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Deglacial to Paraglacial History of the Lake Saint-Jean Lowlands: A Geomorphological Perspective

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Abstract

The Lake Saint-Jean lowland is a particular area in eastern Canada as it constitutes an important Late Quaternary depocenter compared with other surrounding onshore regions. Here, the recent literature about the Late Quaternary history of the Lake Saint-Jean depocenter from the glaciated period to present-day is summarized; subsequently, we present some preserved landscape features that record such history.

Keywords

Late Quaternary • Deglacial • Paraglacial • Lake Saint-Jean • Depocenter

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5.1 Introduction

The Lake Saint-Jean lowlands are an unusual area of eastern Canada where significant volumes of Late Quaternary sediments have been accumulated since deglaciation. As a restricted and relatively confined depocenter, the Lake Saint-Jean lowlands evolved individually and thus recorded the latest Pleistocene and the Holocene through an original morphostratigraphy. In recent years, onshore and offshore investigations have brought new insights on this evolution. Here, we show some of the emblematic landforms and features that illustrate particularly well the deglacial-to-paraglacial evolution of the area from both the onshore and offshore domains.

5.2 Lake Saint-Jean Lowlands

The Lake Saint-Jean lowlands are located in southern Québec, Canada (Fig. 5.1). They correspond to an 85 km long and 45 km wide low-relief area consisting of the western end of the Saguenay Graben (Kumarapelli 1985; Cousineau and Longuépée 2003). This low-relief is flanked by the 800 to 1000 m a.s.l. moderate- to high-relief of the Laurentian Shield. Rocky basement occasionally crops out in Lake Saint-Jean lowlands as ridges or extensive highs while downstream the Saguenay River incised the Saguenay Fjord within the graben structure. The modern Lake Saint-Jean is draining a 78,000 km^2 catchment area. It has mean and maximum depths of 11.6 and 68 m, respectively. The modern-day Lake Saint-Jean has a long axis of 42 km and a shorter one of 20 km. The three major tributaries (Péribonka, Mistassini and Ashuapmushuan rivers) enter the lake flow from the north and the northwest (Fig. 5.1). These rivers are subjected to strong seasonal discharge fluctuations inducing a rise of about 4 m, from the mean lowstand level in April (about 101 m a.s.l.) to the highstand level in June (about 105 m a.s.l.). The mean annual discharge is 1528 m^3 s^{-1} at

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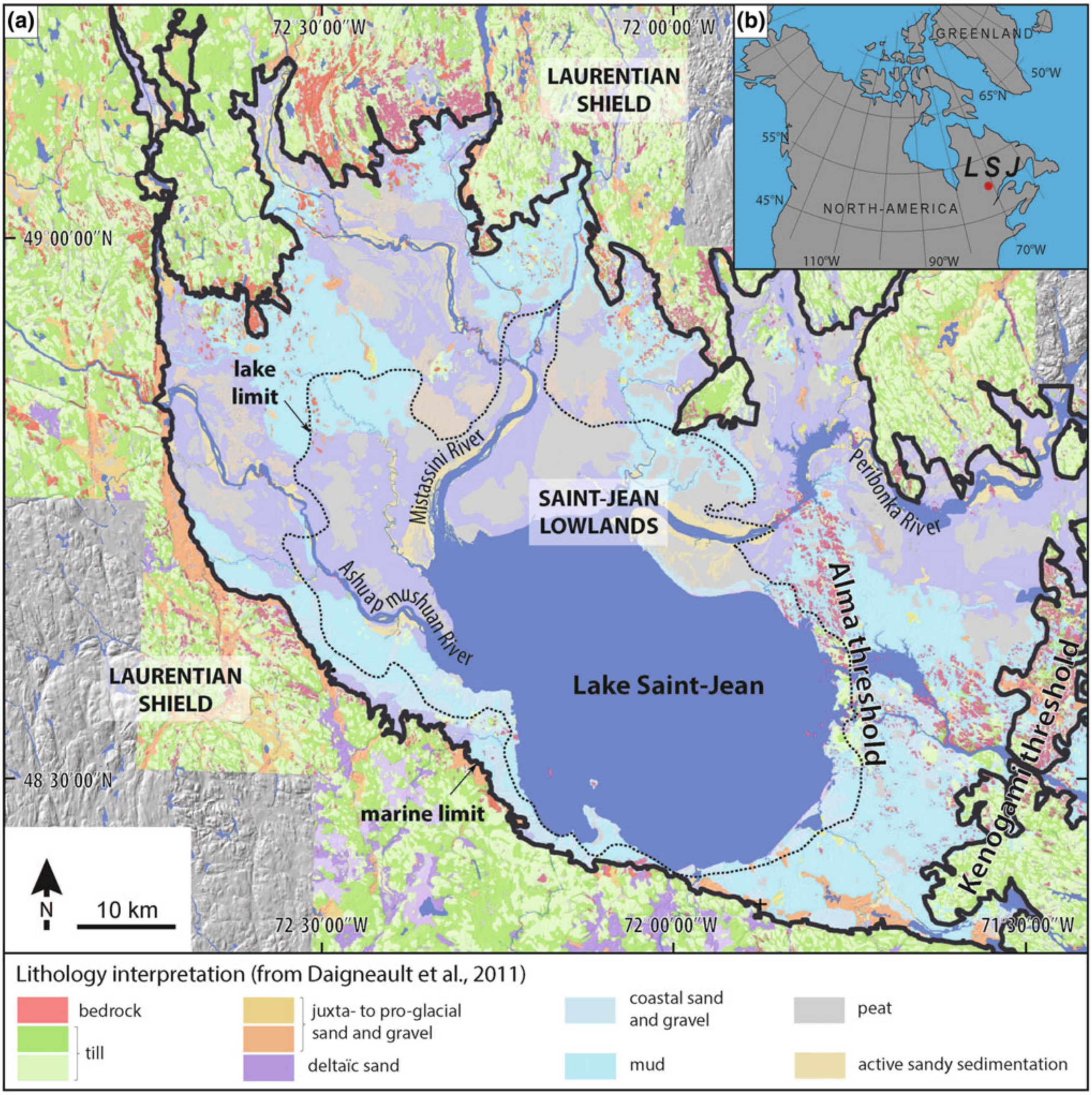


Fig. 5.1 Location maps (modified from Nutz et al. 2015a). **a** Quaternary deposits in the Lake Saint-Jean basin (modified from Roy et al. 2011). **b** Location of Lake Saint-Jean basin in North America

the outlet, in the southeastern part of the lake. The water renewal has been estimated to occur 4–5 times per year (Roy et al. 2011). Prevailing winds blow from northwest and west, but also from the southwest during summer (Meteorological Survey of Canada, http://www.climat-quebec.qc.ca).

5.2.1 Late Quaternary History

The retreat of the Laurentide Ice Sheet (LIS) margin is relatively well documented from the Last Glacial Maximum (LGM) to the Holocene (e.g. Fulton et al. 1986; Syvitski and

Praeg 1989; Shaw et al. 2002; Occhietti et al. 2001, 2004, 2011; Dyke 2004; Occhietti 2007; Nutz 2013; Dietrich et al. 2017). It is generally accepted that the LIS margin reached the northern shore of the present-day Saint-Lawrence Estuary between 13.6 and 11.55 cal ka BP. Afterwards, the LIS margin retreated northwestward up to the southeast edge of the Lake Saint-Jean lowlands (Fig. 5.2a) marking the onset of deglaciation in the area. The age of this stage is still a matter of debate. Previous studies suggest an age at c. 10.8 cal ka BP (Tremblay 1971a; Occhietti et al. 2011), whereas Nutz (2013) proposes an older age around c. 13.1 cal ka BP. Coevally with the progressive northwestward retreat of the LIS margin (Fig. 5.2b), marine waters invaded the newly deglaciated, glaci-isostatically flexured basement (Tremblay 1971a; Roy et al. 2011; Daigneault et al. 2011; Nutz et al. 2014, 2015a) forming a northwestern branch of the Goldthwait Sea (Dionne 1972) referred to as the Laflamme Gulf (Laverdière and Mailloux 1956). At its maximum extent, the Laflamme Gulf extended up to 50 km north of the present-day Lake Saint-Jean northern shoreline (Figs. 5.1 and 5.2c; Daigneault et al. 2011; Nutz et al. 2015a). At that time, the intense glaci-isostatic uplift led to significant rates of relative sea level (RSL) fall estimated around 3.5 cm y^{-1} in the northwest part of the area (Nutz 2013). The marine Laflamme Gulf became Lake Saint-Jean (Fig. 5.2d) once the connection with the Saguenay fjord ended due to the emergence of the Kenogami sill around 8.5 ± 0.6 cal ka BP (Roy et al. 2011). During the subsequent lacustrine period, the lake level continued to fall due to the differential glaci-isostatic uplift between the northwest and the southeast areas (Fig. 5.2e), but at slower rates estimated around 0.5 cm y^{-1} in the northwest part of the area. The LIS margin continued to retreat northward to leave the Saint-Jean lowlands catchment around 7.5 cal ka BP (Occhietti et al. 2011). After 7.5 cal ka BP, the lake level continuously dropped until 1926 C.E. to reach its lowest-stand during the Holocene at 2.5 m below the current lake level. Dam emplacement in 1926 raised and stabilized the lake level at its present-day configuration (Fig. 5.2f).

5.2.2 Stratigraphic Organization

The Lake Saint-Jean lowlands display a comprehensive stratigraphic record of the latest Quaternary, which appears very similar across the entire Lake Saint-Jean depocenter (Nutz et al. 2015a). In general, the sedimentary succession consists of lowermost sand and coarse-grained sediment bodies corresponding to glacigenic deposits such as basal till and ice-contact fans. These deposits are overlain by the Laflamme Mud Fm., covering extensive areas below the marine limit. This formation forms a sheet-like unit that grades vertically from proximal to distal ice-front-related fine-grained deposits to marine and then lacustrine prodeltaic fine-grained sediments, reflecting the progressive retreat of the ice-front and the subsequent transition to a continental ice-front. Above, the Laflamme Mud Fm. is overlain by diachronous deltaic and coastal sand wedges that fringe the basin and correspond to Gilbert deltas, mouth-bar deltas, spits, cuspates and beach ridges that have progressively prograded basinward following the falling base level.

5.3 Geomorphological Markers

The latest Quaternary history of the Lake Saint-Jean lowlands is documented by numerous remarkable onshore landforms and offshore features. The first group includes glacigenic features associated with the deglacial period. The second group comprises features associated with the subsequent paraglacial period.

5.3.1 Deglacial Period

The deglacial period is a relatively short period in the evolution of the Lake Saint-Jean lowlands corresponding to the period during which the LIS ice margin retreated over the area (Fig. 5.2a, b). Although eskers and ice-contact fans were identified in former studies and geomorphological maps, recent swath bathymetry imagery and seismic data now offer unprecedented images of well-defined, buried, ice-contact features preserved beneath the Laflamme Mud Fm. within Lake Saint-Jean.

5.3.1.1 Mega-Scale Glacial Lineations (MSGLs)

The swath bathymetry imagery of the Lake Saint-Jean floor reveals abundant elongate positive ridges (Fig. 5.3a, b) that are 1–3 km long, 100–200 m wide with heights ranging from 5 to 10 m. They represent subglacial mega-scale glacial lineations (MSGLs) indicating fast-flowing ice (Clark 1993; Stokes et al. 2013; Ó Cofaigh et al. 2013). MSGLs are broadly oriented NW–SE, parallel to the orientation of the graben structure, suggesting topographically controlled ice-flow. The occurrence of fast-flowing ice influenced by the topography supports the presence of an ice stream in the Lake Saint-Jean lowlands during the deglaciation, as proposed by Tremblay (1971a) and Nutz (2013). The reinterpretation of two groups of glacial striae previously identified by Tremblay (1971a) in the area suggests a transition from topographically independent to topographically controlled ice-flow, revealing that this ice stream evolved only during the deglaciation. A first group (black arrows, Fig. 5.2a), showing flow directions independent of topography, is interpreted to reflect the LIS climax

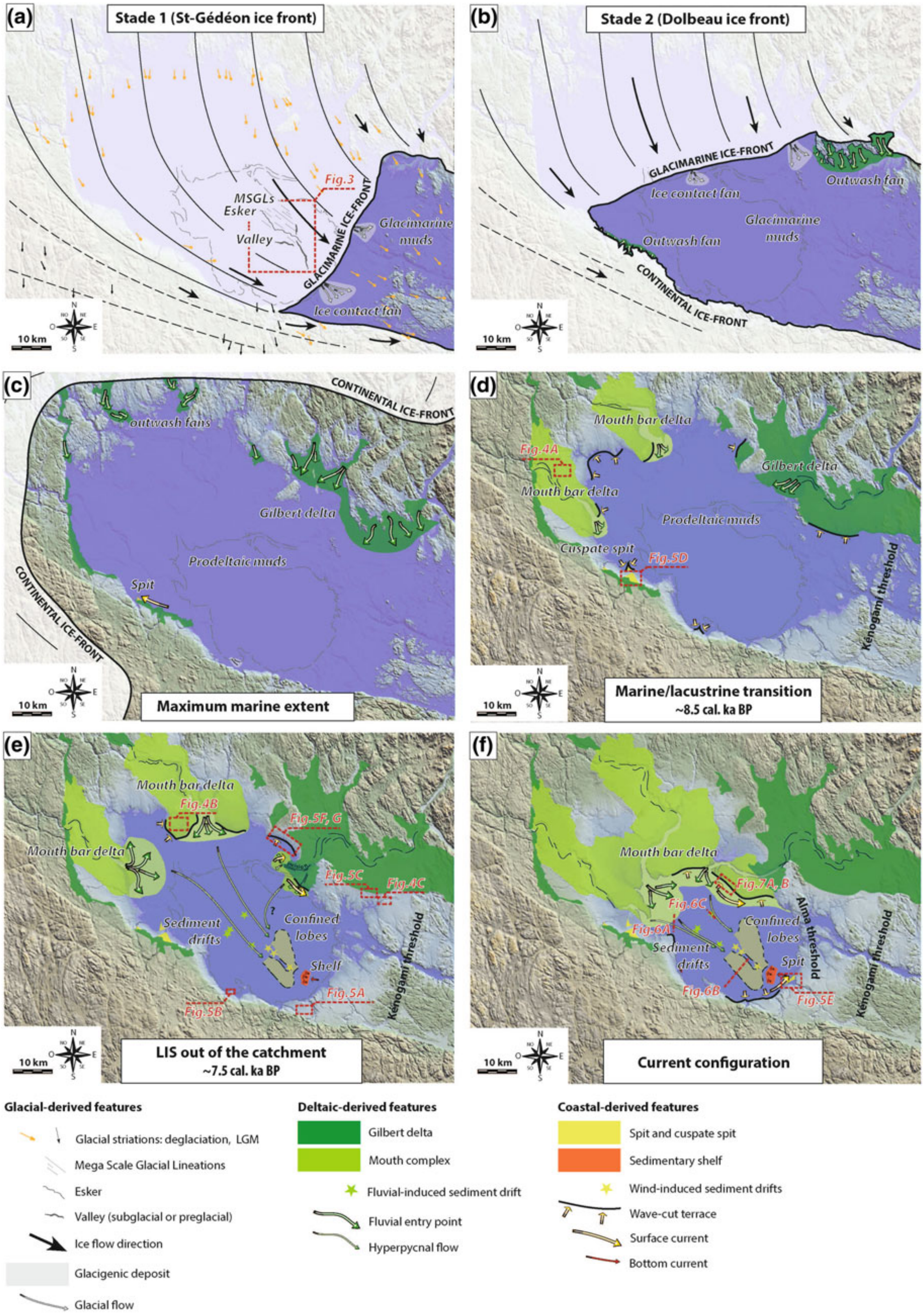


Fig. 5.2 Paleogeography and active sedimentary systems in the Lake Saint-Jean lowlands for six time steps from 13.1 cal ka to present-day (modified from Nutz 2013)

during the LGM when ice-sheet thickness overcame topographic controls on ice-flow patterns. A second group (orange arrows, Fig. 5.2a), displaying orientations parallel to the topography, is attributed to flow patterns associated with deglaciation when the ice thickness decreased enough to allow topographic control on ice-flow.

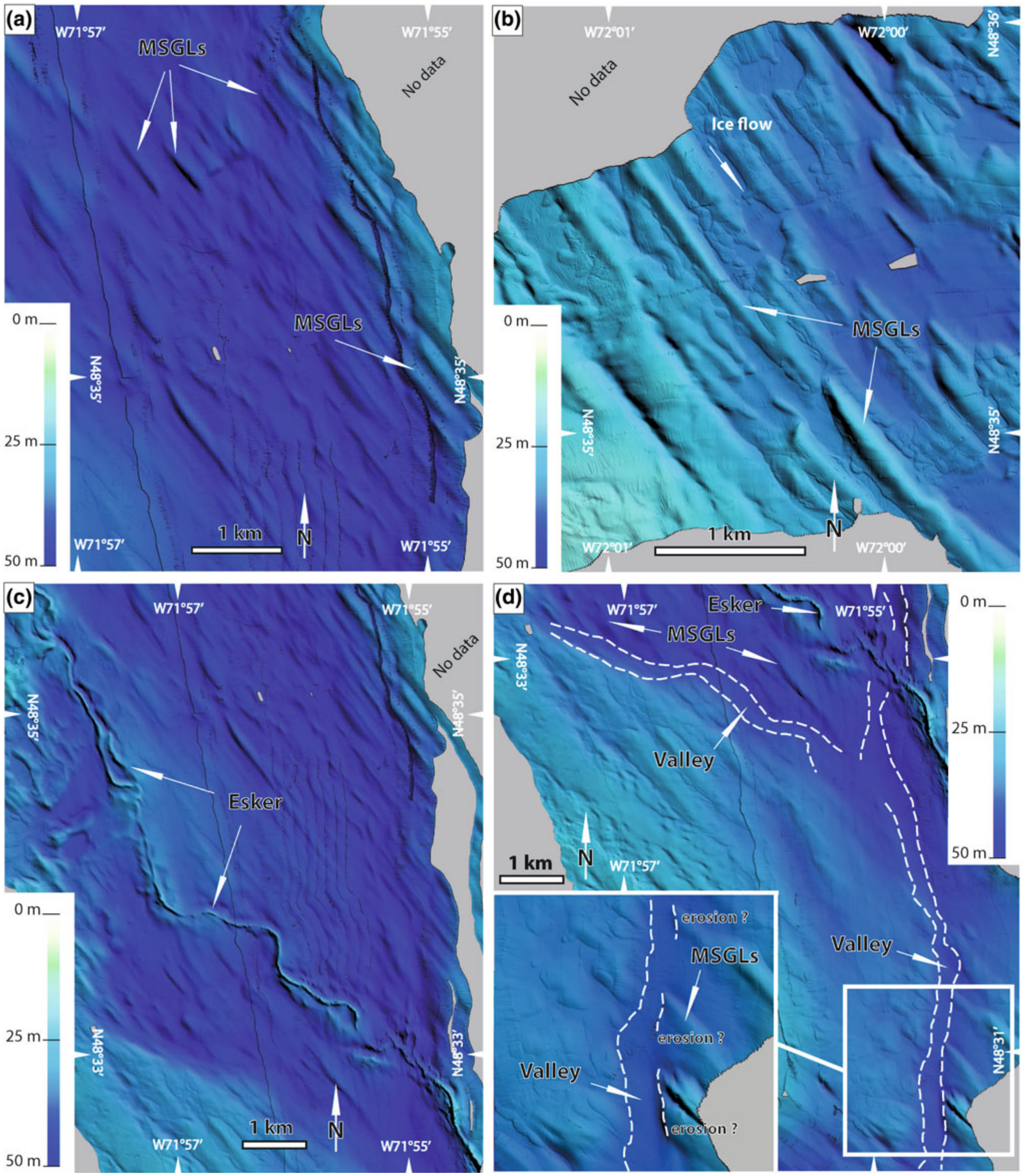


Fig. 5.3 Swath bathymetry imagery showing subglacial features in the Lake Saint-Jean lowlands deposited during the ice margin retreat (location Fig. 5.2a, b). **a** and **b** Mega-Scale Glacial Lineations (MSGLs). **c** Esker. **d** Preglacial fluvial or small tunnel valleys

5.3.1.2 Eskers

Several discontinuous relicts of eskers are identified onshore in the Lake Saint-Jean lowlands (Daigneault et al. 2011; Nutz 2013; Nutz et al. 2015a), but their preservation state is low. The swath bathymetry imagery reveals for the first time the presence of a well-preserved esker draped by the Laflamme Mud Fm. (Fig. 5.3c). This esker is oriented NNW–SSE to NW–SE; it is >10 km long, 80–100 m wide and 7–10 m high. Eskers are usually interpreted as the casts of subglacial R-channels (Brennand 2000; Cumming et al. 2011; Storrar et al. 2014). As characterized by a rounded crest, the esker most likely represents the infilling of a subglacial channel (Perkins et al. 2016). The short length and the relative straight morphology of the identified esker are typical of a type-II esker sensu Brennand (2000), indicating deposition and infill during ice-sheet retreat. Similar to MSGLs, this esker is parallel to the depression, suggesting topographically controlled ice-flow during deglaciation.

5.3.1.3 Valleys

Elongate negative morphologies are also identified in Lake Saint-Jean. Two segments, about 2–3 km long and 100 m wide, merge to form a single segment, more than 5 km long, 150–200 m wide and 5–10 m deep (Fig. 5.3d). These elongated negative morphologies can be interpreted either as preserved segments of small valleys cut into the subglacial sedimentary substrate (e.g. Kehew et al. 2012) by meltwater during deglaciation or as preglacial fluvial channels subsequently draped by glacigenic and glacimarine deposits. Valleys seem to truncate the MSGLs and are in places sealed by the esker described above. This might support a deglacial origin of these valleys. However, seismic data do not display clear evidence for incision in the underlying glacial deposits, supporting a preglacial fluvial origin. At present, it is difficult to determine the origin of these valleys.

5.3.2 Paraglacial Period

The paraglacial period is considered to have started after c. 12.6 cal ka, as soon as the LIS margin retreated beyond the marine limit (Fig. 5.2c–f). This period was characterized by the presence of a large marine water body grading to a lacustrine water body due to glaci-isostatic rebound. During that period, sedimentation is characterized by regressive coastal and deltaic landforms, rapidly perched after their deposition. In the central water body, sedimentation relates to low energy settling of fluvially derived turbid plumes, replaced after c. 7.5 cal ka by higher-energy conditions associated with recurrent bottom currents (Nutz et al. 2014, 2015a, b). Some of the most prominent landforms developed in terrestrial, coastal and subaqueous domains during this period are presented in the following sections.

5.3.2.1 Aeolian Dunes

Several aeolian dune fields are known in the Lake Saint-Jean lowlands (Côté et al. 1990; Daigneault et al. 2011). Dunes are parabolic, 50–600 m long, 50–400 m wide and 1–15 m high (Fig. 5.4). They are similar to those generally observed in high-latitude settings (Wolfe 2007). Aeolian parabolic dunes systematically developed over previous subaqueous deltaic deposits that were progressively raised due to glaci-isostatic rebound, revealing that aeolian processes constituted an important agent for the reworking of subaerial landscapes. Dune initiation likely started relatively quickly after emersion. Subsequently, the growth of vegetation interrupted the activity of dunes and led to fossilization. That is the reason why older are dune fields, higher in elevation they are. This is supported by both radiocarbon and OSL ages ranging between 9.7 and 4.3 ka BP (Côté et al. 1990; Nutz et al. 2015b). All dune fields indicate similar directions of migrations from northwesterly, westerly and southwesterly winds and suggest a relatively constant orientation of prevailing winds (Nutz et al. 2015b) in the area from deglaciation up to the present-day. Reconstructed palaeo-wind directions interestingly indicate the absence of important or recurrent northerly winds, which would be expected from katabatic air flows associated with the LIS.

5.3.2.2 Beach Ridges

Beach ridges represent the most abundant coastal landforms in the Lake Saint-Jean lowlands (Fig. 5.5a–c). They are especially well developed in the southwestern and southern parts of the basin. Beach ridges correspond to continuous, mound-shaped and linear accumulations of clastic sediments (sand, gravel, boulder and detritus such as shells or wood) built parallel to the shore. They frequently form strandplain systems in the form of undulating topography, reflecting the successive creation of beaches, rapidly abandoned due to the continuous water level fall (e.g. Billy et al. 2015; Schuster and Nutz 2017). Beach ridges indicate that the Laflamme Gulf and Lake Saint-Jean were impacted by significant wave action during the entire duration of the regression (Fig. 5.2d–f).

5.3.2.3 Spits

In addition to beach ridges, other coastal landforms developed in the form of spit systems during the paraglacial period. Spit systems are particularly well preserved in the western, southwestern and southern sectors (Nutz 2013; Nutz et al. 2014, 2015a). Two particularly well-preserved examples are discussed below. The first example is a cuspate spit (Ashton et al. 2001; Bouchette et al. 2014) emplaced in shallow waters and grew normal to the shoreline (Fig. 5.5d). The second example is a sandspit that developed during the lowest stand of the lake, before the artificial lake level rise of 1926 (Fig. 5.5e), in the form of a large asymmetric ridge

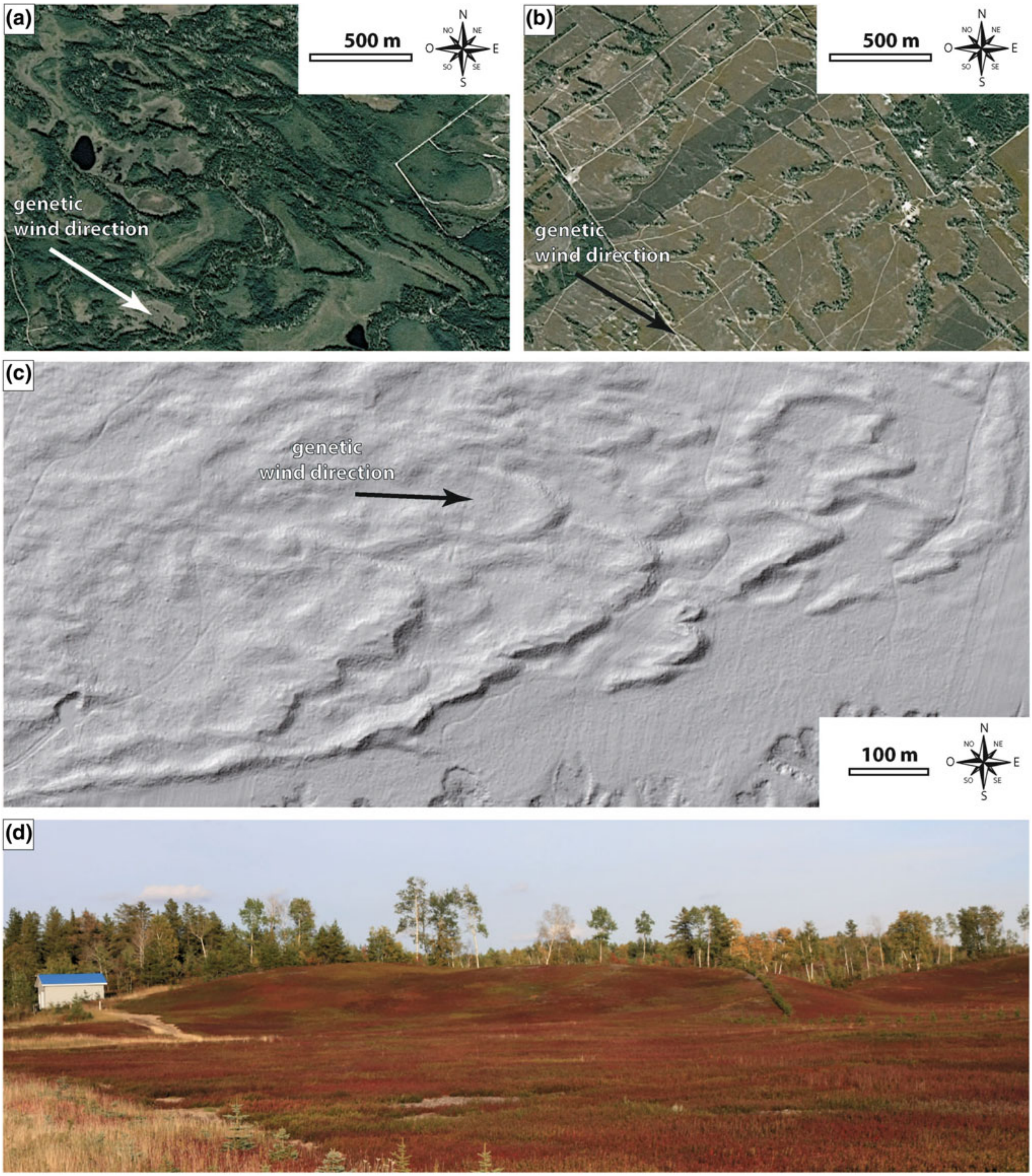
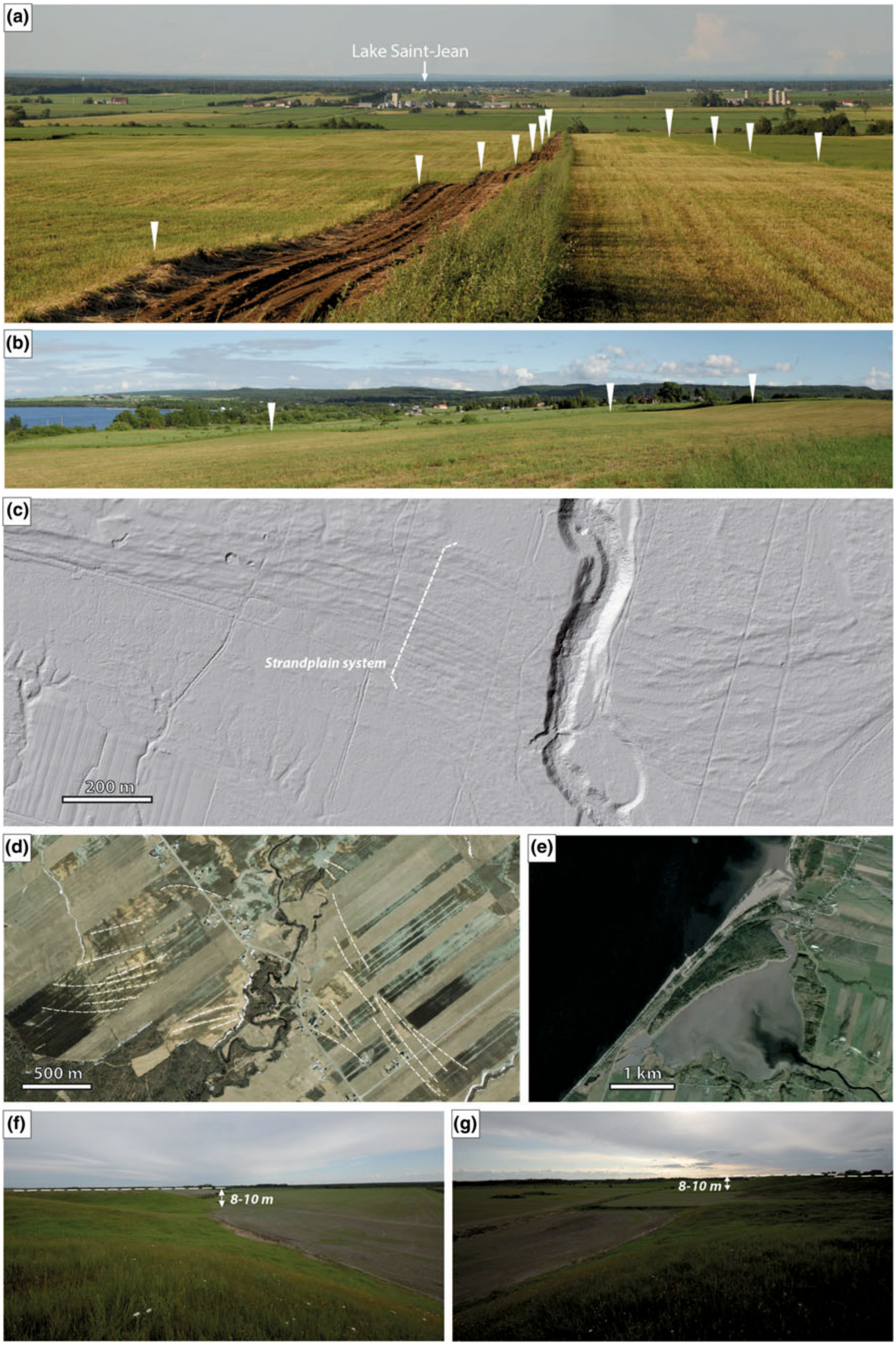


Fig. 5.4 Landforms related to aeolian dynamics in the Lake Saint-Jean lowlands emplaced during the paraglacial period of the basin (see location Fig. 5.2). **a** and **b** Satellite view (GoogleEarth 2017) of parabolic dunes, white arrows indicate the prevailing orientation of the genetic wind. **c** Lidar view of fossil parabolic dunes. **d** Ground view of a fossil aeolian dune

attached to the mainland at one end and growing obliquely to the coastline in the direction of the more recurrent longshore drift (Uda 2005; Bird 2008; Randazzo et al. 2015). Spits and cuspate spits are large-scale coastal landforms that are genetically related to waves and longshore drift. Thus, similar to beach ridges, sand spits and cuspate features


(a)
Lake Saint-Jean
(b)
(c)
Strandplain system
200 m
(d)
500 m
(e)
1 km
(f)
8-10 m
(g)
8-10 m

◀ **Fig. 5.5** Landforms related to coastal dynamics in the Lake Saint-Jean lowlands deposited during the paraglacial period of the basin. **a** and **b** Beach ridges (whites arrows) and swales in the western and southwestern parts of the depocenter (location Fig. 5.2e). **c** Lidar view showing successive beach ridges and swales. **d** Satellite image (GoogleEarth 2017) of a fossil cuspate foreland in the western part of the basin (location Fig. 5.2d). White dotted lines underline paleo-shorelines. **e** Satellite image (GoogleEarth 2017) of the St-Gédéon sandspit in the southern part of the lake (location Fig. 5.2f). **f** and **g** Wave-cut terrace in the eastern part of the depocenter (location Fig. 5.2)

suggest that waves and related longshore drift strongly influenced coastal sedimentation.

5.3.2.4 Wave-Cut Terraces

Several generations of wave-cut terraces have been identified in the Lake Saint-Jean lowlands (Tremblay 1971a, b). Daigneault et al. (2011) reported on the lateral extent of the wave-cut terraces, especially in the north and northeastern sectors. Some form more than 10 km long linear escarpments, with up to 10 m of erosion (Fig. 5.5f, g), and are partly dissected by recent drainage. Wave-cut terraces are coastal landforms resulting from erosional dynamics of wave impact along a shoreline (Trenhaile 1978, 2000). Locations of predominant wave-cut terraces in the northeastern and eastern areas reveal more efficient and energetic waves, attributed to the predominance of westerly winds in the basin and either support relative constant wind directions through time.

5.3.2.5 Hyperpycnal System

An important component in the origin of subaqueous features in Lake Saint-Jean is the fluvially derived sedimentation associated with hyperpycnal flows (Nutz et al. 2014). Hyperpycnal processes resulted in different landforms identified on the floor of Lake Saint-Jean. Erosional channels are observed at the Peribonka (Nutz et al. 2014) and Ashuapmushuan (Fig. 5.6a) river mouths. These channels show incisions ranging between 5 and 16 m (Nutz et al. 2014; Fig. 5.6a) compared to the surrounding lake floor. Laterally, erosional channels are associated with confined lobes (Nutz et al. 2014; here Fig. 5.6b) that represent the depositional areas of hyperpycnal flows. Recently collected acoustic stratigraphy profiles allowed documentation of the complete architecture of these lobes. The lobe on the western trough is 6 km wide, and reaches 10 m thick, draping the underlying Laflamme Mud Fm. and progressively attenuating the underlying topography (Fig. 5.6b). The deposition of confined lobes indicates that hyperpycnal flows transported a large amount of sediment into the lake during the Late Quaternary evolution of the depocenter.

5.3.2.6 Sediment Drifts

A specificity of Lake Saint-Jean consists of abundant features on the lake floor genetically related to wind-induced bottom currents (Fig. 5.6c; Nutz et al. 2014, 2015b). These are attributed to the emplacement of an internal wind-induced circulation due to the action of wind on the lake surface. Numerical modeling suggests that wind-induced circulations display a constant first-order pattern (Nutz et al. 2015b) whatever the orientation of the forcing wind (NW, W and SW). Pushed by wind, surface waters migrate from the upwind to the downwind side of the lake where water mass flows are forced to plunge initiating downwelling and reversed bottom currents that progressively flow toward the upwind side of the lake to reconnect with surface currents. Wind-induced circulations is supposed to develop during longer than 12 h storm events associated with wind intensity exceeding 10 $m\,s^{-1}$, circumstances currently occurring only a few days per decade. Velocities of generated currents range from 0.35 to 0.7 $m\,s^{-1}$ at the surface and from 0.2 to 0.4 $m\,s^{-1}$ along the lake floor. Among the resulting depositional features are positive mounds that are 100–500 m long and 5–10 m high, deposited on flat or inclined surfaces onto the lake floor referred to as sediment drifts. Some are typical elongated separate drifts (Fig. 5.6c) *sensus* Faugères et al. (1999) that traditionally develop in the marine realm. Indeed, in addition to those identified in Lake Saint-Jean, only few examples of sediment drifts are known in lake systems (Johnson et al. 1980; Tiercelin et al. 1992; Ceramicola et al. 2001; Gilli et al. 2005; Manley et al. 2012; Wagner et al. 2012). Combining sediment drifts with the abundant wave-related coastal landforms, Lake Saint-Jean has been among the pioneer examples used to recently develop the concept of wind-driven lake (Nutz et al. 2018). Wind-driven lakes share a sedimentation dominated by wave-related processes and wind-induced lake-scale water circulation. They are characterized by the construction of beach ridges, spits or cuspate spits along their shorelines, and by sediment drifts, sedimentary shelf progradation and erosional surfaces in their deeper, offshore domains. Wind-driven lakes are observed worldwide; they are relatively shallow regarding their sizes as expressed by the I_{WWB} index (Nutz et al. 2018), a ratio of the maximum representative fetch relative to mean basin depth. An index value greater than three is supposed to favor the evolution of a lake as a wind-driven lake.

5.4 Recent Geomorphological Processes

The anthropogenic lake level rise in 1926 is the last event that strongly impacted the evolution of the Lake Saint-Jean lowlands. The rise of the base level led to a change in the

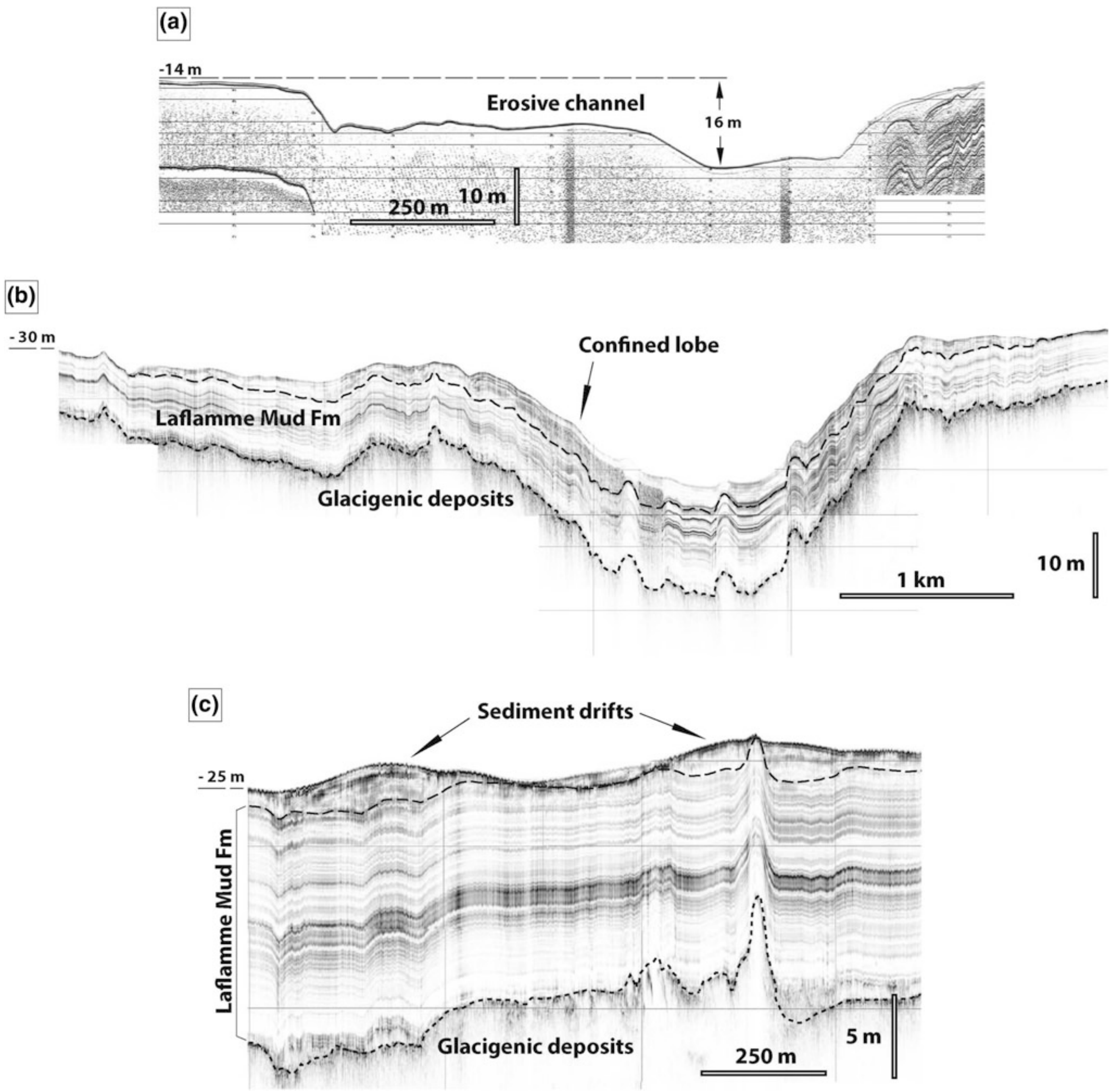


Fig. 5.6 Features related to hyperpycnal system and bottom currents in the Lake Saint-Jean developed during the paraglacial period of the basin (location Fig. 5.2f). **a** Erosional channel in front of the Ashuapmushaun river mouth. **b** Confined lobe in the western trough. **c** Mounds interpreted as sediment drift onto the lake floor. Note the three units constituting the common stratigraphic organization: glacigenic deposits at the base draped by the Laflamme Mud Fm. and bottom currents related features at the top

equilibrium profile of the lake margin, and enhanced erosion along the shore (Tremblay 1971b). Wave-cut terraces are now the predominant coastal landforms along the modern Lake Saint-Jean shoreline (Fig. 5.7a, b), in contrast to previous periods characterized by the coexistence of wave-cut terraces, constructive beach ridges and spit systems. Some parts of the lakeshore have been monitored since the lake level rise, and shoreline retreat has been measured. Between 1927 and 1966, erosion rates ranged between 1.2 and 3.2 m y^{-1} along the southeastern downwind sides of the lake (Tremblay 1971b). Today, mean erosion rates are around 0.2–0.3 m y^{-1} but maximum erosion rates reach 2–3 m y^{-1} in some places of the eastern part of the lake and despite the construction of shore protection measures, intense shoreline retreat has occurred. The second important geomorphic process in the Lake Saint-Jean lowlands is mass movement. These processes were

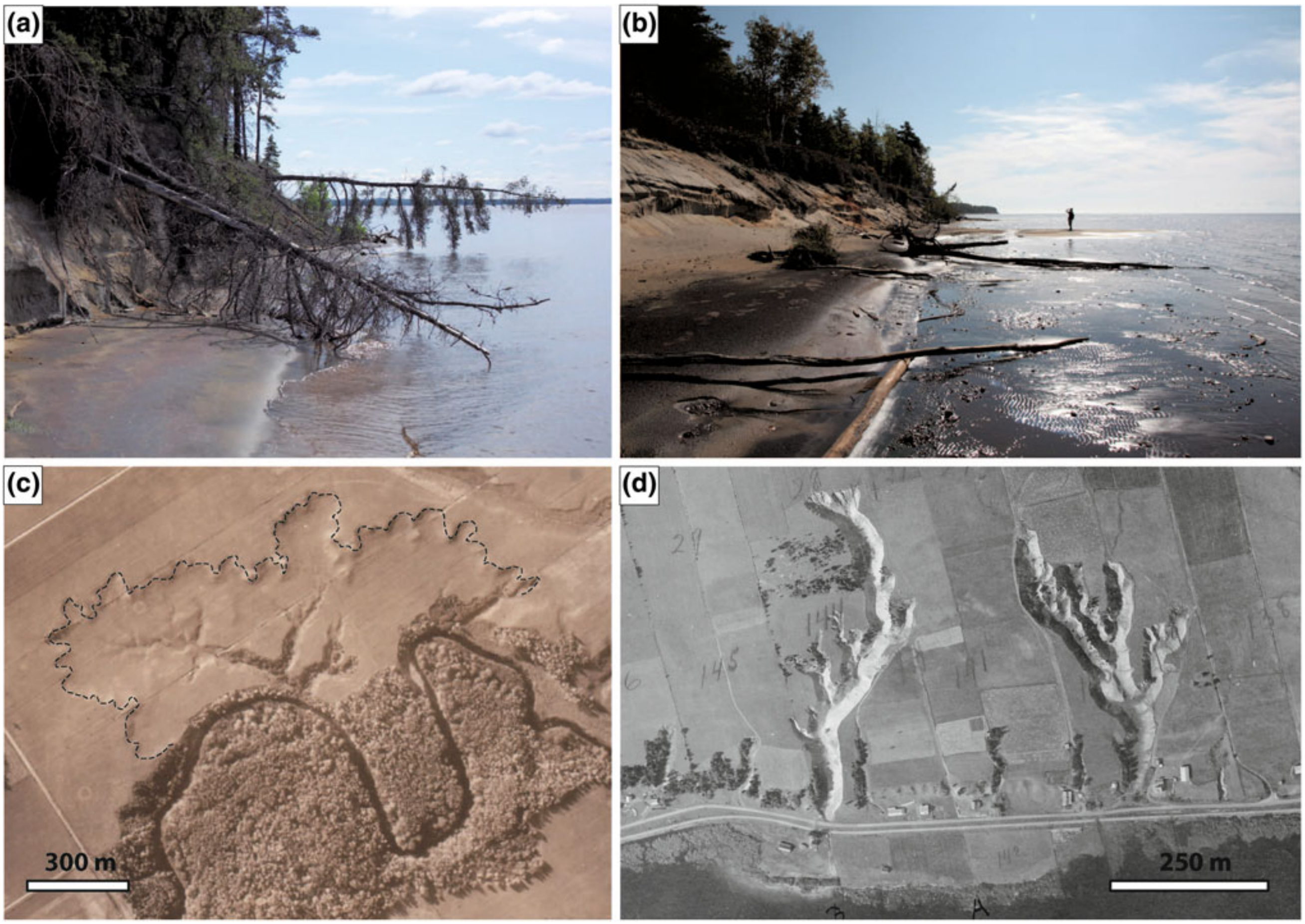


Fig. 5.7 Landforms associated with recent geomorphic processes. **a** and **b** Active wave-cut terraces as revealed by trees progressively falling in the lake along the Pointe-Taillon (eastern shore of Lake Saint-Jean). **c** and **d** Landslides in the Laflamme Mud Fm. (aerial photos from 1926, courtesy Rio Tinto Alcan)

identified since the 1960s (Chagnon 1968; La Rochelle et al. 1970, 1977), especially concerning localized places. Chagnon (1968) inventoried more than 20 landslides in the vicinity of Desbiens in the southern part of the depocenter among which the dramatic Saint-Jean-Vianney event of 1971 caused the death of 31 people. Mass movements are attributed to the exceptional sensitivity of muds comprising the Laflamme Mud Fm., as they meet all the criteria to behave as quick clay (e.g. Andersson-Sköld et al. 2005). Mass movements are observed both along the lake shore and along bluffs of incised rivers in the form of lobate or elongate scars extending over hundreds of meters (Fig. 5.7c, d). Finally, since the equilibration of the lake margin with the 1926 lake level will sustain erosion of the Lake Saint-Jean shoreline, and since the extensive subaerial exposure of the Laflamme Mud will likely continue to initiate mass movements, these two major geomorphic processes will probably continue to significantly impact landscapes and local communities of the Lake Saint-Jean lowlands in the near future.

5.5 Conclusion

The Lake Saint-Jean lowlands form a striking product of combined geomorphological processes that occurred since the last deglaciation. As a result, landscapes provide a valuable set of spatially diversified landforms which originated from different periods of the depocenter evolution. The acquisition of the high-resolution swath bathymetry imagery provided key elements dealing with the deglacial period of the area. Documenting sedimentation associated with the paraglacial period led to new paradigms concerning the evolution of restricted marine and lacustrine systems, especially about the role of wave-related deposition and erosion in the shaping of lacustrine systems. The development of wind-induced features onto the floor of the modern Lake Saint-Jean is an important characteristic of the area that makes it unique in eastern Canada. Finally, since 1926 the Lake Saint-Jean lowlands constitute an outstanding example of a geomorphological system controlled by both natural and anthropogenic forcings, combining mass movements in sensitive muds derived from the glacial history of the depocenter and intense lake shore erosion due to the anthropogenic lake-level rise.

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