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Seismic stratigraphy of Waterton Lake, a sediment-starved glaciated basin in the Rocky Mountains of Alberta, Canada and Montana, USA

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Abstract

Upper and Middle Waterton lakes fill a glacially scoured bedrock basin in a large (614 km^2) watershed in the eastern Front Ranges of the Rocky Mountains of southern Alberta, Canada and northern Montana, U.S.A. The stratigraphic infill of the lake has been imaged with 123 km of single-channel FM sonar ('chirp') reflection profiles. Offshore sonar data are combined with more than 2.5 km of multi-channel, land-based seismic reflection profiles collected from a large fan-delta. Three seismic stratigraphic successions (SSS I to III) are identified in Waterton Lake resting on a prominent basal reflector (bedrock) that reaches a maximum depth of about 250 m below lake level. High-standing rock steps (reigels) divide the lake into sub-basins that can be mapped using lake floor reflection coefficients. A lowermost transparent to poorly stratified seismic succession (SSS I, up to 30 m thick) is present locally between bedrock highs and has high seismic velocities (1750–2100 m/s) typical of compact till or outwash. A second stratigraphic succession (SSS II, up to 50 m thick), occurs throughout the lake basin and is characterised by continuous, closely spaced reflectors typical of repetitively bedded and rhythmically laminated silts and clays most likely deposited by underflows from fan-deltas; paleo-depositional surfaces identify likely source areas during deglaciation. Intervals of acoustically transparent seismic facies, up to 5 m thick, are present within SSS II. At the northern end of Upper Waterton Lake, SSS II has a hummocky surface underlain by collapse structures and chaotic facies recording the melt of buried ice. Sediment collapse may have triggered downslope mass flows and may account for massive facies in SSS II. A thin Holocene succession (SSS III, <5 m) shows very closely spaced reflectors identified as rhythmically laminated fine pelagic sediment deposited from interflows and overflows. SSS III contains Mt. Mazama tephra dated at 6850 yr BP.

Keywords: Rocky Mountains; seismic stratigraphy; glaciated lake basins

1. Introduction

In deep, steep-sided valleys typical of the Rocky Mountains and western Cordillera, geophysical investigations of lake basins are important because they offer the possibility of understanding glacial history where the primary glacial geomorphological record in surrounding valleys has been partially destroyed by postglacial subaerial mass-wasting and fluvial activity. Such lake basins commonly contain a potentially high-resolution sedimentary record of

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lateglacial and postglacial change (Finckh et al., 1984; Leonard, 1986; Mullins and Eyles, 1996; Desloges and Gilbert, 1998). Seismic reflection techniques are increasingly being used to investigate such fills and much new stratigraphic information has recently been acquired from basins in the European Alps, the Cordillera and mid-continent of North America (Mullins et al., 1990, 1991; Eyles et al., 1990, 1991; Eyles and Mullins, 1997; Curzi et al., 1992; Van Rensbergen et al., 1998).

1.1. Objectives and significance of this paper

The purpose of this paper is to present the results of a geophysical study of Waterton Lake in Waterton-Glacier International Peace Park in Alberta, Canada and the adjacent Glacier National Park of Montana, U.S.A. (Figs. 1–3A). The area straddles the boundary zone between the Front Ranges of the Rocky Mountains and the adjacent Foothills to the east. During late Wisconsin glaciation, the area was influenced by ice flowing northeastward from the Rocky Mountains (Cordilleran Ice Sheet) and by ice flowing southwestward (Laurentide Ice Sheet; Fig. 3B; Dawson, 1890; Horberg, 1954; Alley and Harris, 1974; Karlstrom, 1987; Clague, 1989; Little, 1998). Here, we report the results of applying recently developed FM 'chirp' sonar profiling to image the infill of Waterton Lake. Offshore sonar data are integrated with multi-channel seismic data collected from the surrounding margins of the lake. Our data identify a thick (50 m) lateglacial infill stratigraphy below Waterton Lake and resolve the lateglacial and postglacial history of the lake basin, particularly the roles of Cordilleran and Laurentide ice. Data from Waterton Lake can be compared with offshore seismic data collected recently from nearby Lake McDonald (Fig. 1; Mullins et al., 1991).

2. Physical setting of Waterton Lake

Waterton Lake lies within the southern Rocky Mountains of Alberta and Montana where mountain summits locally reach elevations of over 2500 m above sea level (masl). Small cirque glaciers occur on the highest northeast-facing peaks (Stalker and Harrison, 1977; Osborn, 1985). Eastward-directed regional thrust faulting of resistant Neoproterozoic dolostones, quartzites and more easily eroded argillites gives rise to prominent northwest-trending ridges and valleys (Figs. 2 and 5A). The Waterton River originates in Montana (Fig. 1) and flows northward counter to the regional bedrock strike within a narrow valley that is fault- or joint-controlled (Babcock, 1973; Scheidegger, 1983). The valley is about 30 km long and some 2 km wide along most of its length.

Waterton Lake is an example of the 'open system glacial/interglacial lake basins' of Glenn and Kelts (1991) typical of mountain zones (so-called 'fiord-lakes' or 'perialpine lakes'). Waterton Lake is about 17 km long and is divided into three separate waterbodies (Upper, Middle and Lower; Fig. 2). The international border at 49º00′ crosses Upper Waterton basin. Upper Waterton Lake is 9 km long, averages 1 km wide and is separated from Middle Waterton Lake (4 km^2) by a large rock bar and a shallow strait where water depths are less than 4 m (the Bosporus; Figs. 2 and 3A, Fig. 5A). Mean lake level is at 1279 masl but there are strong inter- and intra-seasonal variations of up to 3 m. In addition, seiches are common in response to strong northeastward-flowing chinook winds that drain through the Rocky Mountain valleys.

The principal drainage inputs to Upper Waterton Lake are from Cameron Creek, which has constructed a gravel fan now occupied by Waterton town site (Figs. 2 and 3A, Fig. 5A), and from the Waterton River in Montana (Fig. 1). This latter drainage basin includes about a dozen small (<1 km^2) cirque glaciers (Osborn, 1985). The principal sediment source to Middle Waterton Lake is from large fan-deltas at the mouths of Blakiston and Sofa creeks (Fig. 3A, Fig. 4). Progradation of the fans has resulted in separation of Middle Waterton Lake from Lower Waterton Lake by a narrow strait (the Dardanelles; Figs. 2 and 4).

2.1. Bedrock geology

The Waterton Lake basin is cut into Mesoproterozoic strata of the Purcell Supergroup (equivalent to the Belt Supergroup of Montana). These dip steeply to the west as a result of eastward thrusting across Late Jurassic strata during the Laramide

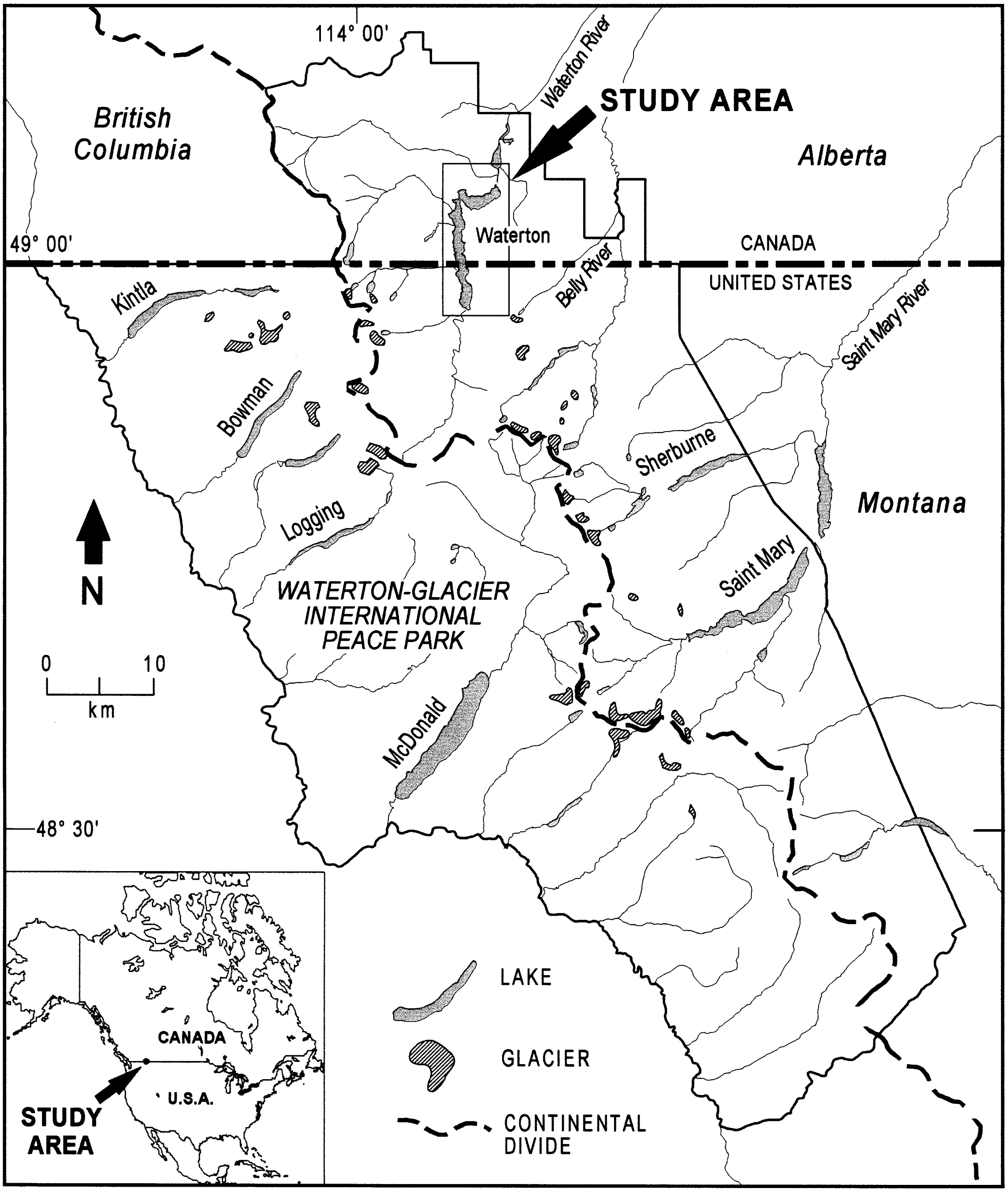


Fig. 1. Map of Waterton Glacier International Peace Park showing location of study area.

Orogeny (Aitken and McMechan, 1991). Two prominent thrusts (the Lewis and Mt. Crandell thrusts) cross the lake (Douglas, 1952). The geology is dominated by alternations of relatively soft, shallow water and intertidal argillites and more resistant limestones and dolomites whose strike runs northwest–

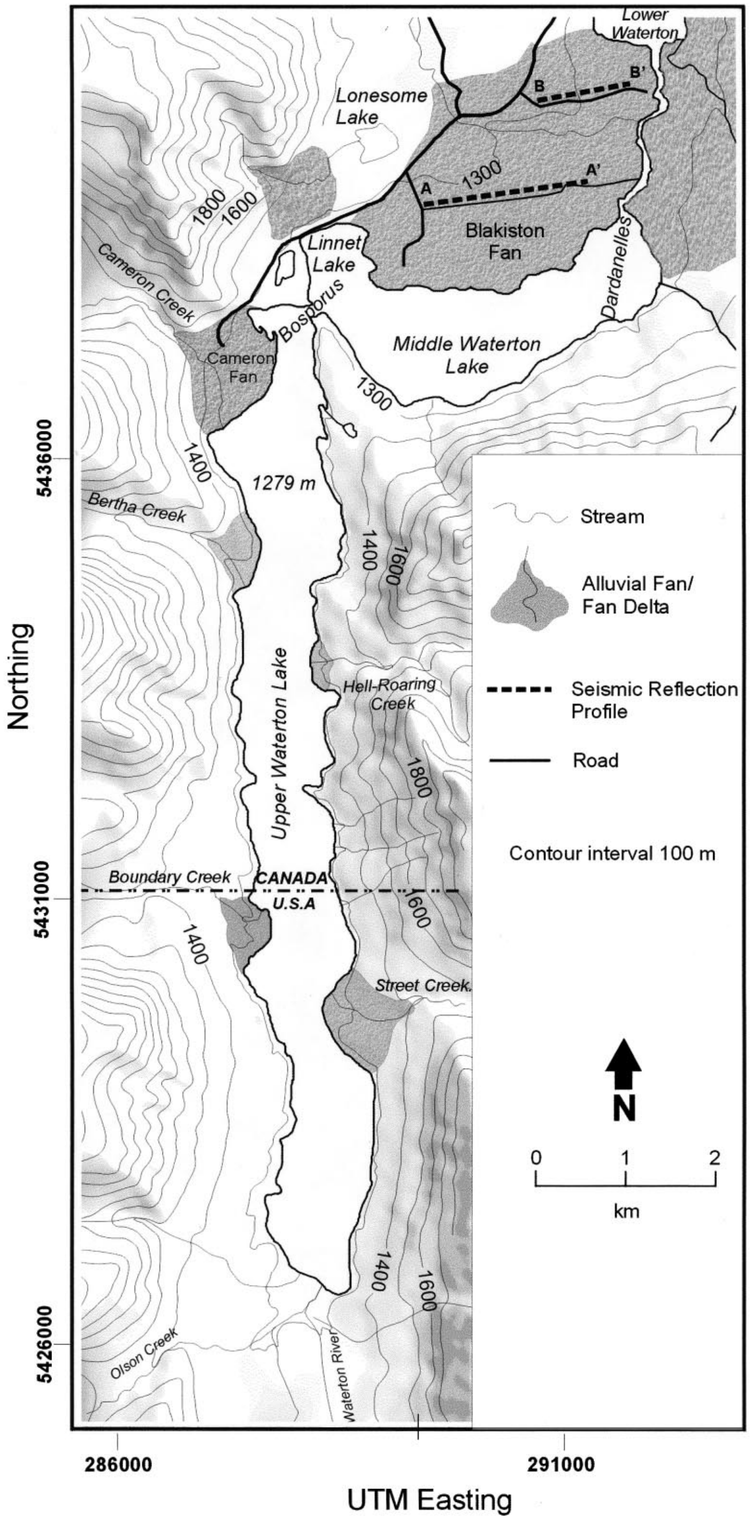


Fig. 2. Waterton Lake study area with location of land-based seismic profiles (A–A', B–B'). Offshore sonar track lines are shown in Fig. 6.

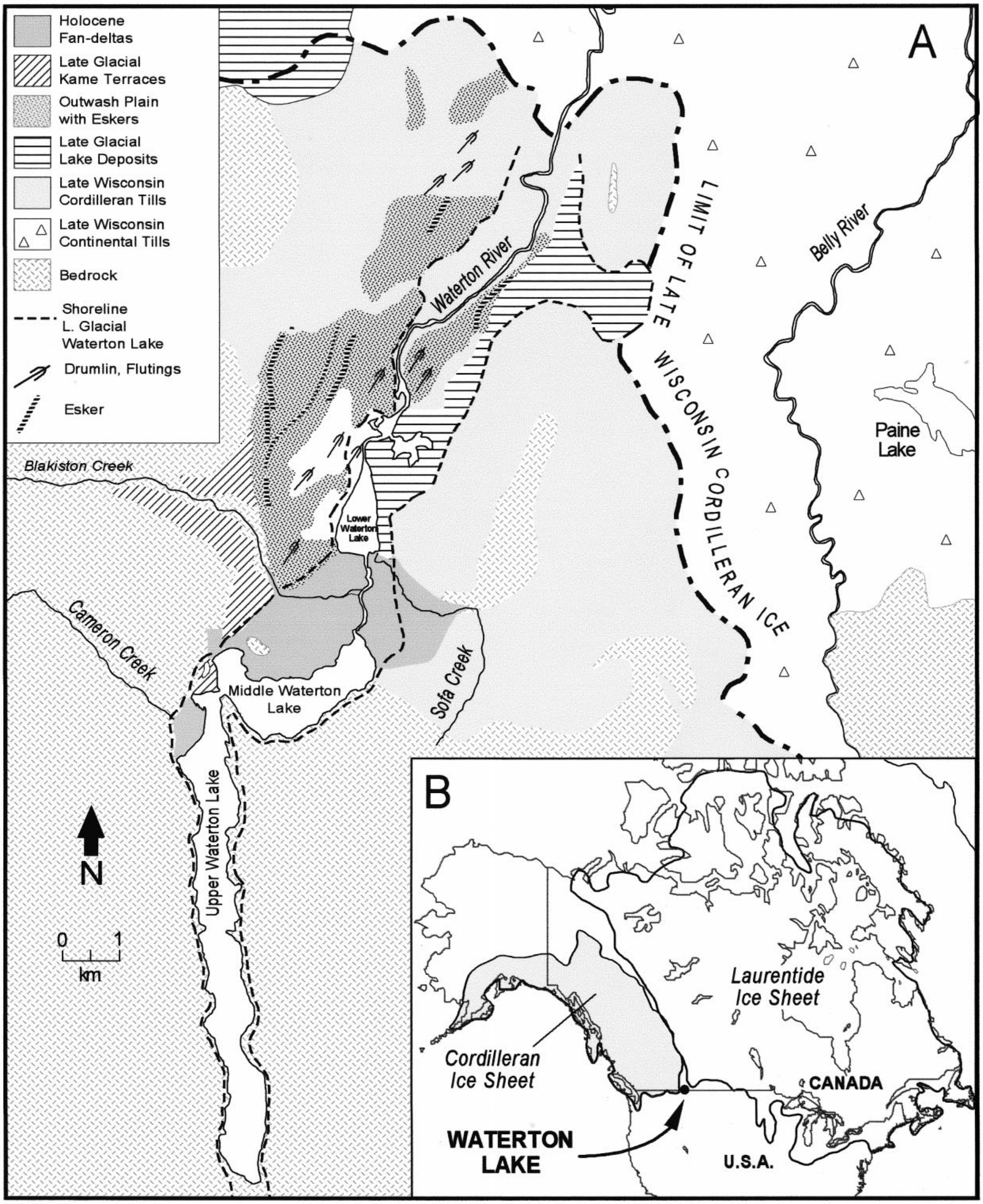


Fig. 3. (A) Glacial geomorphology and surficial sediment of Waterton Lakes study area, based on mapping by Horberg (1954), Harrison (1976) and Little (1998) with additions from authors' fieldwork. (B) Waterton Lake district within the context of the Cordilleran and Laurentide Ice Sheets; the two ice masses were not confluent in the vicinity of Waterton lakes unlike areas to the north (see text).

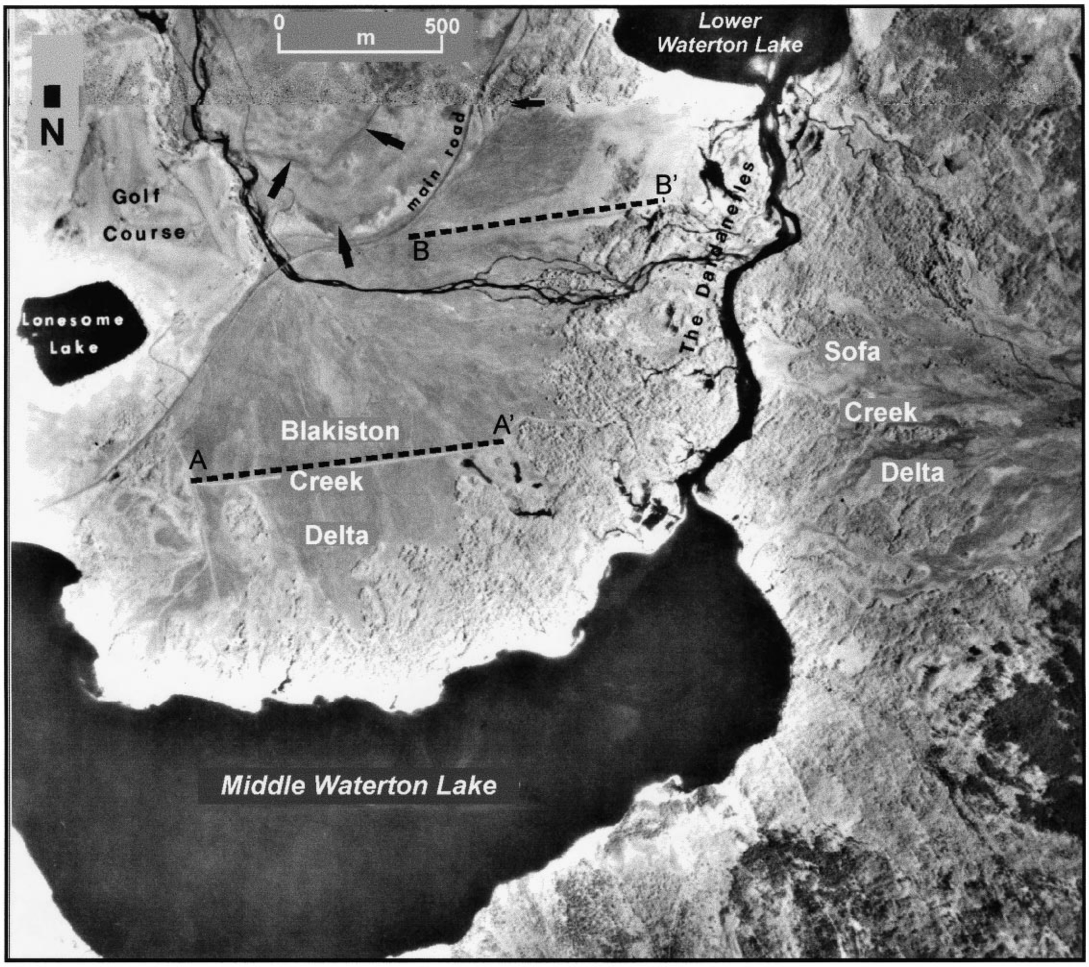


Fig. 4. Large fan-deltas at the mouth of Blakiston and Sofa creeks (see Figs. 2 and 3A) with location of land-based seismic profiles (Fig. 14). Lonesome Lake is a large kettle basin formed by melt of ice trapped within kame terraces (Fig. 3A).

southeast oblique to the long axis of the lake basin. The presence of resistant carbonates, repeated by thrusting, results in prominent glacially scoured rock steps (reigels) that divide the basin thalweg into discrete sub-basins. A prominent reigel, composed of Altyn Formation dolomite, is partially breached and separates Lower from Middle Waterton Lake at the Bosporus (Fig. 2). The orientation and width of Waterton Valley abruptly changes downbasin of the reigel (Figs. 2 and 5A). The Mt. Crandell Thrust gives rise to another large reigel near the international border (Figs. 2 and 7).

2.2. Pleistocene geology

Waterton Valley functioned as an outlet for a lobe of the Cordilleran Ice Sheet lobe (Waterton Glacier) which was composed of ice streams derived from tributary valleys. The maximum northeastern extent of the Waterton lobe, and others, on the adjacent Foothills and Plains is marked by coarse-grained, carbonate-rich tills, large mountain-sourced erratic blocks, lateral and end moraines and ice-flow indicators such as drumlins and eskers (Harrison, 1976; Clague, 1989; Little, 1998). Similarly, the maximum westward extent of the Laurentide Ice Sheet (continental ice) is marked by prominent belts of

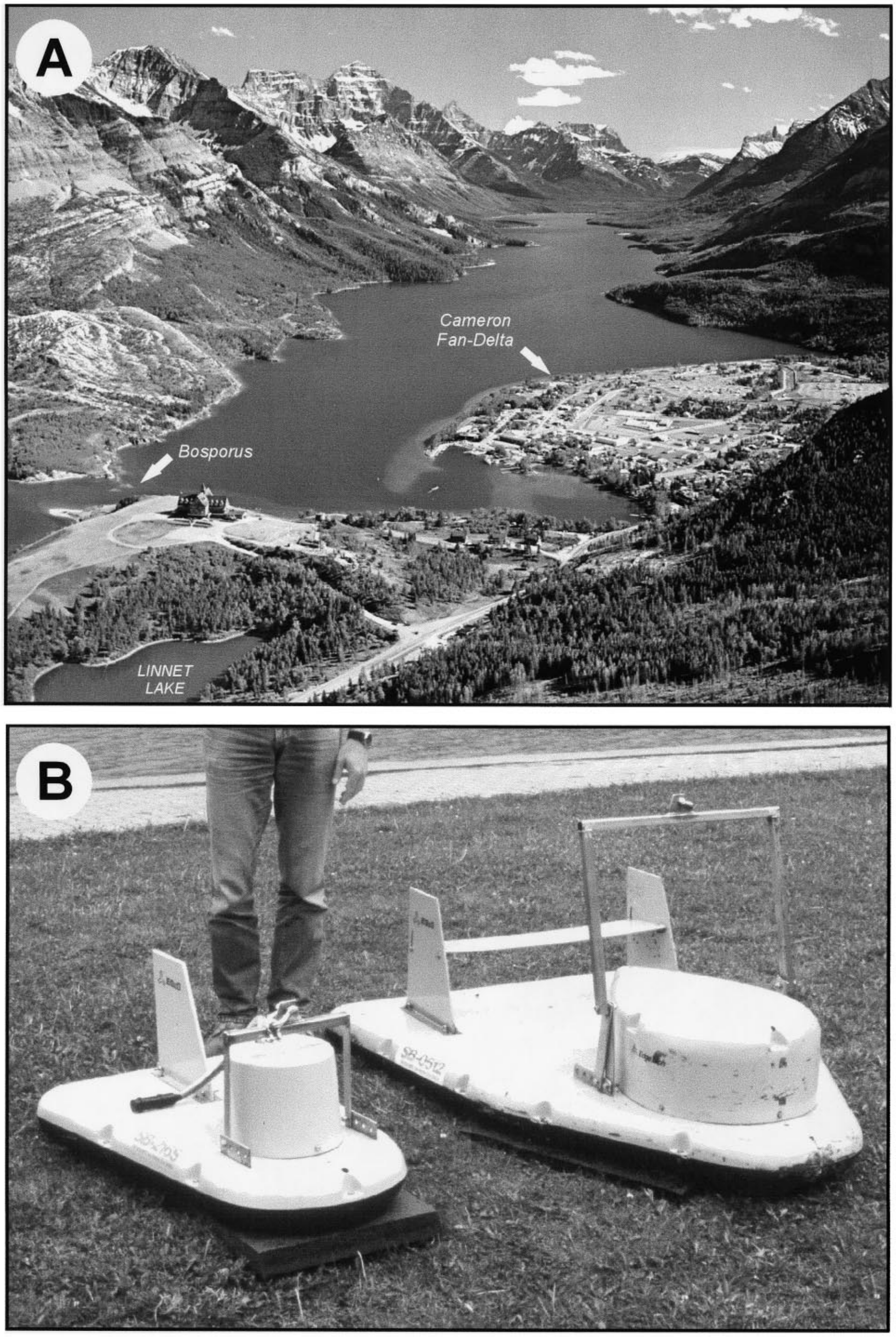


Fig. 5. (A) Upper Waterton Lake looking south across international border into Montana with Cameron fan-delta and Waterton townsite in foreground. A large rock bar crosses the valley at the Bosporus; other reigels form prominent points around the lake shore and are numbered R1 to R4 in Fig. 7A. The hotel in foreground is built on a remnant of a kame terrace; Linnet Lake is a large kettle basin formed by the melt of buried ice (see also Fig. 3A, Fig. 11 and Fig. 15). (B) Tow vehicles (fish) employed on Waterton Lake; at left is SB-216S (using a frequency range of 2–15 kHz), at right is SB-512 (500 Hz to 12 kHz). Towfish are equipped with piston-type transducers and linear hydrophone arrays.

hummocky moraine and fine-grained tills containing crystalline 'shield' erratic lithologies. Age dating of the maximum extent of Cordilleran and Continental ice has shown that the two ice masses were confluent north of the study area (e.g., Jackson et al., 1997) but recent dates from the Waterton area suggest that Laurentide ice reached its maximum extent at about 20,000 yr BP, well before Cordilleran ice at 14,000 yr BP (Horberg, 1954; Jackson et al., 1997; Little, 1998; Fig. 3B). Waterton Valley was free of ice by 12,000 yr BP and there are no extensive Holocene ice advances recorded in the area (Osborn, 1985).

A well-developed glaciated valley landsystem (Boulton and Eyles, 1979) is preserved north of Lower Waterton Lake (Fig. 3A). Lateral moraines and kame terraces along the valley sides stand above belts of hummocky moraine, crevasse-fillings, eskers and drumlins along the valley floor. This landsystem was deposited during the retreat of Waterton Glacier (Harrison, 1976).

3. Objectives and methods

The objectives of this study are (1) to determine the infill stratigraphy of Upper and Middle Waterton lakes using lake-based FM sonar and land-based multi-channel seismic profiling, and (2) to identify likely depositional processes from seismo-facies and better resolve the glacial history of Waterton Valley.

3.1. Lake-based FM sonar profiling

Sonar data were acquired using EdgeTech's X-STAR FM high-resolution digital subbottom FM profiling system in Lower and Middle Waterton lakes deployed from the University of Toronto's research vessel *Nautilus*. FM sonar profilers employ user-selectable swept sonar impulses ('chirp pulses') to generate high-resolution normal-incidence seismic reflection images of the sub-bottom stratigraphy. The acoustic return received at two sets of hydrophones is matched/filtered with the outgoing FM pulse, to increase the signal to noise ratio (up to 40 dB). We employed two different tow vehicles (fish) on Waterton Lake in order to maximise resolution and penetration (Fig. 5B). The SB-216S tow vehicle transmits an FM pulse that is linearly swept over a frequency range of 2–15 kHz for 20 ms; this allows high resolution imaging of the uppermost (approx. 30 m) of the sediment column. A second tow vehicle (SB-512) equipped with four transducers generates a selectable bandwidth between 500 Hz and 12 kHz allowing improved penetration in areas of sandy bottom sediments. Both FM sources were operated at peak output of 2 kW and a ping rate of 6–8 pulses/s. The fish were towed approximately 0.5 m below the lake surface at a boat speed of 2 m/s (approx. 3.5 knots). The sonar system typically resolves reflectors within the upper 50 m of the sediment column with a decimetre-scale vertical resolution. A total of 123 km of sonar profiles was collected over a 3-day period. Some track lines were duplicated to allow direct comparison of penetration and resolution using varying source frequencies.

Seismic profiles were plotted on a GSP-1086 EPC graphic recorder with a time-varying gain that increased linearly (0.5 dB/m) below the lake floor. Sediment profiles and navigation maps (using GPS technology) were generated in real time. Navigational fixes by GPS were recorded with seismic traces on 4 mm DAT tape and were confirmed by dead reckoning using prominent points along the shoreline and an additional hand-held GPS instrument.

Post-cruise processing of sonar data involved conversion to SEG-Y format, application of a time-variant gain function (TVAGC) to equalize reflection amplitudes and band pass filtering to remove unwanted low-frequency noise (e.g., boat engine). Depth conversion of sonar sections was based on a water column velocity of 1450 m/s and sediment column velocities of 1550–2100 m/s determined from land-based multi-channel seismic records.

3.2. Land-based multi-channel seismic profiling

In addition to offshore sonar profiling, a land-based seismic reflection survey was completed along transects across the lower part of the Blakiston Creek fan-delta. These transects were sited close to offshore seismic track lines in Middle Waterton Lake (Figs. 4 and 6) to allow direct comparison of the two data sets. We used a 24-channel EG and G seismograph with a 5-kg hammer and 100-Hz geophones. Profiles were collected using a roll-along box and common mid-point (CMP) shooting with 5 m shot

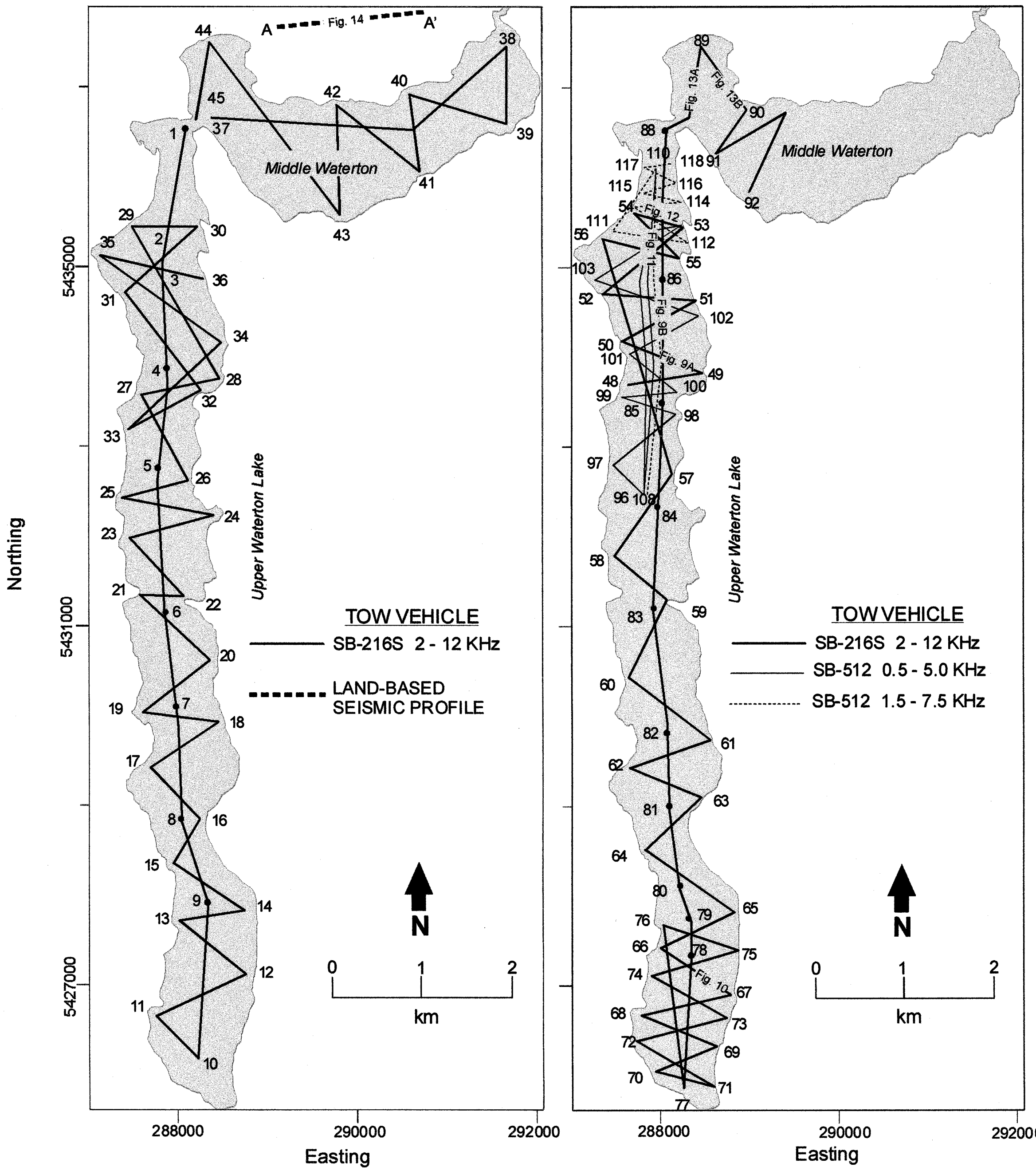


Fig. 6. Location of sonar track lines (123 km) on Upper and Middle Waterton lakes and land-based seismic reflection transects *A–A′* and *B–B′* (2.5 km) on lower part of Blakiston Fan (Fig. 4).

and receiver spacings. This configuration provided continuous 12-fold subsurface coverage and 2.5 m subsurface sampling interval. Data acquisition and processing steps involved two-dimensional filtering to remove background noise and surface waves, normal move-out correction and common mid-point stacking (Davies and King, 1992; Boyce et al., 1995; Boyce and Koseoglu, 1997).

4. Results

4.1. Sonar bathymetry

Lake bottom bathymetry was mapped using sonar water bottom returns (Fig. 7A). We caution that the use of low-frequency subbottom profiling equipment to measure the depth of steep-sided basins is subject to errors created by the broad beam width of the system (e.g., McQuillan and Ardus, 1977). Thus the data presented here are regarded as 'apparent' depths only and not necessarily 'true depths'. Data indicate a maximum apparent water depth in Upper Waterton Lake of 145 m and delineate two primary depositional basins (North and South). The basins are separated by a prominent bedrock reigel (R3) marking the Mt. Crandell Thrust that crosses Upper Waterton Lake close to the international boundary (Fig. 7A). In contrast, water depths in Middle Waterton Lake are less than 15 m.

4.2. Mapping of lake floor reflection coefficients

Reflection coefficients derived from the amplitude of sonar first arrival data provide a measure of the ability of basin floor sediments to reflect or transmit sound. As a consequence, the systematic mapping of reflection coefficient data can provide a rapid guide to lake floor substrates and bottom hardness. Areas of hard bottom, such as bedrock, are identified in Waterton Lakes by areas of high reflection coefficients (>-10 dB; Fig. 7B). Such areas occur along most of the shallower water margins of Upper Waterton Lake. Areas of high reflectivity also occur across much of Middle Waterton Lake where water depths are shallow and the lake floor consists of sand and silt. In Upper Waterton Lake, zones of lower reflection coefficients (< -25 dB) correspond to acoustically transmissive zones in deep water, and identify fine-grained lake floor sediments and thick sediment infills preserved between bedrock highs (Fig. 7B). Mapping of lake bottom reflectivity was particularly useful in identifying the cross-basin extent of bedrock highs and depositional basins (see below).

4.3. Bedrock topography

In Upper Waterton Lake, the steeply dipping, glacially scoured bedrock side slopes of the modern valley can be directly correlated below lake level with a prominent basal reflector on sonar profiles. This reflector forms 'acoustic basement' and shows prominent large-scale convex diffractions and a distinct hummocky surface form of glacially streamlined bedrock (Figs. 8–13). The slope on the bedrock reflector agrees with that of the valley sides above water level; simple extrapolation of this surface down into the axial parts of the basin provides an estimate of the maximum depth to bedrock of more than 250 m below lake level.

A very distinctive feature of the bedrock floor of Upper Waterton Lake is the presence of rock steps (reigels) that mark the strike of resistant, steeply dipping Proterozoic carbonates (Fig. 5A). Reigels are numbered R1 to R4 in Fig. 7A. Reflection coefficient and bathymetric mapping (Fig. 7) shows that some reigels form continuous barriers across the lake floor and restrict the overlying sediment fill to several sub-basins. The prominent, sharply defined reigel that crosses Upper Waterton Lake close to the international boundary (R3; Fig. 7A), forms a continuous cross-basin barrier. Substantial differences in sediment thickness occur on either side of this reigel (Fig. 8). Other reigels in Upper Waterton Lake (R2, R4; Fig. 7A) constrict the valley but do not form continuous across-basin barriers. Both the southern and northern terminations of Upper Waterton Lake are defined by bedrock (Figs. 8 and 11).

The bedrock surface in Middle Waterton Lake was not imaged by sonar profiling but was identified on land-based seismic profiles as a relatively continuous reflector at a two-way time of 120–180 ms (Fig. 14). This reflector has a gently undulating surface form with broad channels having a relief of over 50 m.

5. Description of sediment infill in Waterton Lake

Lake-based sonar and land-based seismic reflection profiling permitted geophysical imaging of the sediment stratigraphy below the Upper and Middle Waterton lakes to depths of 180 m below lake

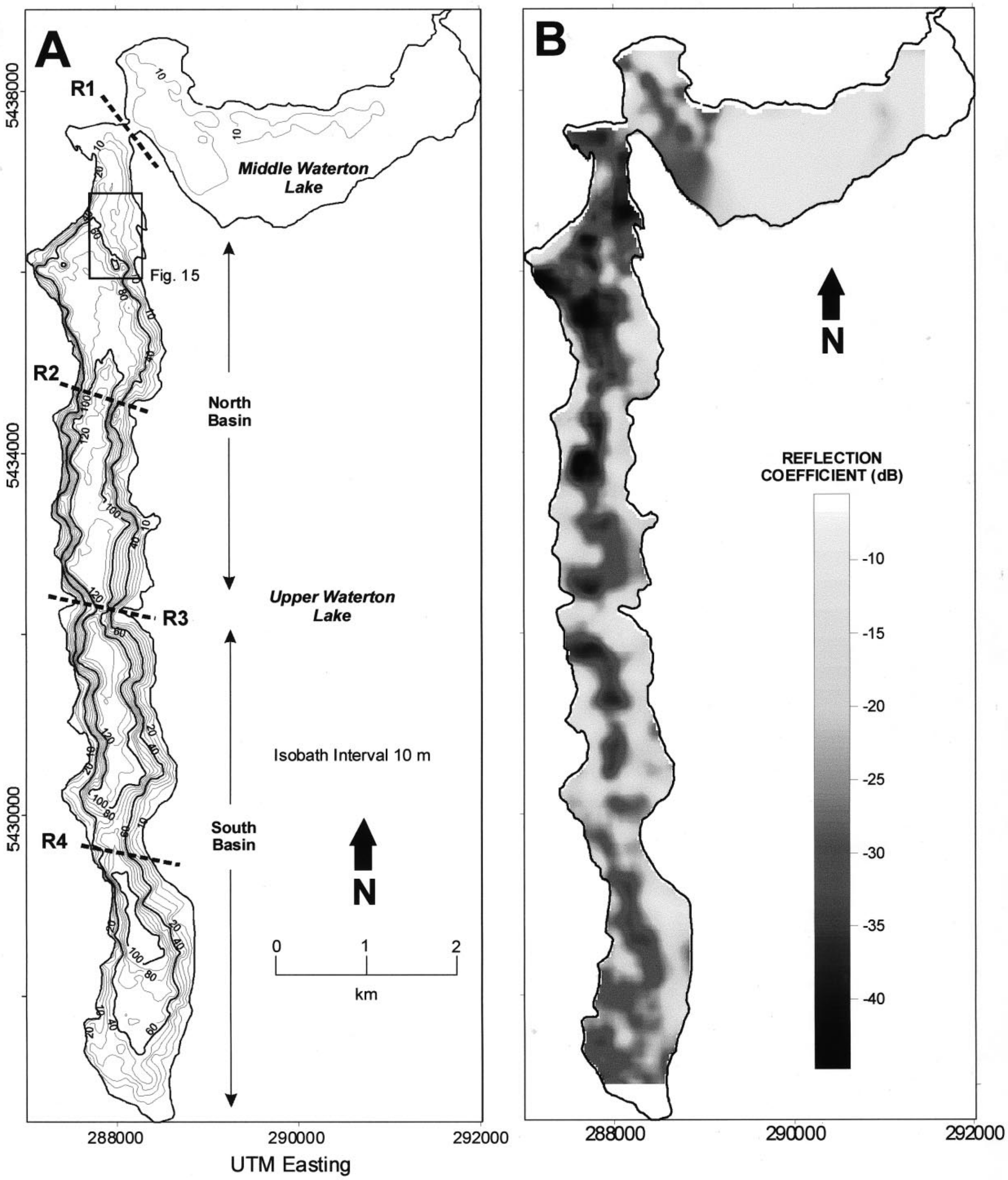


Fig. 7. (A) Sonar bathymetry of Waterton lakes derived from sonar water bottom first arrivals. Water depth is calculated assuming a water column velocity of 1450 m/s. Reigels are numbered R1 to R4 (see Fig. 8). Maximum water depth is 145 m. Area of lake floor south of bedrock reigel R1 is shown in Fig. 15. (B) Reflection coefficient characteristics of lake floor substrates; areas of high reflection coefficient (light-toned areas) are bedrock. Darker-toned, acoustically transmissive areas are sediment (see text for details).

level (Figs. 8–14). A maximum penetration depth below the lake floor of 60 m was achieved. Zones of gasified sediment are identified by acoustically ‘bright’ zones of high amplitude below which there is complete loss of reflection returns (GS; Fig. 8). The presence of gas in sediment is usually attributed to decomposition of organic matter but the Waterton area lies close to a large natural gas field and out-gassing of hydrocarbons from bedrock may also occur (see also Gilbert et al., 1993; Mullins et al., 1996; Richardson and Davis, 1998).

The sediment infill below the Upper and Middle Waterton lakes consists of three seismic stratigraphic successions (abbreviated below as SSS I, SSS II and SSS III) that are defined by distinct seismic facies (Fig. 8). The lowermost (SSS I) is mostly transparent with weak diffractions. This is overlain by a well-stratified succession (SSS II) characterised by parallel, closely spaced reflectors. An uppermost succession (SSS III) is defined by very closely spaced reflectors with a prominent basal reflector.

5.1. Seismic stratigraphic succession (SSS I)

This succession varies in thickness from less than 10 m to more than 30 m and is characterized by a lack of internal reflectors (acoustic ‘transparency’) together with the presence of widely dispersed diffractions (Fig. 8). It is most clearly imaged at the southern end of Upper Waterton Lake where it rests directly on bedrock and fills a sub-basin immediately south of reigel R4 (Fig. 8). The upper surface of this succession is defined by a prominent but discontinuous reflector that has an undulatory surface form below overlying stratified seismic facies of SSS II. The succession cannot be recognized on sonar data from Middle Waterton Lake (Fig. 13) but can be tentatively correlated with a 20 to 50 m thick acoustically transparent succession resting on bedrock identified from land-based seismic profiling on Blakiston Creek fan-delta (Fig. 14).

5.2. Seismic stratigraphic succession (SSS II)

This comprises a thick (<50 m) package of acoustically stratified sediment characterised by parallel, closely spaced and gently undulating reflectors showing alternating high and low seismic amplitudes (Figs. 8–10). This succession makes up the bulk of the fill below the Middle and Upper Waterton lakes. Strata are, for the most part, flat-lying and parallel with the modern lake floor, except where SSS II is draped conformably over small-scale bedrock hummocks at the south end of Upper Waterton Lake and below a zone of hummocky topography at the northern end of the lake (Figs. 8 and 11A).

Vertical spacing of reflectors within SSS II suggests decimetre- to metre-scale bed thicknesses. Sonar profiles of the thicker basin fills between bedrock reigels R1, R2 and R3 (Figs. 8–10) show that reflector frequency decreases with depth as do relative amplitudes of alternating layers. These characteristics strongly suggest thickening and coarsening of sediment layers with increasing depth (Fig. 9). Repetitively spaced, high-amplitude reflectors may indicate the presence of distinct ‘packages’ within SSS III consisting of smaller-scale ‘fining-upward’ sequences. Transparent, reflector-free zones up to 5 m thick, are also present within SSS II below both Upper and Middle Waterton lakes (Figs. 9 and 13).

The upper surface of SSS II at the northern end of Upper Waterton Lake shows hummocks with enclosed depressions, with a surface relief of up to 15 m (Fig. 7A, Figs. 11 and 15). Reflectors within the hummocks pass laterally, below adjacent bathymetric depressions, into chaotic facies showing smeared reflectors and numerous point diffractions (Figs. 11 and 14). Chaotic facies are also present as a thin (<2 m) zone in the near-surface of the hummocks. A prominent near-vertical structure occurs between two hummocks shown in Fig. 11B. Other examples of enclosed depressions associated with deformed sediment at depth occur immediately north of reigel R2 (Figs. 8 and 9). There, uppermost strata are steeply downwarped over areas of intense deformation at depth. SSS II also shows local areas of downwarping in Middle Waterton Lake but the full lateral and vertical extent of these structures cannot be determined (Fig. 13).

SSS II shows an abrupt change in thickness either side of the prominent bedrock reigel (R3) that divides the North from the South basin of Upper Waterton Lake (Fig. 8). The thickest accumulation occurs on the south side of the reigel which, together with the gentle northward slope of the modern lake floor (Fig. 8), suggest that the South basin was filled

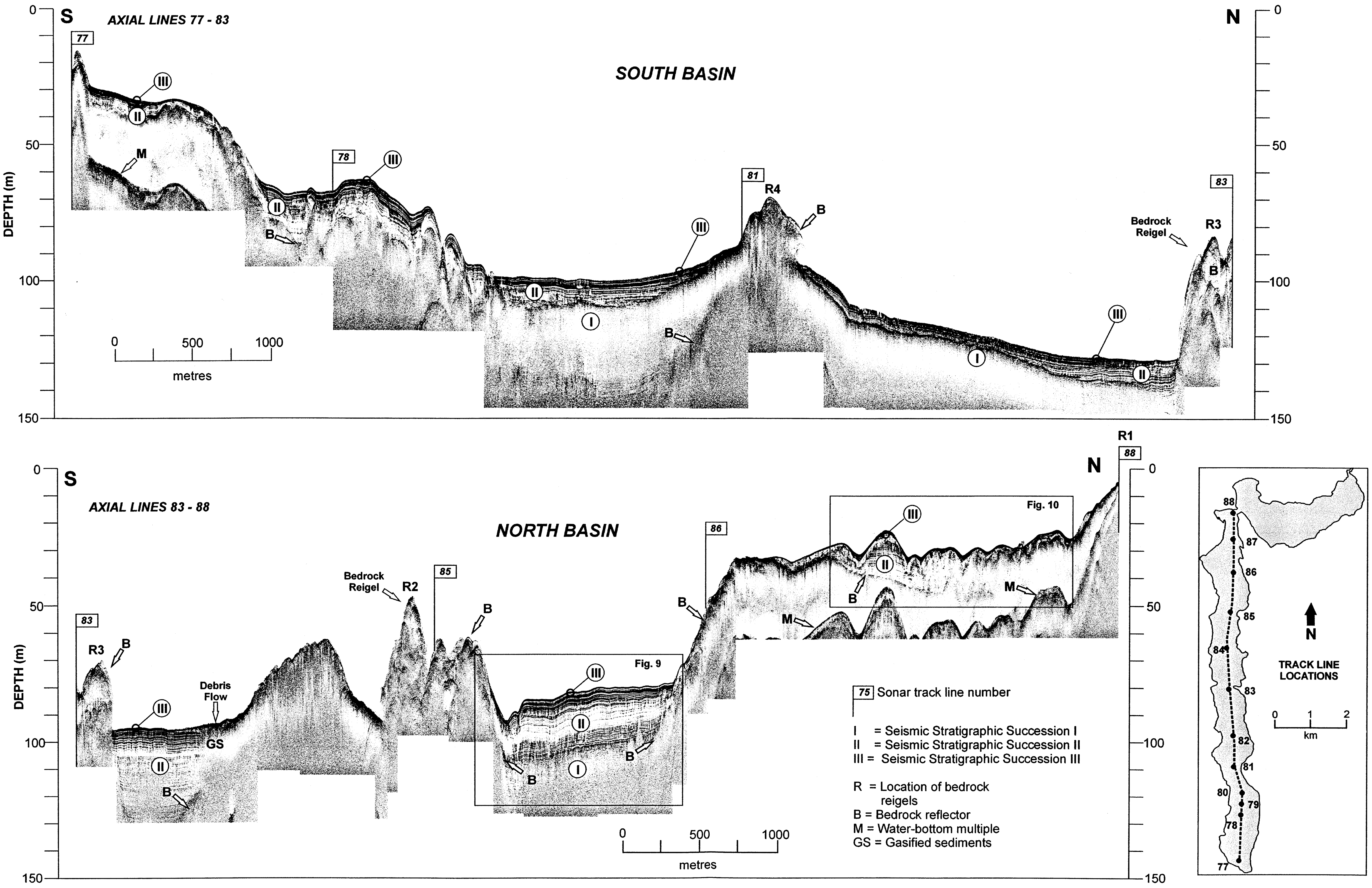


Fig. 8. 10 km long axial sonar profiles from North and South basins of Upper Waterton Lake collected using a SB-216S tow-vehicle (Fig. 5B and Fig. 6).

from a southerly source. This agrees with the continued presence of glaciers to the south of the basin and the known southerly retreat of the last Pleistocene ice lobe to occupy the Waterton Valley. Information from the North basin is less clear but it is very likely that the Cameron Creek and Blakiston Creek valleys were the principal sources of sediment during deglaciation (see below).

5.3. Seismic stratigraphic succession (SSS III)

This consists of a thin layer (average 3 m, maximum 5 m) of acoustically transparent sediment forming a drape across the flat or hummocky and deformed surface of SSS II and, locally, across bedrock highs (Figs. 8–11 and 13). SSS III is dominated by very closely spaced parallel reflections that are of relatively high amplitude when compared with SSS II. The base of SSS III is defined by a prominent high-amplitude reflector. Offshore of the modern Cameron fan-delta, sediments of SSS III are draped over deformed and erosionally truncated sediments of SSS II and pass up slope into gently dipping delta front strata of the fan-delta (Fig. 13). Sonar data show the presence of small lobate masses of transparent sediment with hummocky tops adjacent to steep bedrock slopes such as on the south side of R2 (Figs. 8 and 10).

6. Interpretation of sediment infill

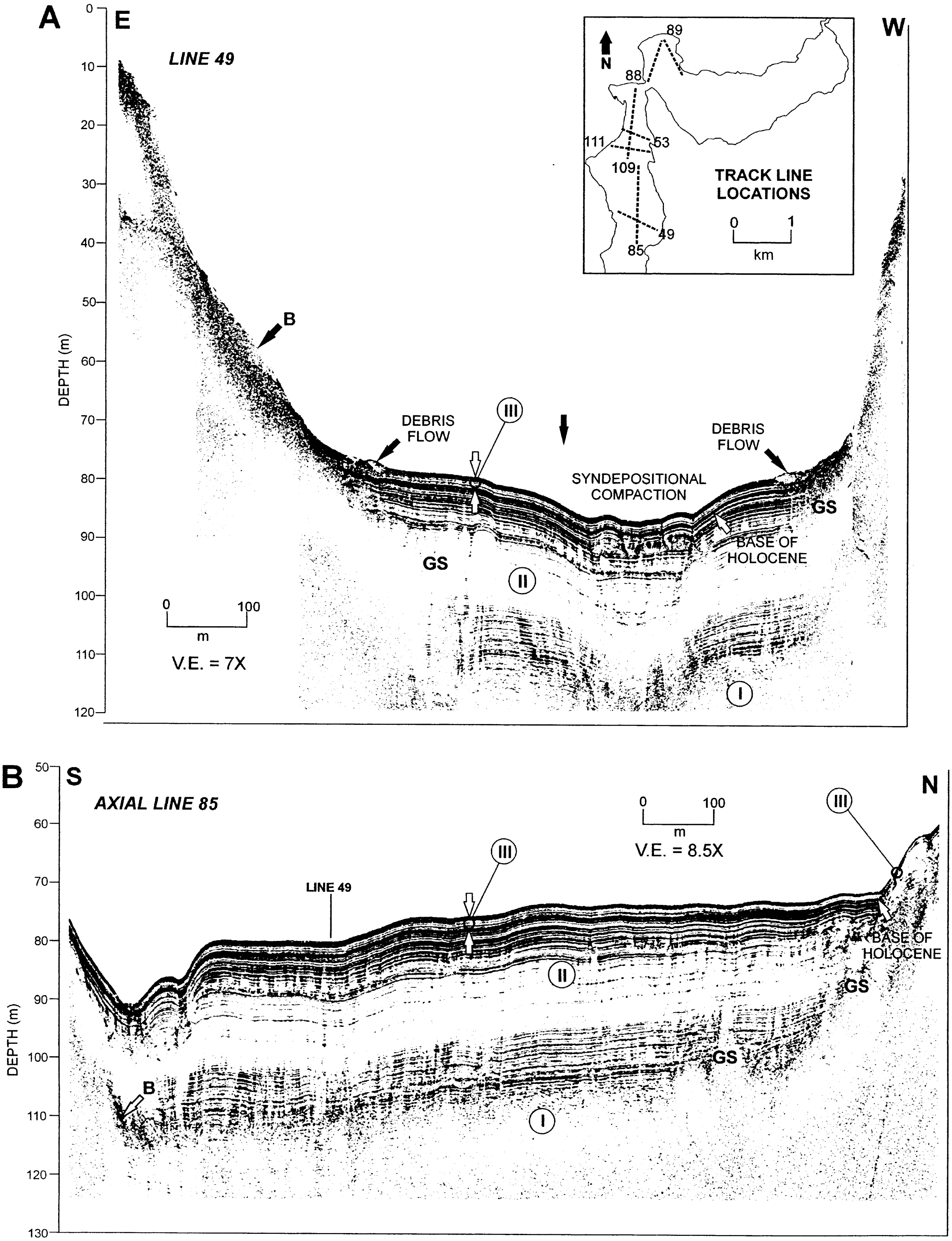
6.1. SSS I

This is the oldest sedimentary unit that can be recognised below the Waterton lakes. The succession is characterised by discontinuous reflectors and, on land-based seismic transects, by relatively high interval velocities of between 1750 and 2100 m/s. This suggests the presence of coarse-grained, poorly stratified and well-compacted sediment such as coarse gravel, till or morainal debris typically found at the margins of valley glaciers. The geometry and range of thickness of SSS I (10 to at least 30 m) do not, unfortunately, provide any additional clues and thus, the sedimentology and origin of this succession cannot be identified. Such sediments are only preserved in a deep bedrock basin between reigels R2 and R3 within Upper Waterton Lake (Fig. 8) and in Middle Waterton Lake in the lee of the bedrock reigel at the Bosporus (Fig. 14). Again, however, direct correlation of strata identified as SSS I in Upper and Middle Waterton lakes cannot be demonstrated.

6.2. SSS II

Seismic facies within succession II are characterised by very closely spaced continuous reflectors, and the succession is present below most of Middle and Upper Waterton lakes (Figs. 8 and 12). A most important characteristic is that such reflectors can be traced over large areas of the basins thereby recording quasi-basin-wide events. By comparison with other published seismic profiles SSS II can be identified as repetitively bedded and rhythmically laminated (‘varved’?) silty clays (Hsu and Kelts, 1984; Mullins and Eyles, 1996). Given the basin-wide occurrence of reflectors, such sediments are most likely to have been deposited by underflows (quasi-continuous turbidity currents) or discrete (episodic) turbidity currents released from the fronts of glacier-fed fan-deltas (Fulton, 1965; Ashley, 1975; Hsu and Kelts, 1984; Eyles and Eyles, 1992). Such facies dominate the lateglacial fills of many glaciated lake basins (Finckh et al., 1984; Mullins and Eyles, 1996) and are well-described from outcrops in the Cordillera of western Canada (e.g., Fulton, 1965) (Fig. 16).

Lateglacial glaciolacustrine successions typically show well-defined upward thinning/fining trends composed internally of lowermost beds of silt and fine sand several metres thick, to overlying laminated facies (<1 cm thick). Such fining-up sequences (variably named ‘packets’, ‘bundles’, ‘microsequences’ and ‘microcycles’) are common in fine-grained turbidite successions; their origin has been extensively discussed by Piper and Stow (1991). Within glaciolacustrine successions, such trends typically result from waning sediment supply and increasing distance from the sediment sources (i.e. ice) during regional deglaciation and glacier retreat (e.g., Fulton, 1965; Eyles and Clague, 1991). Repetition of such sequences upward in SSS II (Figs. 8–10) could reflect variation in sediment supply created either as a result of the progressive deglaciation of different tributary valleys, outburst floods from ice-dammed lakes and/or fluctuations in lake water depths (e.g.,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LINE 49
DEPTH (m)
TRACK LINE
LOCATIONS
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89
88
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53
109
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85
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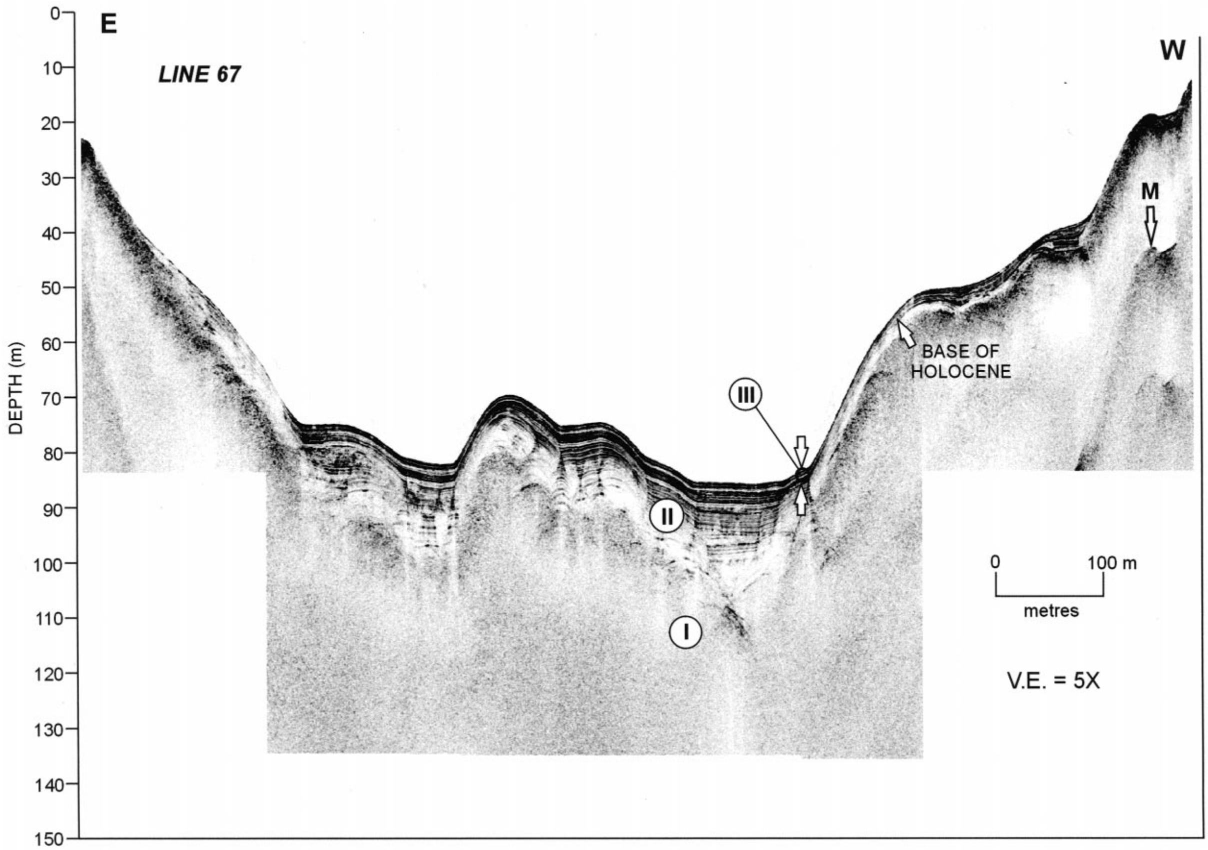
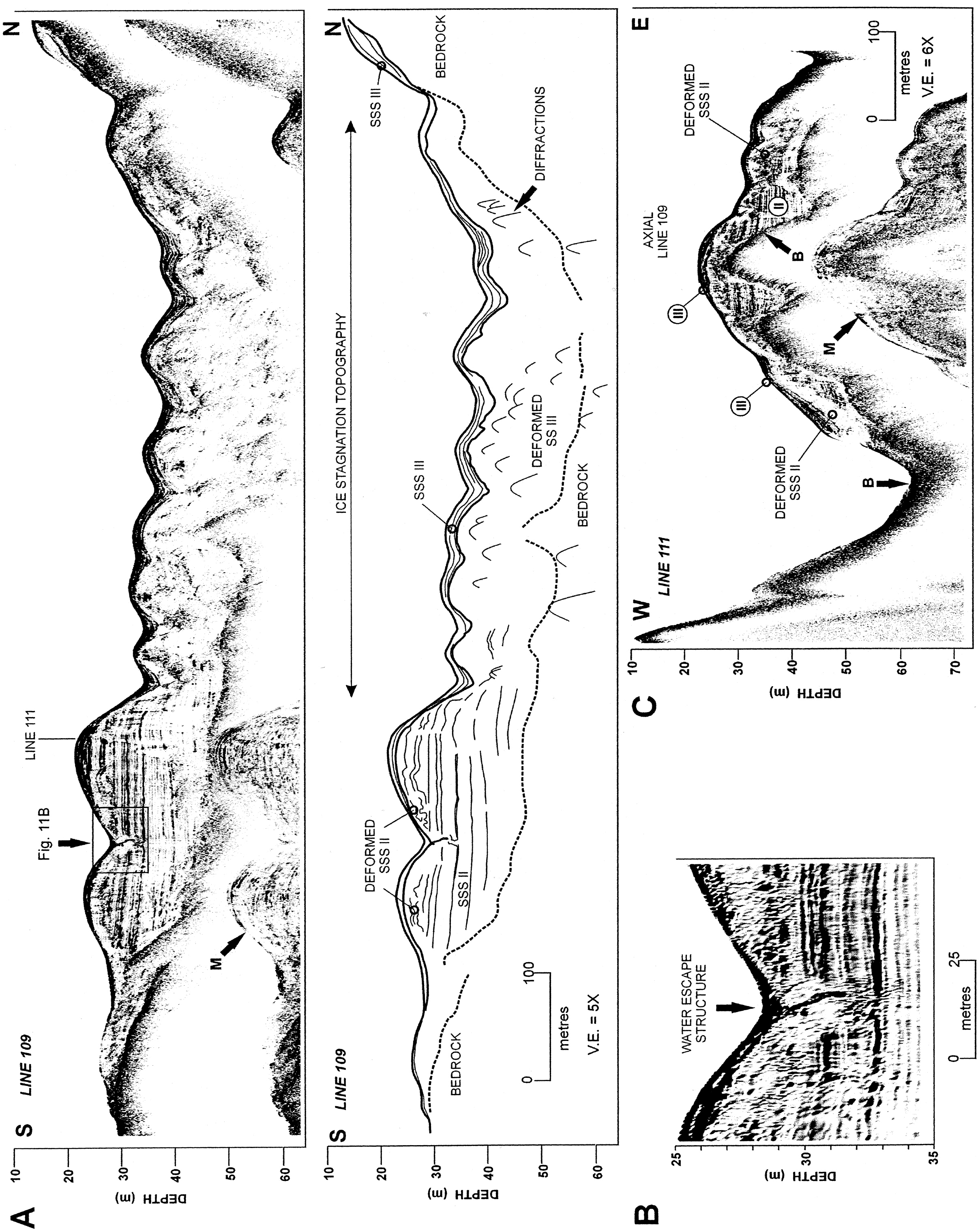


Fig. 10. Crossing sonar profile from North basin of Upper Waterton Lake (Fig. 6) collected using a SB-216S tow vehicle (Fig. 5B). *VE* = vertical exaggeration. Note closely spaced faults produced by differential compaction.

Fulton, 1965; Shaw, 1975). Other possible controls include channel switching and the migration of fan-delta lobes and associated turbidite flow pathways (Piper and Stow, 1991).

The hummocky topography developed on SSS II at the far northern end of Upper Waterton Lake (Figs. 8, 11 and 15) is interpreted as the product of the melt of ice blocks buried within sediment (e.g., Larocque, 1985). This area of the lake floor lies close to kame terraces along the northwest margin of the Waterton Valley that show large dead-ice depressions ('kettle lakes') in glaciofluvial gravels (Linnet Lake, Lonesome Lake; Figs. 2 and 5A). The chaotic and transparent seismo-facies that are closely associated with collapsed dead-ice topography in Upper and Middle Waterton lakes (Figs. 11, 12 and 15) are interpreted as laminated sediments that were homogenized during episodes of downslope mass flow triggered by the melt of buried ice blocks. Similarly, it can be argued that sediment collapse and downslope slumping into deeper water was responsible for downbasin deposition of thick (up to 5 m) beds of acoustically transparent, reflection-free seismo-facies within SSS II (Figs. 8, 9 and 13). In Middle

Fig. 9. Sonar profiles across (A) and along (B) the thick basin fill between reigels R2 and R1 in North basin of Upper Waterton Lake using a SB-216S tow-vehicle (Fig. 5B). Profiles show three seismic-stratigraphic successions (SSS I to III) identified in this study. Note intervals of massive seismo-facies within SSS II likely resulting from downslope mass flow accompanying melt of ice buried at northern end of the basin (Figs. 11 and 15). *VE* = vertical exaggeration.


A
B
C
LINE 109
LINE 111
AXIAL LINE 109
S
N
W
E
DEPTH (m)
Fig. 11B
M
B
ICE STAGNATION TOPOGRAPHY
DIFFRACTIONS
BEDROCK
SSS III
SSS II
DEFORMED SSS II
DEFORMED SS III
WATER ESCAPE STRUCTURE
metres
V.E. = 5X
V.E. = 6X

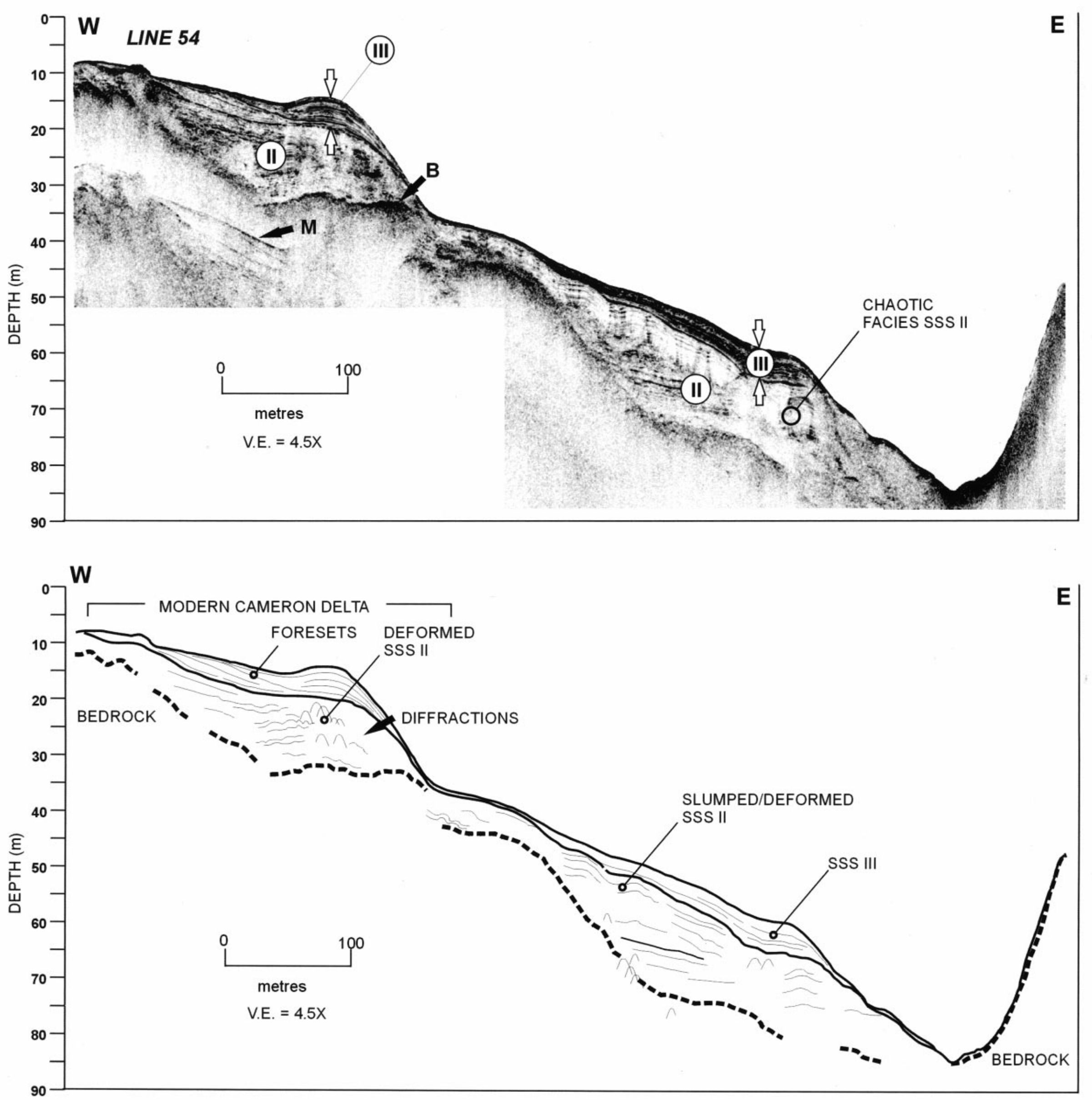
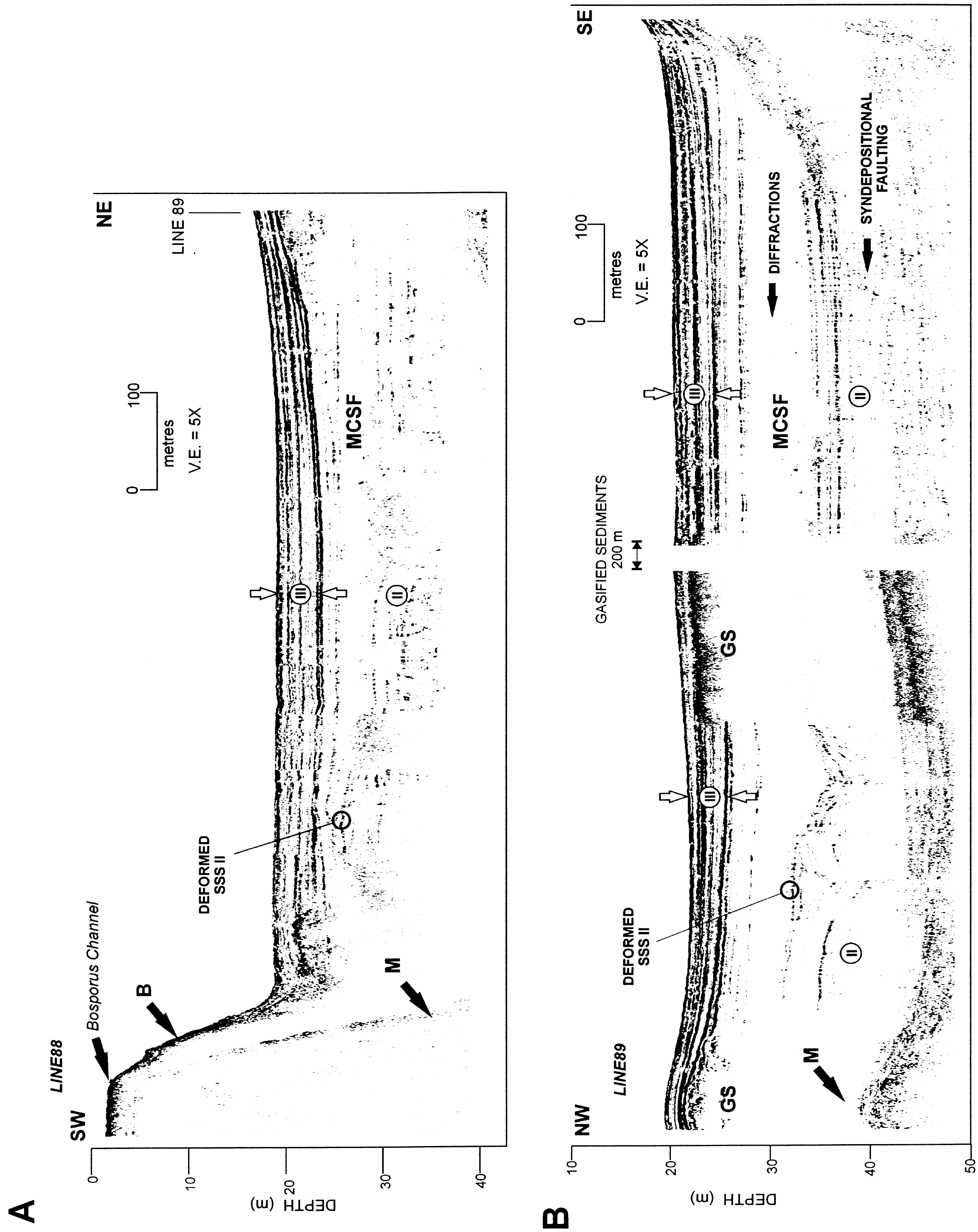


Fig. 12. Offshore sonar profile oriented perpendicular to front of modern Cameron Creek fan-delta in northern Upper Waterton Lake (Fig. 6) collected with SB-216S tow vehicle. Strata of SSS II show deformation resulting from downslope collapse. *VE* = vertical exaggeration.

Fig. 11. (A, B, C) Sonar profiles across hummocky lake floor near northern end of Upper Waterton Lake collected with SB-512 tow vehicle (Fig. 5B and Fig. 6). Hummocky topography results from postdepositional collapse of sediment (SSS II) over dead ice and is shown in more detail in Fig. 15. Chaotic reflectors below hummocks result from homogenisation of sediment during collapse. Near-vertical structure in (B) is interpreted as a water-escape structure. Dark reflector package that drapes hummocky topography is Holocene sediment (SSS III).


A
B
SW
NE
LINE88
LINE 89
Bosporus Channel
B
M
DEFORMED SSS II
III
II
MCSF
0
100
metres
V.E. = 5X
DEPTH (m)
0
10
20
30
40
NW
SE
LINE89
GS
GASIFIED SEDIMENTS 200 m
DIFFRACTIONS
SYNDEPOSITIONAL FAULTING
50

Waterton Lake these facies rest directly on collapsed seismo-facies and have a broadly channelled geometry (Fig. 13). The same reflection-free seismo-facies are present in the lateglacial fill of Lake McDonald 35 km south of Waterton Lake in Glacier National Park, Montana and in several of the Finger Lakes of Upper New York State (Mullins et al., 1991; Eyles and Mullins, 1997; Halfman and Herrick, 1998). Their origin has been varyingly related to rapid sedimentation of massive or weakly stratified silts and sands by meltwater outburst floods, downslope mass movement from oversteepened delta fronts, earthquake activity during deglaciation, lake level changes and glacio-isostatic rebound, and downslope collapse of sediment from areas underlain by downwasting dead ice (see discussion in Halfman and Herrick, 1998). Alternatively, the massive reflection-free facies could record episodes of low energy when turbidity currents were weak or absent. Nonetheless, given the burial of ice below facies of SSS II at the northern end of Waterton Lake and the generation of collapsed 'kettled' topography when such ice melted (Figs. 11 and 15), downslope gravitational collapse and sediment gravity flow may be responsible for the massive, reflection-free seismic facies within SSS II. Rapid collapse is possibly suggested by a large-scale vertical structure interpreted as having been formed by water escape (Fig. 13).

In addition to deformation structures and massive seismo-facies, small-scale vertical faults are common in the thicker infills of Upper Waterton Lake (Figs. 8–10). These are interpreted as the result of differential compaction of under-consolidated beds of high porosity over an irregular basal topography (e.g., Williams, 1987).

6.3. SSS III

SSS III forms a thin (<5 m) continuous sediment drape that blankets flat-lying or deformed strata of SSS II (Figs. 8, 11 and 12) and that also passes directly into modern delta foresets of the Cameron fan-delta (Fig. 12). SSS III can be directly correlated with very finely laminated Holocene muds recovered in cores from Upper and Middle Waterton lakes (D.G. Smith, pers. commun., 1998). Coring also identified the presence of Mt. Mazama tephra, dated at 6850 yr BP. This tephra occurs widely in the basal Holocene of cirque lakes in the Waterton area (Luckman and Osborn, 1979; D.G. Smith, pers. commun., 1998) and may account for the prominent basal reflector found at the base of SSS III. The draped form of SSS III together with its local occurrence on bedrock highs suggests deposition of very fine sediment from interflows or overflows rather than by bathymetrically controlled underflows. Small lobate masses of transparent sediment at the foot to steep bedrock slopes (Figs. 6, 8 and 9) are interpreted as the product of downslope slumping or debris flow.

7. Glacial sedimentary history of waterton lake

7.1. Glacial sedimentation

The bulk of the stratigraphic infill of the Waterton lakes consists of seismic facies interpreted as glaciolacustrine silty clays deposited during deglaciation (SSS II). Older deposits, perhaps subglacial ice-proximal sediments such as till, are only present in a sub-basin between reigels in Upper Waterton Lake (SSS I; Fig. 8) and in Middle Waterton Lake in the lee of the bedrock high separating that lake from Upper Waterton Lake (Fig. 14).

Several authors have suggested that large proglacial lakes were trapped in Rocky Mountain valleys by the Laurentide Ice Sheet margin (Dawson, 1890; Horberg, 1954; Alley and Harris, 1974). In contrast, recent age dates reported by Little (1998) show that Laurentide ice was retreating from the Waterton area when Cordilleran glaciers reached their maximum extent just before 14,000 yr BP. Lateglacial glacio-

Fig. 13. (A) Sonar profile from Middle Waterton Lake adjacent to Bosporus rock reigel (Fig. 6) and Blakiston fan-delta. Profile shows flat lake floor and underlying seismic-stratigraphic successions (SSS II and III). Note massive chaotic seismo-facies (*MCSF*) resting on strata of SSS II deformed by melt of buried ice; reflection-free seismo-facies may record downslope mass flow triggered by collapse over melting ice and may be equivalent to thinner downbasin facies south of the Bosporus (Fig. 9). *VE* = vertical exaggeration. *M* = Multiple. (B) Sonar profile parallel to front of Blakiston Fan and perpendicular to profile A (above) in Middle Waterton Lake showing channelled form of chaotic seismo-facies (*MCSF*) resting on deformed facies of SSS II.

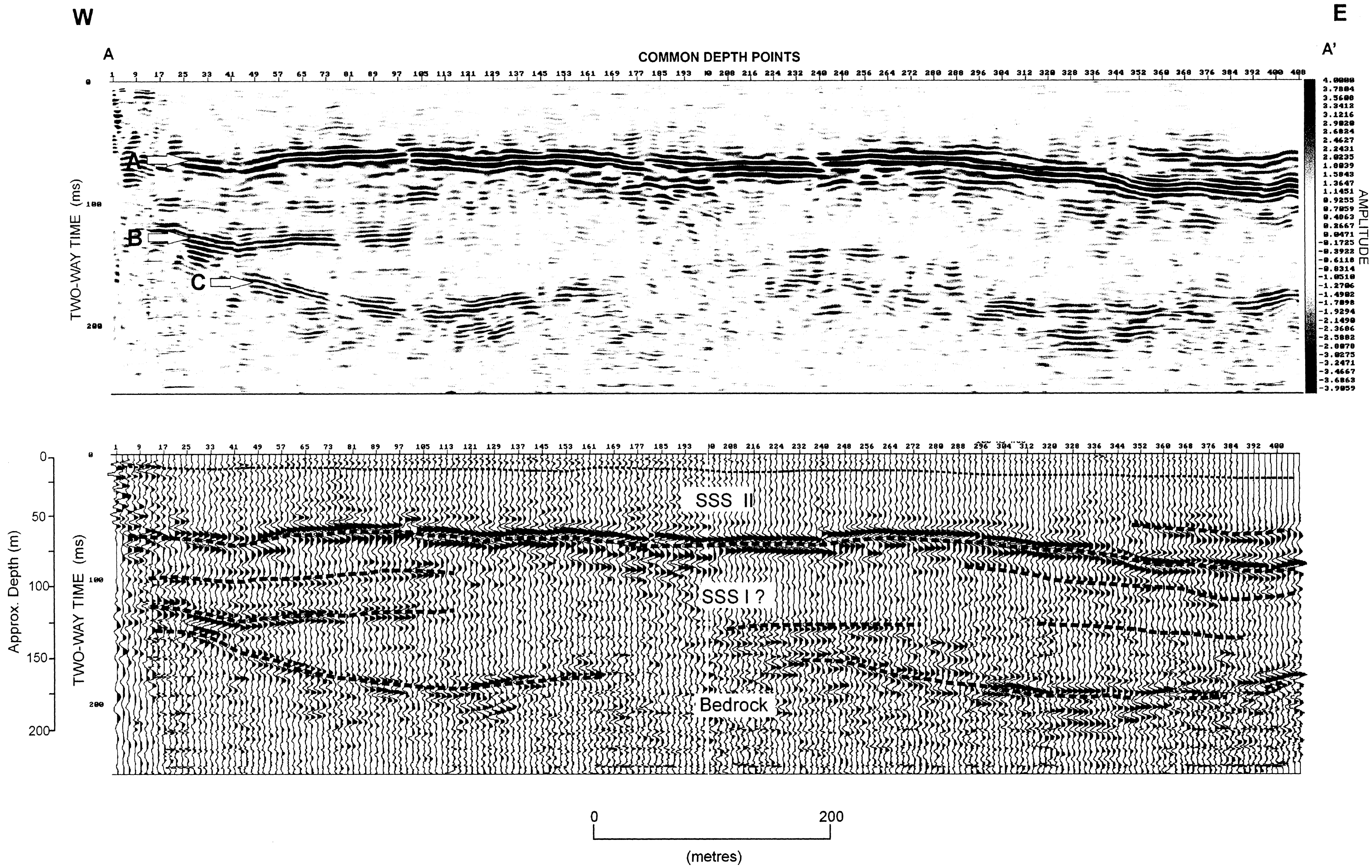


Fig. 14. Multi-channel land-based seismic profile collected from lower portion of Blakiston Creek fan-delta (Figs. 4 and 6).

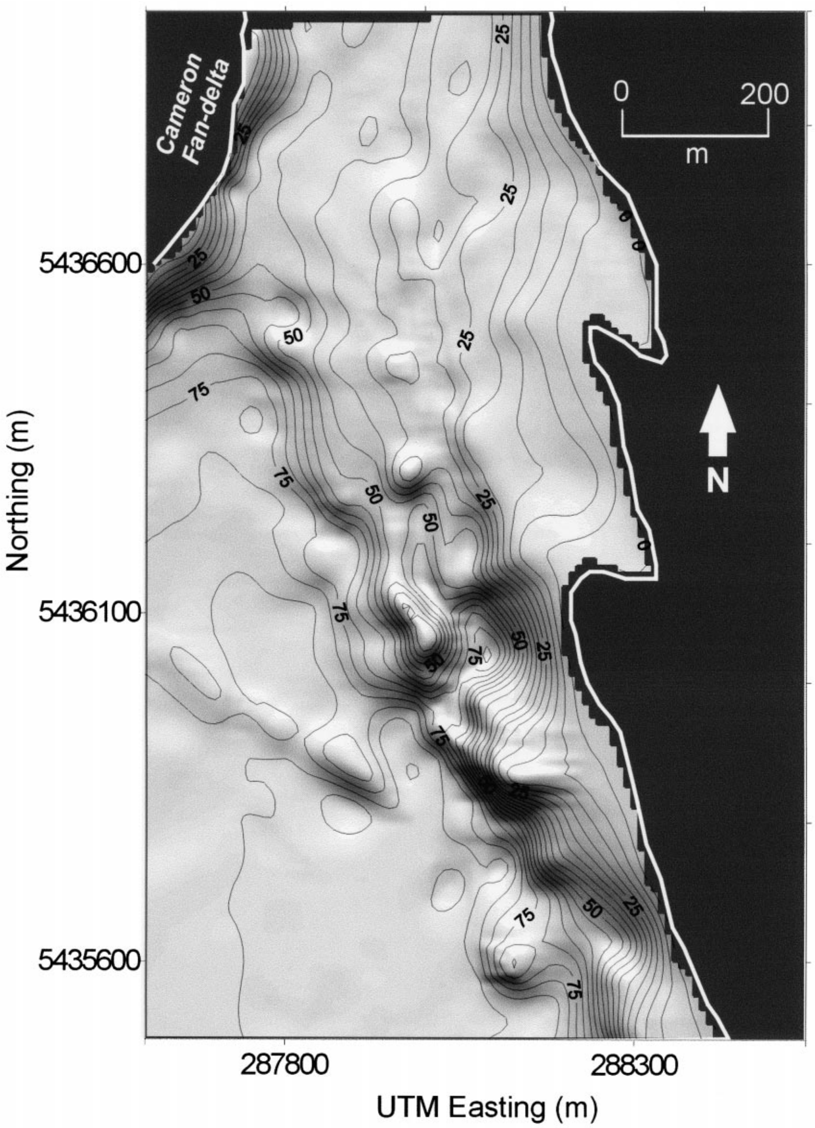


Fig. 15. Hummocky lake floor topography at the northern end of Upper Waterton Lake resulting from collapse of glaciolacustrine sediment of SSS II deposited over dead ice (see text and Fig. 11). Topography has been smoothed by Holocene sediment cover (SSS III).

lacustrine sediments correlative with SSS II occur downvalley of Lower Waterton Lake where they onlap subglacially deposited landforms (Fig. 3A). Glaciolacustrine strata are present up to elevations of 1340 masl which is the same elevation as that of the upper surface of kame terraces preserved along the northwestern valleyside of Waterton Valley between the Upper and Middle lakes (Fig. 3A). Kame terraces are remnants of a large lateglacial fan-delta built at the mouth of Blakiston Creek (Harrison, 1976) that was likely the source of postglacial lacustrine sediment to the Upper and Middle Waterton lakes. Correspondingly, palaeodepositional surfaces within SSS II in the North basin of Upper Waterton Lake appear to dip south from the Bosporus (Fig. 8). Seismo-facies and reflector geometries typical of proximal coarse-grained fan-deltaic sediments (e.g., Rossi and Rogledi, 1987; Lonne, 1993, 1995;

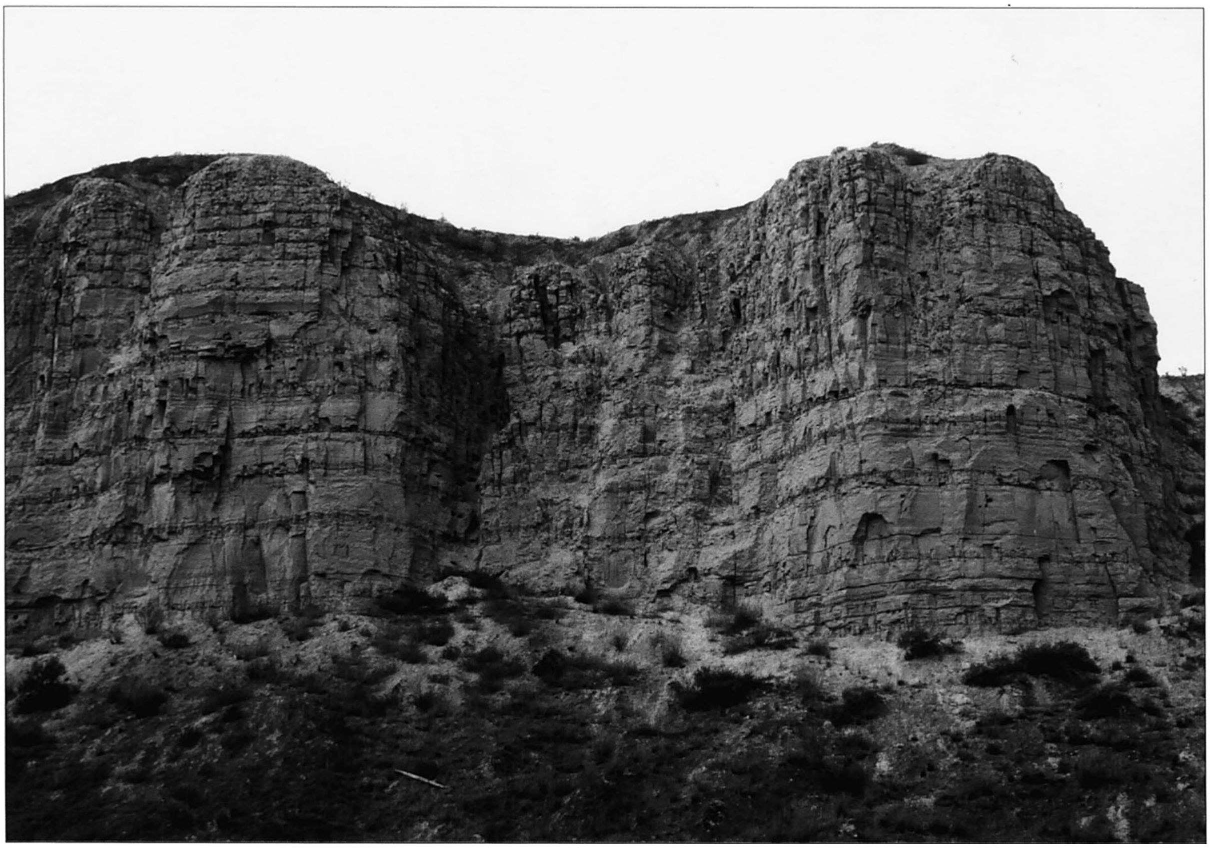


Fig. 16. 15 m high outcrop of rhythmically bedded (varved) lateglacial silts exposed on western margin of Shuswap Lake, British Columbia (see Fulton, 1965). Note thinning and fining produced by waning sediment supply and increasing distance during glacier retreat.

Back et al., 1998) cannot be recognised on our sonar data but glacier-fed fan-deltas at the mouth of Blakiston and Cameron creeks were likely the principal sources of fine-grained glaciolacustrine sediments (SSS II) in the Upper and Middle Waterton lakes. In contrast, the upper Waterton Valley was the source of sediment in the South basin of Upper Waterton Lake as recorded by the northerly-sloping palaeodepositional surfaces within SS II and abrupt changes in sediment thickness either side of reigels (Fig. 8).

Kettle lakes (Linnet Lake, Lonesome Lake) near the mouth of Blakiston Creek (Fig. 2) record lateglacial burial and melt of ice and occur very close to where subaqueous dead-ice topography occurs on SS II (Figs. 8 and 15). Burial of dead-ice blocks in this area of Waterton Valley was likely promoted by rapid progradation of the fan-deltas during deglaciation. The prominent bedrock reigel that separates modern day the Upper from the Middle Waterton Lake (Fig. 2) may have caused local ice stagnation by severing the retreating and thinning glacier margin, thereby stranding dead-ice blocks (e.g., Fleisher, 1986). Harrison (1976) suggested that Middle Waterton Lake occupied a single large ice-collapse depression but the limited extent of deformation within SSS II below the lake (Figs. 8 and 13) is not consistent with this model and suggests only local trapping of dead-ice blocks.

Waterton Glacier reached its maximum extent just before 14,000 yr BP (Little, 1998) and most of Waterton Valley was ice free by 12,000 yr BP with extensive forest cover by 10,000 yr BP (Osborn, 1985). The absence of identifiable ice-contact morainal bank deposits along the basin floor together with the occurrence of SSS II throughout the length of the Upper Waterton Lake basin suggest rapid evacuation of the lake basin by a calving Waterton Glacier. The difference in elevation between the uppermost glaciolacustrine sediment exposed in Waterton Valley (1341 masl) and the basin floor below SS II in Waterton Lake (1149 masl) suggests that lateglacial water depths approached 200 m; in contrast, Harrison (1976) suggested that ice thickness during the glacial maximum was no more than 400 m.

7.2. Holocene sedimentation

Postglacial sediment supply to the Waterton lakes has been very limited given the restricted thickness (<5 m) of Holocene sediment (SSS III). The drape-like geometry of these sediments suggests slow pelagic deposition of very fine-grained suspended sediment from dilute interflows or overflows. Essentially, the Holocene history of these basins can be characterized as 'sediment-starved'. Starvation has been promoted by low amounts of orographic precipitation created by the location of the Waterton area within the rain-shadow zone east of the Rocky Mountains. Crude estimates of annual accumulation rates, based on the thickness of SSS III and elapsed time since deglaciation, range between 0.3 to 0.5 mm/a. These values can be contrasted with much higher rates obtaining in wetter parts of the Rocky Mountains such as 1–6 mm/a in Lake Louise (Leonard, 1985) and 1 mm/a in Hector Lake (Leonard, 1986). In this regard, it is significant that the Waterton area lacks any geomorphic evidence (e.g., moraines) of glacier re-expansion (Neoglaciation) during the Holocene (Osborn, 1985), also reflecting a lack of precipitation. Consequently, renewed glacial erosion and enhanced meltwater and sediment supply to lake basins, such as recorded in lake sediments elsewhere in the Rocky Mountains (Leonard, 1986), has not been a feature of the Holocene history of the Waterton lakes.

Bedrock strata across the Waterton drainage basin are dominated by resistant dolostones, quartzites and silicified argillites. Modern rivers entering Upper Waterton Lake (Cameron Creek, Waterton River) transport very little fine-grained suspended sediment and there are no significant sources of sediment from the valley sides. It is likely that, outside extreme flood events, underflow deposits are not being deposited in Upper Waterton Lake. Gravelly fans at the mouths of Street, Hell-Roaring and Boundary creeks (Fig. 2) are limited to bedrock benches along the steep valley sides and have no downslope subaqueous delta component on seismic profiles.

At the present day, only Middle Waterton Lake has a significant sediment input from the large fan-deltas at the mouths of Blakiston and Sofa creeks (Fig. 4). The progradation of these fan-deltas reflects erosion and reworking of glacial sediment upvalley. The growth of these fan-deltas has not, apparently, resulted in a thicker Holocene section in Middle Waterton Lake likely because of shallow water depths and the inability to accommodate sediment; erosional benches at 5 m below modern lake level indicate a lower lake level in the recent past. It is likely that water depths in Middle Waterton Lake are rising in the long term in response to fan progradation and aggradation in the area of the Dardanelles, thereby damming the Waterton River (Fig. 2).

8. Conclusions

Land-based multi-channel seismic data, together with lake-based sonar seismic reflection profiling, have identified the form of the bedrock basins and stratigraphic infill of Waterton Lake (Upper and Middle) in the southern Rocky Mountains of Alberta and Montana. The fill is dominated by thick (up to 50 m) lateglacial deepwater glaciolacustrine deposits (seismic stratigraphic succession II) that is in turn draped by a relatively thin (<5 m) succession of Holocene pelagic sediment (succession III). The fill of the Waterton lakes is contained in several sub-basins defined by prominent rock steps (reigels). Older strata of possible ice-contact origin (till/outwash; seismic stratigraphic succession I) are not widely preserved suggesting the lake basins were largely cleared of sediment during glacier expansion and backfilled from glacier-fed fan-deltas during deglaciation.

This stratigraphic history of Waterton Lake is similar to that recognised for many other 'open-system deep glacial/interglacial lake basins' where a thick lateglacial glaciolacustrine fill, deposited during deglaciation, is overlain by fine-grained Holocene sediment (Glenn and Kelts, 1991) and where pre-existing sediment was removed by glacier advance (Mullins and Eyles, 1996; Eyles and Mullins, 1997). Holocene sediments in Waterton Lake are, however, unusually thin compared with other basins (e.g., Eyles et al., 1998; Halfman and Herrick, 1998), reflecting the 'rain shadow' location of the basin which prohibited renewed Neoglacial expansion of glaciers and any enhanced sediment supply to Waterton Lake.

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