology described by Bernatchez et al. (2012). In green = accumulation rates. In red, orange, and yellow = erosion rates

the LIS which formed an ice stream in the Laurentian Channel (e.g., Stea et al. 1998, 2011; Shaw et al. 2006). Consequently, in eastern Canada, the global sea-level rise due mostly to the thermal expansion and freshwater flux from the melting land-based ice sheets, is exacerbated by the subsidence movement associated with the collapse of the peripheral forebulge that migrated northward after the MIS 2 deglaciation.

Glaciers that covered the Magdalen Islands during the LGM did not leave obvious evidence in the landscape except the thin till exposed in a few cliffs (Figs. 19.5 and 19.12). The landscape of the archipelago originates from three different types of processes: structural, periglacial, and coastal.

For the landforms of structural origin, the volcanic hills adjacent to the sandstone platforms are the most peculiar characteristic (Figs. 19.2 and 19.3). This is the first obvious aspect when approaching the islands by boat. On the sandstone platforms, which are erosion surfaces, the cryopediments and dry valleys are the dominating landforms. Coastal landforms are dominated by cliffs, tombolos, and littoral spits. In spite of their spectacular development, the large double tombolos that connect the rocky islands are very recent and have developed mostly during the last two millennia.

The Quaternary deposits, which are clearly visible at the top of the cliffs, do not have much expression in the surface. A particularly striking aspect when looking at aerial photos is the absence of raised shorelines generally evident in areas that have been submerged by the post-glacial seas. This is easily explained by the intensity of periglacial processes, especially the cryopedimentation that occurred under the influence of the periglacial climate which persisted for more than 10 ka after the LGM on the southern archipelago. It is on this part of the archipelago that the cryopediments, the dry valleys and the ice-wedge pseudomorphs or composite-wedge casts are the best developed. On the northern islands (PAL and Grande Entrée), the evidence of periglacial activity is absent or almost unnoticeable (a few low dry valleys only). The fact that raised shorelines have been obliterated by cryopedimentation does not exclude any influence of the RSL variations on the landscape evolution. Cryopedimentation implies widespread areal erosion characterized by a dynamics of very mobile divagating channels which is incompatible with the valleys incision. The

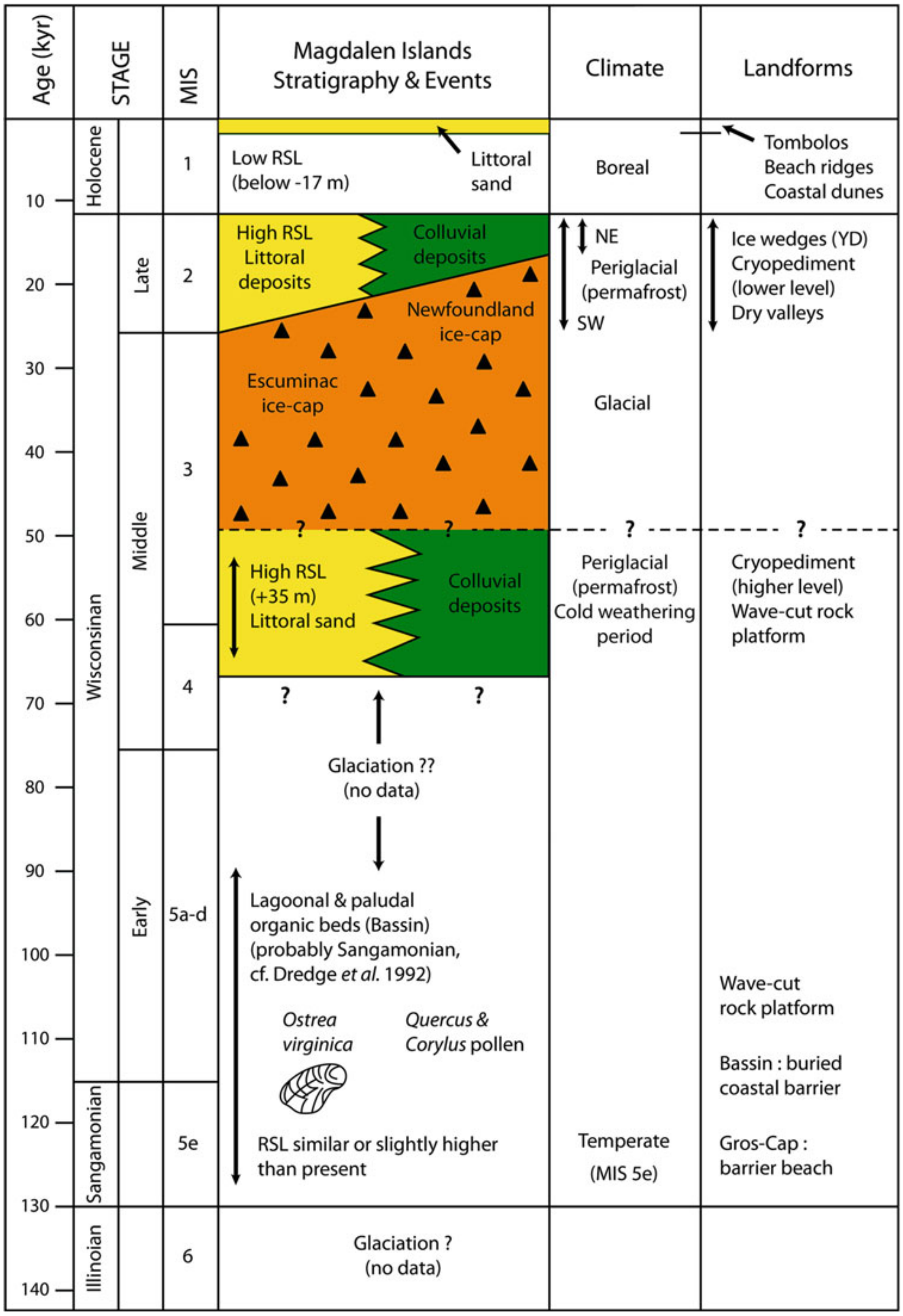

Fig. 19.16 Time diagram of terrestrial and marine Quaternary deposits and landforms on the Magdalen Islands. MIS = Marine isotope stage

formation of cryopediments was done in two phases associated with high RSL: during the MIS 3 and after the MIS 2 deglaciation. When the RSL dropped after 11 kyr owing to the glaci-isostatic rebound and the migration of the fore-bulge, cryopedimentation has been replaced by an incision dynamics (Fig. 19.12). A wide system of flat-floored valleys and asymmetric vallons developed. As the RSL passed below modern level and large parts of the seafloor of the Gulf of St. Lawrence emerged after 10 ka, valleys incised the seafloor to reach the retreating shoreline. With the Holocene RSL rise, the valleys were partly submerged and transformed into rias (Fig. 19.13).

Despite the small size of the archipelago, the landscape of the Magdalen Islands has a uniqueness that can be largely explained by its geographical location in the center of the Gulf of St. Lawrence.

References

Agglomération des Îles-de-la-Madeleine (2010) Schéma d'Aménagement et de développement révisé

Attention FragÎles (2009a) Oiseaux des milieux marins, dunaires, humides et forestiers des Îles de la Madeleine, Îles-de-la-Madeleine

Attention FragÎles (2009b) Plantes des milieux marins, dunaires, humides et forestiers des Îles de la Madeleine, Îles-de-la-Madeleine

Attention FragÎles (2010) Portrait du territoire de la réserve écologique de l'île Brion, Îles-de-la-Madeleine

Barnett RL, Bernatchez P, Garneau M, Juneau M-N (2017) Reconstructing late Holocene relative sea-level changes at the Magdalen Islands (Gulf of St. Lawrence, Canada) using multi-proxy analyses. J Quat Sci 32:380–395

Barnett RL, Garneau M, Bernatchez P (2016) Salt-marsh sea-level indicators and transfer function development for the Magdalen Islands in the Gulf of St. Lawrence, Canada. Marine Micropaleontol 122:13–26

Barr SM, Brisebois D, Macdonald AS (1985) Carboniferous volcanic rocks of the Magdalen Islands, Gulf of St. Laurence. Can J Earth Sci 22:1679–1688

Bernatchez P, Drejza S (2015) Réseau de suivi de l'érosion côtière du Québec maritime—Guide pour les utilisateurs. Laboratoire de dynamique et de gestion intégrée des zones côtières et Chaire de recherche en géoscience côtière. Université du Québec à Rimouski, octobre 2015

Bernatchez P, Dubois J-MM (2004) Bilan des connaissances de la dynamique de l'érosion des côtes du Québec maritime laurentien. Géog Phys Quat 58:45–71

Bernatchez P, Drejza S, Dugas S (2012) Marges de sécurité en érosion côtière : évolution historique et future du littoral des îles de la Madeleine. Chaire de recherche en géoscience côtière, Laboratoire de dynamique et de gestion intégrée des zones côtières, Université du Québec à Rimouski. Rapport remis au ministère de la Sécurité publique du Québec, juillet 2012

Bernatchez P, Dugas S, Fraser C, Da Silva L (2015) Évaluation économique des impacts potentiels de l'érosion des côtes du Québec maritime dans un contexte de changements climatiques. Laboratoire de dynamique et de gestion intégrée des zones côtières, Université du Québec à Rimouski. Rapport remis à Ouranos

Bernatchez P, Fraser C, Friesinger S, Jolivet Y, Dugas S, Drejza S, Morissette A (2008) Sensibilité des côtes et vulnérabilité des communautés du golfe du Saint-laurent aux impacts des changements climatiques. Laboratoire de dynamique et de gestion intégrée des zones côtières, Université du Québec à Rimouski. Rapport de recherche remis au Consiortium OURANOS et au FACC

Brisebois D (1981) Lithostratigraphie des strates permo-carbonnifères, de l'archipel des Îles-de-la-Madeleine. Ministère de l'énergie et des ressources du Québec, DPV-796

Caputo R (2007) Sea-level curves: Perplexities of an end-user in morphotectonic applications. Global Planet Change 57:417–423

Chalmers R (1895) Surface geology of southern New Brunswick, northwestern Nova Scotia and a portion of Prince Edward Island. Geological Survey of Canada, Annual Report

Czudek T, Demek J (1970) Pleistocene cryopedimentation in Czechoslovakia. Acta Geog Lodziensia 24:101–108

Dredge LA, Mott RJ, Grant DR (1992) Quaternary stratigraphy, paleoecology, and glacial geology, Iles de la Madeleine, Québec. Can J Earth Sci 29:1981–1996

Dubois J-MM (1992) Le paysage naturel et son évolution. Infogéographes 1:41–49

Dubois J.-MM, Grenier A (1993) The Magdalen Islands, Gulf of Saint Lawrence. In: Coaslines of Canada. Proceedings of 8th symposium on coastal and ocean management. ASCE, July 19–23, pp 170–182

Dylik J (1957) Tentative comparison of planation surfaces occurring under warm and under cold semi-arid climatic conditions. Biul Peryglac 5:175–186

Environment Canada (2017) Normales climatiques 1981–2010 pour la station des Îles-de-la-Madeleine

Forbes DL, Orford JD, Carter RWG, Shaw J, Jennings SC (1995) Morphodynamic evolution, self-organisation and instability of coarse, clastic barriers on paraglacial coasts. Marine Geol 126:63–85

Fortin JC, Larocque P (2003) Histoire des Îles-de-la-Madeleine. Presses de l'Université Laval

French HM (1973) Cryopediments on the chalk of Southern England. Biul Peryglac 22:149–156

French HM (2007) The Periglacial environment. Wiley, 478 p

French HM, Harry DG (1992) Pediments and cold-climate conditions, Barn Mountains, unglaciated northern Yukon, Canada. Geogr Ann 74A:145–157

Giles PS (2008) Windsor Group (Late Mississipian) stratigraphy, Magdalen Islands, Quebec: a rare eastern Canadian record of late Visean basaltic volcanism. Atl Geol 44:167–185

Goldthwait JW (1915) The Occurrence of Glacial Drift on the Magdalen Islands. Geological Survey of Canada. Museum bulletin no. 14

Grant DR (1980) Quaternary sea-level change in Atlantic Canada as an indication of crustal develelling. In: Morner NA (ed) Earth Rheology, Isostasy and Eustasy. Wiley, London, pp 201–214

Hamelin LE (1959) Sables et Mer aux Îles-de-la-Madeleine. Province de Québec, 1958. Ministère de l'industrie et du commerce, Québec

Hamilton KGA (2002) Îles-de-la-Madeleine (Magdalen Is.): a glacial refugium for short-horned bugs (Homoptera: Auchenorrhyncha)? Le Naturaliste Can 126:25–39

Han G, Ma Z, Chen N, Thomson R, Slangen A (2015) Changes in mean relative sea level around Canada in the twentieth and twenty-first centuries. Atmos Ocean 53:452–463

Hétu B, Gray JT, Gangloff P, Archambault B (2003) Postglacial talus-derived rock glaciers in the Gaspé Peninsula, Québec (Canada). In: Philips SM, Springman SM, Arenson LU (eds) Proceedings of 8th international conference on Permafrost., pp 389–394

Koohzare A, Vanicek P, Santos M (2008) Pattern of recent vertical crustal movements in Canada. J Geodyn 45:133–145

Josenhans HW, Lehman S (1999) Quaternary stratigraphy and glacial history of the Gulf of St. Lawrence, Canada. Can J Earth Sci 36:1327–1345

Juneau M-N (2012) Hausse récente du niveau marin relatif aux Îles-de-la-Madeleine. Mémoire de maîtrise en géographie, Université du Québec à Rimouski

La Flèche MR, Camiré G, Jenner GA (1998) Geochemistry of post-Acadian, Carboniferous continental intraplate basalts from the Maritimes Basin, Magdalen Islands, Québec, Canada. Chem Geol 148:115–136

Lauriol B, Godbout L (1988) Les terrasses de cryoplanation dans le nord du Yukon: distribution, genèse, âge. Géog Phys Quat 42:303–314

Laverdière C, Guimont P (1974) Un froid à sol fendre. GEOS 18–20

Liverman D, Catto N, Batterson M, Mackenzie C, Munro-Stasiuk M, Scott S, Sommerville A (2000) Evidence of late glacial permafrost in Newfoundland. Quat Intern 68:163–174

Loring D, Nota D (1973) Morphology and sediments of the Gulf of St. Lawrence. Service des Pêches et des Sciences de la Mer, Bulletin 182

Mayle FE, Cwynar LC (1995) A review of multi-proxy data for the Younger Dryas in Atlantic Canada. Quat Sci Revs 14:813–821

Mott RJ, Grant DR, Stea RR, Occhietti S (1986) Late-glacial climatic oscillation in Atlantic Canada equivalent to the Allerød/younger Dryas event. Nature 323:247–250

Owens EH (1977) Temporal variations in beach and nearshore dynamics. J Sed Pet 47:168–190

Paquet G (1989) L'évolution de la plate-forme gréseuse de l'île du Cap aux Meules (Îles-de-la-Madeleine). Mémoire de maîtrise, Université de Montréal

Poirier J (1970) Fente de gel fossile aux Îles-de-la-Madeleine. Rev Géog Montréal 24:319–320

Prest VK, Teresme J, Matthews JV Jr, Federovich LS (1976) Late-Quaternary history of Magdalen Islands, Quebec. Marit Sed 12:39–59

Quinlan G, Beaumont C (1981) A comparison of observed and theoretical postglacial relative sea level in Atlantic Canada. Can J Earth Sci 18:1146–1163

Quirion F (1988) Plan quinquennial d'aménagement forestier des Îles-de-la-Madeleine. Ministère de l'Énergie et des Ressources, Québec

Rémillard AM, Hétu B, Bernatchez P (2013) The Drift des Demoiselles on the Magdalen Islands (Québec, Canada): sedimentological and micromorphological evidence of a Late Wisconsinan glacial diamict. Can J Earth Sci 50:1–19

Rémillard AM, Buylaert J-P, Murray AS, St-Onge G, Bernatchez P, Hétu B (2015a) Quartz OSL dating of late Holocene beach ridges from the Magdalen Islands (Quebec, Canada). Quat Geochron 30:264–269

Rémillard AM, Hétu B, Bernatchez P, Buylaert J-P, Murray AS, St-Onge G, Geach M (2015b) Chronology and palaeoenvironmental implications of the ice-wedge pseudomorphs and composite-wedge casts on the Magdalen Islands (eastern Canada). Boreas 44:658–675

Rémillard AM, St-Onge G, Bernatchez P, Hétu B, Buylaert J-P, Murray AS, Vigneault B (2016) Chronology and stratigraphy of the Magdalen Islands archipelago from the last glaciation to the early Holocene: new insights into the glacial and sea-level history of eastern Canada. Boreas 45:604–628

Rémillard AM, St-Onge G, Bernatchez P, Hétu B, Buylaert J-P, Murray AS, Lajeunesse P (2017) Relative sea-level changes and glacio-isostatic adjustment on the Magdalen Islands archipelago (Atlantic Canada) from MIS 5 to the late Holocene. Quat Sci Rev 171:216–233

Richardson J (1881) Report of a geological exploration of the Magdalen Islands. Geological Survey of Canada, Report of Progress (1879–1880), part VIII

Ritchot G (1968) Rapport: cartes géomorphologiques et géotechniques de Rivière-du-Loup, Rimouski-Mont-Joli, Sainte-Anne-des-Monts, Cap-Chat, Gaspé, Iles de la Madeleine. Ministère des affaires municipales, Québec

Rohling EJ, Grant K, Hemleben C, Siddall M, Hoogakker BAA, Bolshaw M, Kucera M (2008) High rates of sea-level rise during the last interglacial period. Nature Geosci 1:38–42

Roy-Bolduc A (2010) Portrait et historique d'utilisation de l'écosystème forestier des Îles-de-la-Madeleine. Centre de recherche sur les milieux insulaires maritimes (CERMIM)

Roy K, Peltier WR (2015) Glacial isostatic adjustment, relative sea level history and mantle viscosity: reconciling relative sea level model predictions for U. S. East coast with geological constraints. Geophys J Intern 201:1156–1181

Sanschagrin R (1964) Magdalen Islands. Ministère de l'Énergie et Ressources du Québec, Geological Report 106

Savard J-P (2008) Étude de la sensibilité des côtes et de la vulnérabilité des communautés du glofe du Saint-Laurent aux impacts des changements climatiques—Synthèse des résultats. Ouranos

Seaman AA, Stea RR, Allard S (2011) The Appalachian Glacier Complex in the Canadian Maritime Provinces during Illinoian and Wisconsinian. Geohydro 2011, CANQUA Meeting, Quebec City

Senneville S, St-Onge-Drouin S, Dumont D, Bihan-Poudec AC, Belemaalem Z, Corriveau M, Bernatchez P, Bélanger S, Tolszczuk-Leclerc S, Villeneuve R (2014) Modélisation des glaces dans l'estuaire et le golfe du Saint-Laurent dans la perspective des changements climatiques, ISMER-UQAR, Rapport final présenté au ministère des Transports du Québec

Service hydrographique du Canada (2017) Marées, courants et niveaux d'eau. http://www.charts.gc.ca/index-fra.asp

Shaw J (2005) Geomorphic evidence of postglacial terrestrial environments on Atlantic Canadian continental shelves. Géog Phys Quat 59:141–154

Shaw J, Gareau P, Courtney RC (2002) Palaeogeography of Atlantic Canada 13–0 kyr. Quat Sci Rev 21:1861–1878

Shaw J, Piper DJW, Fader GBJ, King EL, Todd BJ, Bell T, Batterson MJ, Liverman DJE (2006) A conceptual model of the deglaciation of Atlantic Canada. Quat Sci Rev 25:2059–2081

Stea RR, Piper DJW, Fader GBJ, Boyd R (1998) Wisconsinian glacial and sea-level history of Maritime Canada and the adjacent continental shelf: a correlation of land and sea events. Geol Soc Am Bull 110:821–845

Stea RR, Seaman AA, Pronk T, Parkhill MA, Allard S, Utting D (2011) The Appalachian glacier complex in Maritime Canada. In: Ehlers J, Gibbard PL (eds) Quaternary glaciations—extent and chronology, part II: North America. Elsevier, New York, pp 631–659

Vandenberghe J, Czudek T (2008) Pleistocene cryopediments on variable terrain. Permafr Periglac Proc 19:71–83

Bernard Hétu was awarded a Ph.D. in geography from the Université de Montréal. Officially retired since September 2013, he was a professor in geography at the Université du Québec à Rimouski (UQAR) for 33 years. During his career at the UQAR, he won the Distinction Pascal-Parent (2006), the Achievement award from the Université du Québec (2007) and the Distinction Alcide-C.-Hort (2012) to highlight his contribution in research and development of teaching programs at the UQAR. He has also been a member-researcher of BORÉAS and the Centre for Northern Studies (CEN) for nearly two decades. Since 2013, he has remained active as Associate Professor at the UQAR and the *Université Laval*, both in teaching and research. His past and current research projects are divided between two topics: (1) glacial movements, deglaciation and the reconstitution of long-term changes in relative sea level in Québec's maritime regions (Bas-Saint-Laurent, Gaspésie, Magdalen Islands, and Anticosti); (2) the impact of climate change on the postglacial evolution of the slopes in eastern Québec and the current dynamics of scree slopes in northern Gaspésie.

Dr. Audrey M. Rémillard has received a M.Sc. degree in physical geography from the Université du Québec à Rimouski (UQAR), and a PhD in oceanography at the Institut des Sciences de la mer de Rimouski of the UQAR. Her postgraduate studies focused on the Quaternary history of the Magdalen Islands, located in the center of the Gulf of St. Lawrence, mainly on the last glaciation patterns, the occurrence of periglacial events, and the variations in relative sea-level. She did an internship at Risø National Laboratory (Aarhus University, Denmark) where she developed the first

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