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Geological Association of Canada
c/o Department of Earth Sciences
Memorial University of Newfoundland
St. John's NL Canada A1B 3X5
Tel: (709) 864-7660
Fax: (709) 864-2532
gacpub@mun.ca
gac@mun.ca
www.gac.ca

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Cover Image: This striking image, taken on April 5, 2004, shows the Great Lakes in springtime, with much snow cover remaining in Canada. These iconic water bodies sit at the interface between climate zones in North America, and are highly susceptible to shifts in conditions. Image comes from the moderate resolution imaging spectroradiometer (MODIS). The image is from the NASA Visible Earth Program.

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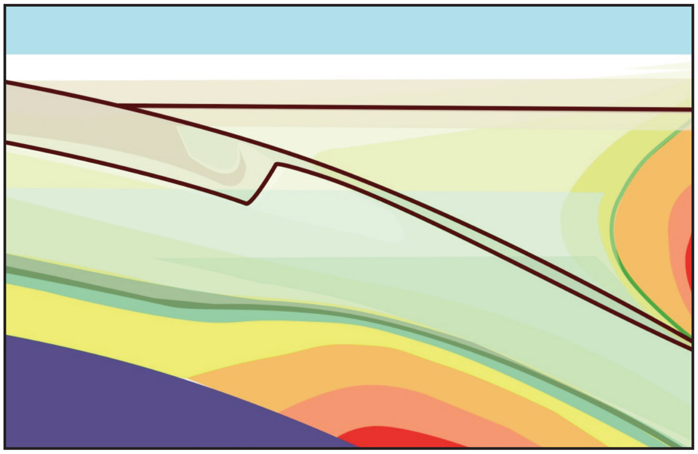
ANDREW HYNES SERIES: TECTONIC PROCESSES



Magmatism and Extension in the Foreland and Near-Trench Region of Collisional and Convergent Tectonic Systems

Adam Schoonmaker[1], **William S.F. Kidd**[2] **and Tristan Ashcroft**[3]

[1]Utica College, 1600 Burrstone Road,
Utica, New York, 13502, USA
E-mail: adschoon@utica.edu

[2]University at Albany, 1400 Washington Avenue,
Albany, New York, 12222, USA

[3]Ursinus College, 601 East Main Street,
Collegeville, Pennsylvania, 19426, USA

SUMMARY

Foreland magmatism occurs in the lower plate during arc–continent or continent–continent collision, although it is uncommon. Ancient examples are recognized by a stratigraphic section into which mafic lavas and/or shallow sills are emplaced at a level at the top of a passive margin cover sequence, or within the overlying deeper water deposits that include mudrocks and flysch-type turbidites. Extensional structures associated with the emplacement of the volcanic rocks may develop slightly prior to or contemporaneous with the arrival of the approaching thrust front. We have selected twelve examples of magmatism in collisional forelands, modern and ancient, and have compared the tectonic associations of the magmatism with the magmatic geochemistry.

Foreland magmatic settings fall into two strikingly distinct geochemical groups: a more enriched alkaline group (Rhine-type) and a more heterogeneous tholeiitic group (Maine-type) that may show traces of prior subduction processes. In the examples where the contemporaneous extensional structures are known, faults and basins develop parallel to the thrust front for the tholeiitic group and have oblique orientations, in several cases at a high angle to the thrust front, for the alkaline group. The geochemical results are quite sufficiently distinct to permit discrimination of these two foreland magmatic rock suites from each other in ancient examples where the foreland setting is clear from geological evidence. However, magmatic products of the same range of compositions can be generated in other tectonic environments (rifts, back-arc basins), so the geochemical characteristics alone are insufficient to identify a foreland basin setting.

The alkaline Rhine-type group formed primarily in response to localized upwelling convective activity from the sub-asthenospheric mantle beneath the lower plate during collision while the tholeiitic Maine-type group formed primarily in response to melting of subcontinental asthenospheric mantle during extension of the lower plate by slab pull, and resulting lithospheric detachment. It is possible that there has been a long-term secular decrease in the occurrence of the Maine-type foreland magmatism since the early Proterozoic.

RÉSUMÉ

Bien que peu fréquent, il arrive qu'un magmatisme d'avant-pays se produise dans la plaque inférieure durant une collision arc-continent ou continent-continent. Des exemples anciens ont été décrits dans une coupe stratigraphique renfermant des laves mafiques et/ou des filons-couches au haut d'une séquence de couverture de marge passive, ou au sein de dépôts de plus grandes profondeurs comme des boues ou des turbidites de type flysch. Des structures d'étirement associées à la mise en place des roches volcaniques peuvent se développer un peu avant ou en même temps que l'arrivée du front de chevauchement. Nous avons choisi douze exemples de magmatisme au sein d'avant-pays de collision, modernes et anciens, et nous avons comparé les associations tectoniques du magmatisme avec la géochimie magmatique.

Les configurations magmatiques d'avant-pays se divisent en deux groupes géochimiques très différents : un groupe alcalin plus enrichi (type-Rhin), et un groupe tholéiitique plus

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Geoscience Canada, v. 43, http://www.dx.doi.org/10.12789/geocanj.2016.43.100 pages 159–178

hétérogène (type-Maine) et qui peut montrer des traces de précédentes activités de subduction. Dans les exemples où les structures d'étirement contemporaines sont connues, les failles et les bassins se développent parallèlement au front de chevauchement pour le groupe tholéiitique, alors que leurs orientations sont obliques, voire à angles aigus au front de chevauchement pour le groupe alcalin. Les résultats géochimiques sont suffisamment distincts pour permettre de distinguer ces deux suites de roches magmatiques dans les exemples anciens où la configuration d'avant-pays est évidente de par sa géologie. Cependant, des produits magmatiques de même type compositionnel peuvent advenir dans d'autres environnements tectoniques (fosses, bassins d'arrière-arc), et donc, la caractérisation géochimique seule ne permet pas de distinguer une configuration de bassin d'avant-pays.

Le groupe alcalin de type-Rhin s'est principalement formé en réponse à une activité d'éruption de convection issue du manteau sous-asthénosphérique sous la plaque inférieure durant la collision, alors que le groupe tholéiitique de type-Maine s'est formé principalement en réaction à la fusion du manteau sous-continental asthénosphérique durant l'extension de la plaque inférieure par étirement de la plaque, et le détachement lithosphérique qui en découle. Depuis le Protérozoïque, est possible qu'il y ait eu une décroissance progressive à long terme des événements magmatiques de type-Maine.

Traduit par le Traducteur

INTRODUCTION

Foreland magmatism that occurs in the outer trench slope of the lower plate during plate convergence is relatively uncommon. In several cases, this occurs when a continental margin enters the trench slope region and begins to interact with the upper plate, resulting in extension as the subducted oceanic lithosphere pulls on the continental margin lithosphere, and extensional failure and detachment of the attached oceanic lithosphere may occur. This model has been invoked for some occurrences; although a localized convective mantle upwelling can alternatively be used to explain magmatism in some foreland regions. We examine the following magmatic areas of Recent and/or Neogene age in the foreland setting: Rhine Graben (Germany), Karacadağ Volcanic Complex (SE Turkey), Penghu Islands (Taiwan), and 'Petit Spots' (outer Japan trench). In all of these areas the associated extension direction relative to the trench or thrust front is clear. We also examine ancient examples in old orogens of the Piscataquis Belt, Maine (Siluro–Devonian Acadian Orogeny); Starks Knob in New York, Jonestown Volcanics in Pennsylvania, and the Cortlandt Complex in New York, (Ordovician Taconic Orogeny); and the early Proterozoic Morel Sills and Ghost Dykes (Wopmay Orogen), and Molson Dykes and Flaherty Volcanics, (Circum-Ungava Orogen) from the Canadian craton (Table 1). We selected these examples because all are clearly associated spatially and temporally with an orogenic foreland setting, and because contemporaneous extensional structures and their regional orientation relative to the thrust front can be identified for most, and reasonably interpreted for the other (Flaherty Formation) of these occurrences.

This paper briefly describes the geological setting of these twelve modern and ancient examples of foreland magmatism and then examines the geochemical compositions of each, seen in the context of the two geological groups that can be defined from the associated extension direction relative to the trench or thrust front.

BACKGROUND

Foredeep magmatism was first described by Hoffman (1987) as magmatic activity occurring in continental margin stratigraphy immediately preceding, or during the onset of flysch deposition and deformation resulting from active arc-–continent collision. Concurrent foreland basin deposition occurs and overlies passive margin stratigraphic sequences. Flexure occurs in the lower plate as it enters the outer trench slope region of a subduction zone and the continental margin begins to interact with the upper plate during collision (Fig. 1). The slab-pull force caused by sinking of the last subducting oceanic lithosphere (and/or some of the continental mantle lithosphere if it delaminates from the crust) may cause extension of the lithosphere, including the continental part (Schoonmaker et al. 2005) allowing mantle upwelling and magmatism into the lower plate. This process may progress to breakoff of the subducted or delaminated slab, which might trigger, or enhance, the magmatism (e.g. Davies and von Blanckenburg 1995; Cloos et al. 2005). We expand Hoffman's (1987) original description of foreland magmatism to include magmatism occurring in the foreland of a continent in the process of colliding either with an arc or with an upper plate continent, and contemporary magmatism emplaced in the toe of the overriding accretionary complex.

An alternative process was identified by Şengör et al. (1978) for extensional tectonism and associated magmatism in an active orogenic foreland, caused by the regional stress field propagating into the foreland lithosphere from a collisional orogen, with consequent extension perpendicular to the maximum compressive stress orientation. The Cenozoic Rhine Graben situated adjacent to the Western Alps provided the type example for Şengör et al. (1978), and illustrates the localized nature of these features.

These processes have been proposed to explain foreland magmatism in young examples such as the Rhine Basin (Bogaard and Wörner 2003; Jung et al. 2005; Lustrino and Carminati 2007), Karacadağ Volcanic Complex, Eastern Anatolia (Pearce et al. 1990; Keskin 2003; Şengör et al. 2003; Ekici et al. 2012), Penghu Islands, Taiwan (Chung et al. 1994; Wang et al. 2012), 'petit spot' volcanoes of the Pacific plate near the Japan Trench (Hirano 2011) and ancient analogue examples such as the Piscataquis Volcanic Belt, Maine (Schoonmaker et al. 2011) and Starks Knob, New York (Landing et al. 2003), and the Precambrian examples identified by Hoffman (1987).

Alternatively, mantle plumes have been suggested to explain magmatism in the Rhine Basin (Ritter et al. 2001; Keyser et al. 2002; Haase et al. 2004) and Eastern Anatolia (Ershov and Nikishin 2004), but not the other young examples listed here. For the older examples, large igneous province (LIP) plume-head association has been suggested for the

Table 1. Summary of sources of geochemical analyses used for this study.

Location	Formation	Age	# of Analyses	Source
Rhine Graben	Rockeskyllerkopf	Quaternary	53	Shaw and Woodland 2012
	Vogelsberg	Miocene	71	Bogaard and Wörner 2003
	Rhön	26–11 Ma	7	Jung et al. 2013
	Hocheifel	44–34 Ma	35	Jung et al. 2006
East Anatolia	Karacadağ (Siverek phase)	Neogene	27	Ekici et al. 2012
Taconic foreland	Cortlandt Complex	446 ± 2 Ma	9	Bender 1980
	Starks Knob	Upper Ordovician (Trenton)	9	Landing et al. 2003
	Jonestown	Middle Ordovician	25	Lash 1986; Smith and Barnes 1994; Ashcroft 2002
Taiwan	Penghu basalt	Miocene	12	Chung et al. 1995; Wang et al. 2012
Japan outer trench slope	Petit spots	8.5 – 0.5 Ma	7	Hirano et al. 2006
Baffin Island (Rae craton)	Bravo Formation	1923 ± 15 Ma	9	Partin et al. 2014
Maine Acadian	West Branch Volcanics	Late Silurian	12	Fitzgerald 1991; Schoonmaker et al. 2005
Wopmay Foreland	Morel Sills	ca. 1.88 Ga	6	Minifie 2010
	Ghost Dykes	ca. 1.88 Ga	9	Minifie 2010
NW Superior Province	Molson Dykes	ca. 1.88 Ga	33	Heaman et al. 2009; Minifie 2010
Belcher Islands	Flaherty Formation	1960 ± 80 Ma	7	Legault et al. 1994

Canadian Proterozoic examples marginal to the Slave and Superior cratons (Minifie 2010).

FORELAND SETTINGS

We divided the examples discussed below into two groups (Rhine-type vs. Maine-type), based on the regional orientation of the associated extensional structures. In this section we review the evidence for a foreland interpretation and the extensional stress orientation associated with each. Rhine-type foreland magmatism is associated with extensional structural orientations that are oblique to, and in several cases at a high angle to, the adjacent thrust front or trench; Maine-type foreland magmatism is associated with extensional structures oriented parallel to the adjacent thrust front (Fig. 2). Some of the settings described here are modern or recent where the foreland position of magmatism and structural orientation is clear, but for the ancient examples their interpretation as foreland basin magmatism critically depends on the stratigraphic relationship between the volcanic units and continental passive margin sedimentary strata and foreland basin clastic rocks (flysch), as well as to subsequent shortening deformation. In the discussion, two additional examples where clear structural data regarding extensional structure orientation are lacking are reviewed briefly, and a predicted assignment made to one of the groups based on their geochemical compositions. The essential properties of the two groups are summarized in Table 1 and discussed in more detail below.

Rhine-Type Foreland Magmatism and Extensional Structures

Modern or recent examples of Rhine-type foreland magmatism include the eponym Rhine Graben (Germany), Karacadağ Volcanic Complex (SE Turkey), Penghu Islands (Taiwan), and the 'Petit Spots' volcanoes of the Pacific seafloor, east of the Japan Trench; we identify one ancient example, the Cortlandt Complex–Beemerville zone (New York). The geochemical character of the Piling Group in the Proterozoic Trans-Hudson Orogen of Canada suggests that it belongs to this group (see discussion).

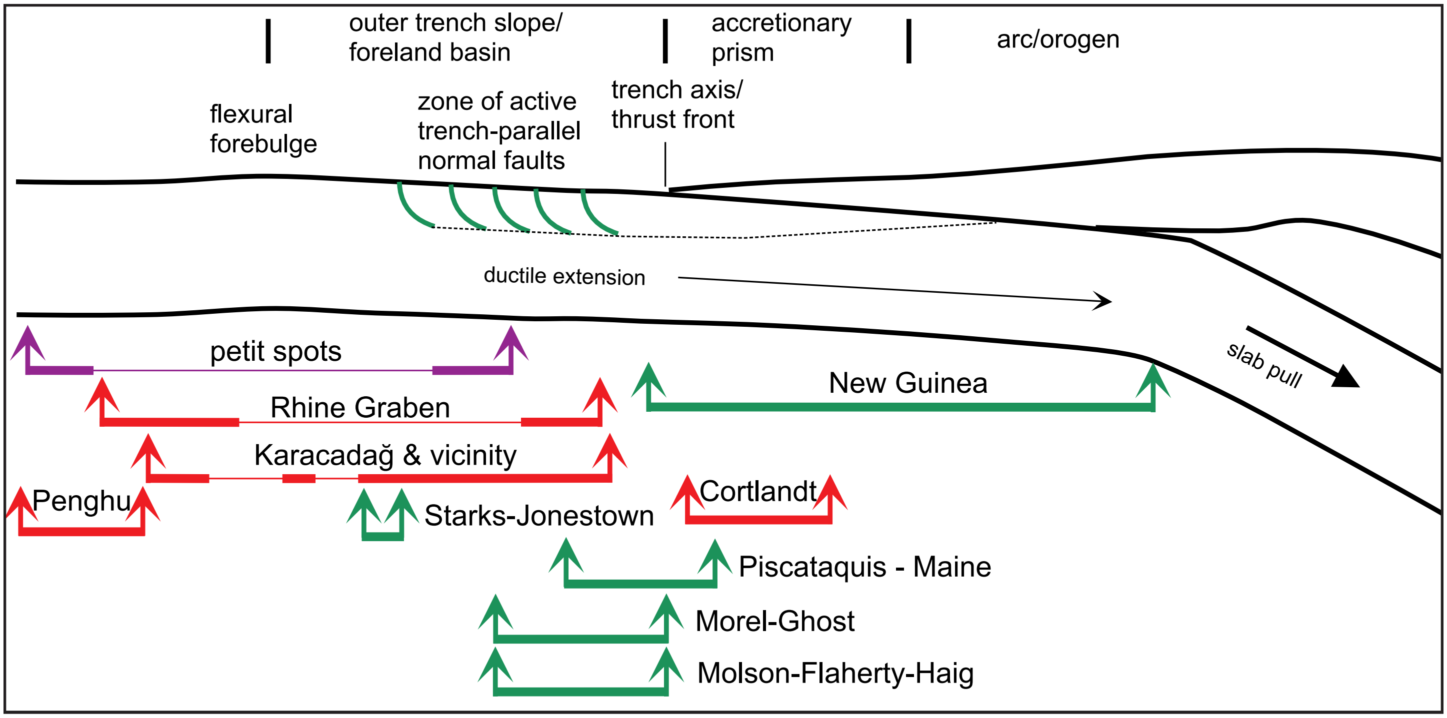

Figure 1. Schematic section of a convergent or collisional tectonic zone. Coloured bars show the observed or estimated relative position and in-line extent of examples used in this paper of foredeep or foreland magmatism at the time of their eruption or intrusion. Positions and extents of pre-Neogene examples based on geological map, stratigraphic, and structural relationships, and stratigraphic and/or isotopic ages (see text for source references). Red and purple: Rhine-type; green: Maine-type. Thicker parts of lines are locations of magmatism. Purple line is for magmatism on oceanic lithosphere; red and green on continental lithosphere.

Rhine Graben (Germany)

Within the European Cenozoic Rift System, the Upper and Lower Rhine basins are associated with significant volcanism of the Central European Volcanic Province (Fig. 3). The longitudinal axes of the Rhine Graben are either oblique (Lower Rhine Basin) or nearly perpendicular (Upper Rhine Basin) to the northern thrust front of the adjacent Alps and the Insubric Line suture to the south. Şengör et al. (1978) were the first to link the main Rhine Graben as a rift structure to the compressional stress orientation induced in the orogenic foreland by the Alpine collision, and to use it as the type example of such structures. The Lower Rhine basin displays evidence for sinistral transtension (Cardozo and Behrmann 2006) but there are numerous normal faults along which significant NE–SW extension has occurred, and earthquake focal mechanisms indicate the current stress field is similarly oriented (Homuth et al. 2014).

Karacadağ Volcanic Complex (SE Turkey)

Karacadağ is a large basaltic shield volcano located in the northernmost Arabian foreland (Fig. 4), where there has been volcanism since the mid-Miocene, although the shield volcano is Pliocene and younger (Ekici et al. 2012, 2014). The longitudinal crest and main fissure eruption source of Mount Karacadağ is oriented close to N–S, nearly perpendicular to the Bitlis suture and the nearby thrust front of the foreland basin in which this magmatism occurs (Şengör and Kidd 1979; Pearce et al. 1990). Furthermore, the N–S oriented Neogene Ackakale Graben located to the southwest suggests the same E–W extension direction. Yürür and Chorowicz (1998) measured structural data in a nearby area (Amanos Range) that indicate a change from N–S contraction to ENE–WSW extension for the most recent fault motions. Ekici et al. (2012) reported eruption of some of the earlier Miocene plateau basalt from fissures on the northern side of the area that are oriented parallel to the nearby thrust front.

Penghu Islands (Taiwan)

The Penghu Islands in the strait west of Taiwan, composed of a series of mafic volcanic flows and shallow sills on the eastern China continental margin (Fig 5), were pointed out by Hoffman (1987) as a likely example of foreland magmatism, based on the age then provided for the volcanic rocks as early Pleistocene or Pliocene. Subsequent work reported consistent K–Ar ages for the volcanics of mid–late Miocene age (16–8 Ma; Juang and Chen 1992; Wang et al. 2012), along with upper middle Miocene marine microfossil ages from interbedded sedimentary layers. Paleostress orientations determined from fracture sets in the volcanics (Angelier et al. 1990) give extensional stress orientations nearly parallel with the current Taiwan thrust front for structures in 16–11 Ma volcanics, and oblique to that thrust front for those in 9–8 Ma volcanics, although the latter orientation is parallel with the present Philippine–Yangtze-Eurasia plate convergence direction across the Manila Trench (shown and referenced on Fig. 5). Dominantly trench-facing ~NNE-striking normal faults, mostly with small displacements and which cut Pliocene and early Pleistocene foredeep strata, have been mapped in the Taiwan Strait up to about

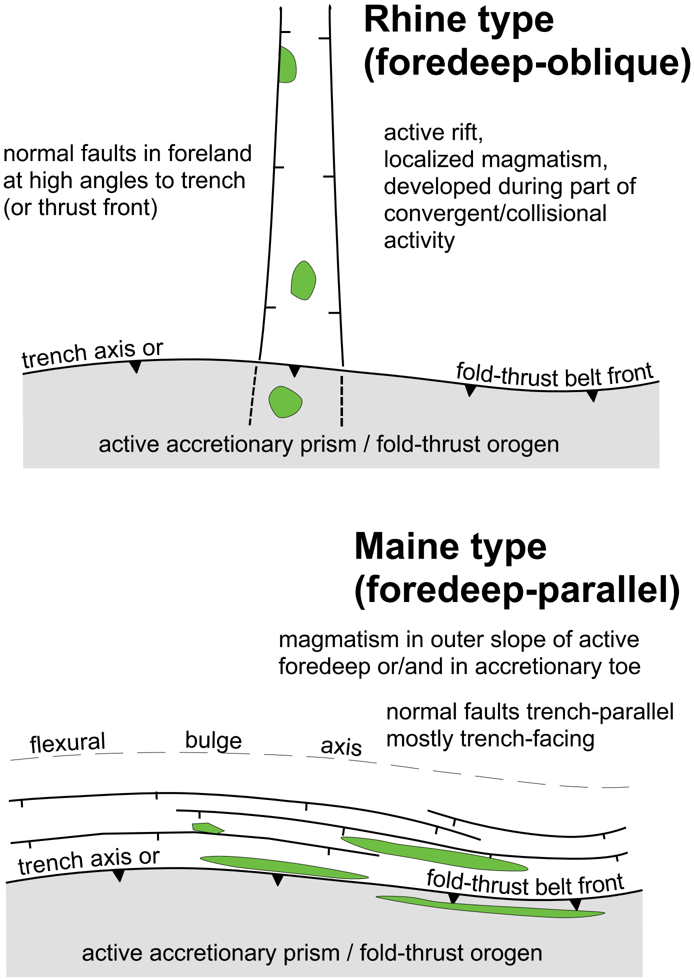

Figure 2. Schematic map-view location and orientation of normal faults and magmatism for Rhine-type compared with Maine-type foreland basins, and their adjacent fold or thrust belts. Normal faults are shown by conventional tick mark symbols on down-thrown sides; green: areas of concurrent magmatism.

100 km west of the active thrust front in Taiwan (Chou and Yu 2002), but no volcanism of this younger age range is known in this area.

'Petit Spots' (NW Pacific Seafloor Adjacent to Japan Trench)

The 'petit spots' are a series of young (ca. 8–0 Ma), small alkaline volcanoes on the Pacific sea floor, east of the Japan Trench (Hirano et al. 2006; Hirano 2011; Fig. 6). The younger ones (estimated by Hirano to be no older than 1 Ma) are in two areas, one (1 on Fig. 6) located on the upper part of the outer trench slope, but the other (2 on Fig. 6) is about 400 km from the trench. The older volcanic rocks (dated as ca. 8–4 Ma) are in the third small group, (3 on Fig. 6) now found close to the trench floor, but which must have been far behind the position of the flexural bulge crest at the time of eruption. Some of the petit spots in the older area (3) form linear chains oriented WNW–ESE (Hirano et al. 2006). The envelope of the area of most of the occurrences in the young group (1) near the trench, and of all the older group (3), are elongated at a high

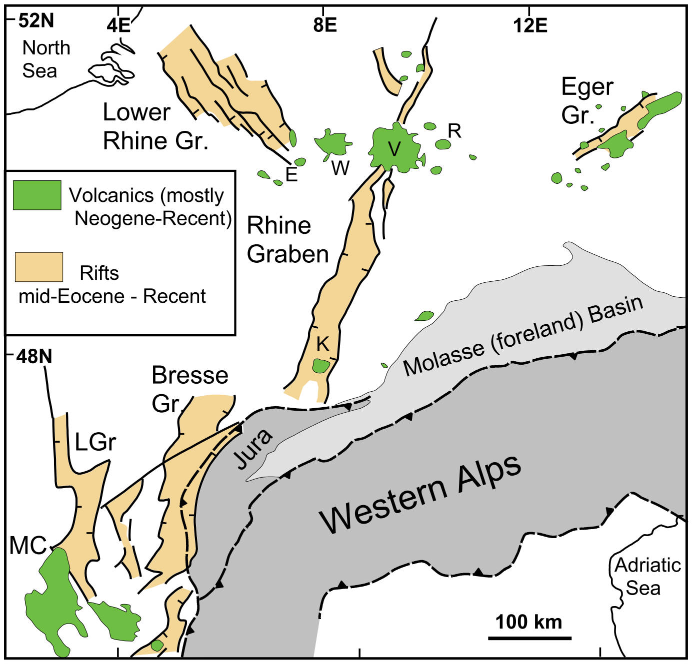

Figure 3. Location of the Rhine Graben and other parts of the European Cenozoic Rift System and magmatism of the Central European Volcanic Province in relation to the western Alps and its northern foreland basin. Map modified from Dèzes et al. (2004). E – Eifel, K – Kaiserstuhl, LGr – Limagne Graben, MC – Massif Central, R – Rhon, W – Westerwald, V – Vogelsburg.

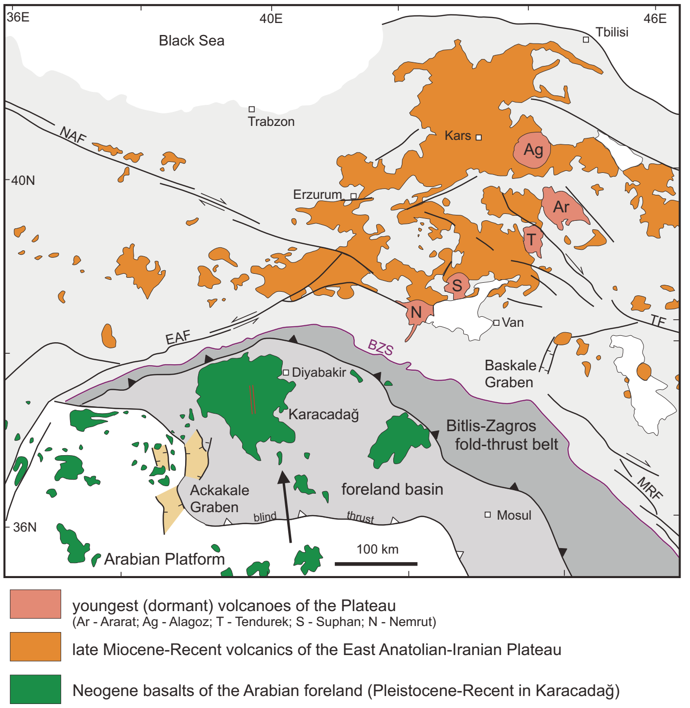

Figure 4. Volcanic rocks of the Eastern Anatolian–Iranian Plateau and adjacent northern Arabian foreland. Red parallel lines in Karacadağ are the summit ridge and eruptive fissure alignment. NAF – North Anatolian Fault, EAF – East Anatolian Fault, BZS – Bitlis–Zagros Suture, TF – Tabriz Fault, MRF – Main Recent Fault. Map modified from Pearce et al. (1990). Black line with arrowhead is direction of Arabian–Eurasian plate motion for 3–0 Ma from MORVEL data (DeMets et al. 2010).

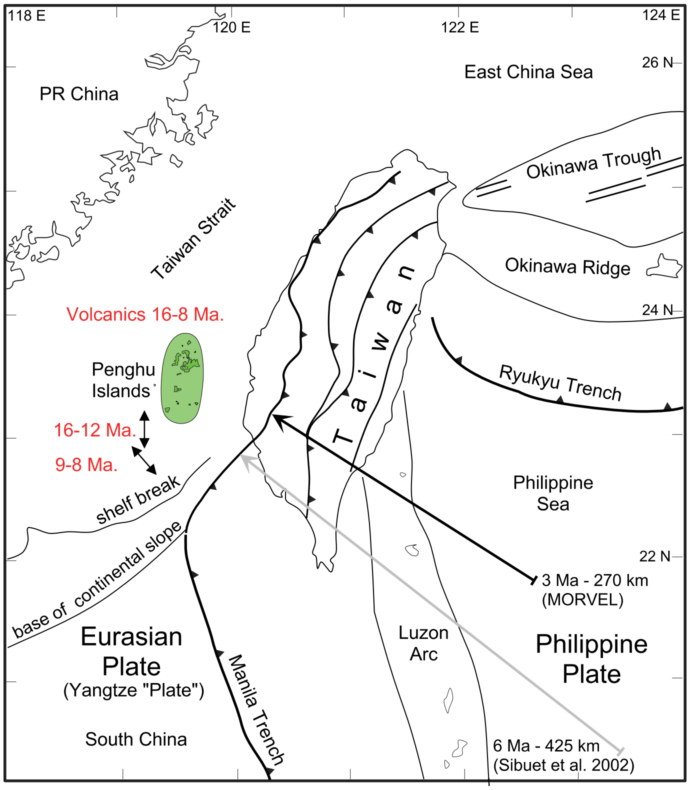

Figure 5. Setting of the Penghu Islands in the Taiwan–East China margin collision. Volcanic age range in Penghu Islands from Juang and Chen (1992). Paleostress extension orientations in Penghu volcanic rocks from Angelier et al. (1990) shown by short double-headed arrows. Map modified from Angelier et al. (1990) and Huang et al. (2006). Single-headed black line with arrow is Philippine–Yangtze plate convergence direction from MORVEL data (DeMets et al. 2010); length of line 270 km for 3 M.y. convergence (rate 90 mm/a). Single-headed grey line with arrow is Philippine–Eurasia plate convergence direction for 8 to 0 Ma, from Sibuet et al. (2002); length of line 425 km for the past 6 M.y. convergence (rate 71 mm/a).

angle to the trench in a similar orientation (Fig. 6), which is also the direction of the NUVEL-1A plate motion vector. Bathymetry and acoustic reflectivity show well-developed trench-parallel normal faulting on the outer trench slope of the Japan and Kurile trenches (Kobayashi et al. 1998). Some of the younger group 1 volcanoes occur within this zone, but their locations show no clear evidence of being controlled by this extension, and those of group 3 are older than and cut by these faults (Hirano 2011). In none of the groups do they appear to be influenced by the old sea floor spreading fabric. While one occurrence (2) is near a large fracture zone, the individual spots in it do not show alignment in chains of this fracture zone orientation, or any other. We think the obliquely oriented overall distribution of these volcanic occurrences, including the younger ones on the outer trench slope, suggest that they belong in the Rhine-type category.

Cortlandt Complex–Beemerville Magmatic Zone (Taconic of New York)

The Cortlandt Complex (ca. 446 Ma) and related zone of dykes leading west to the Beemerville intrusion (Fig. 7) are part of a series of alkaline intrusions forming a zone that cuts at a high angle across the regional Taconic foreland thrust fabric (Bender 1980; Ratcliffe 1981; Domenick and Basu 1982; Bender et al. 1984; Ratcliffe et al. 2012). Dykes within this zone and its overall trend indicate extension approximately NNW–SSE, somewhat oblique, but not at a high angle to the surrounding strike of the Taconic thrust assemblage. This magmatic event and the extensional structures evidenced by the dykes occurred late in the Taconic collisional event (Ratcliffe et al. 2012). It is not known if this zone extends farther west into the Taconic foreland under Silurian and younger cover. In orientation, orogenic timing and geochemistry, this ancient example resembles the younger part of the development of the Rhine Graben.

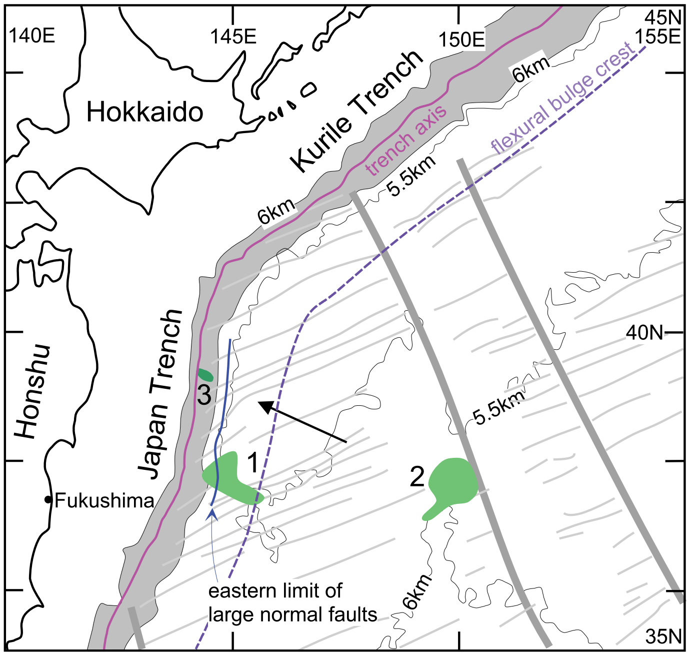

Figure 6. Map of the occurrence of 'petit-spot' volcanism east of the Japan Trench (modified from Hirano et al. (2006), Hirano (2011). Bright green areas (1, 2) are volcanic rocks younger than ca. 1 Ma; small darker green area (3) contains volcanic rocks ca. 8–4 Ma old. Black arrow is NUVEL-1A plate convergence direction. Thin grey lines – Cretaceous spreading magnetic anomalies, thick grey lines – fracture zones, grey shading – Japan Trench below 6 km bathymetric contour.

Maine-Type Foreland Magmatism

We have not identified modern examples of Maine-type foreland magmatism where the magmatism is mostly localized in or immediately below the foreland basin strata, and where the magmatism is dominantly of the Maine-type compositional range. Ancient examples included in this paper are the Piscataquis Volcanic Belt of Maine, Starks Knob and the Jonestown Volcanics of the Taconic Foreland (New York and Pennsylvania, respectively), and the Morel Sills, Ghost Dykes, and Flaherty Volcanics–Haig Sills in the Proterozoic of Canada.

Piscataquis Volcanic Belt (Maine)

The Piscataquis Volcanic Belt, largely exposed in Maine, but extending into New Brunswick and New Hampshire, is latest Silurian–early Devonian in age. Its geographic extent roughly parallels the orogenic fabric of the Acadian Orogeny in this

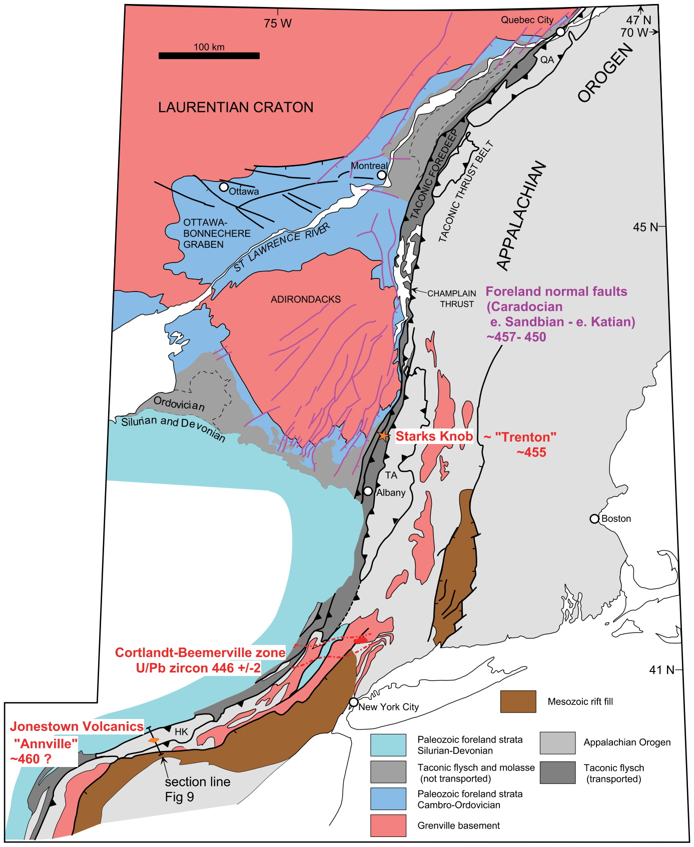

Figure 7. Overview map of the Taconic Laurentian foreland of the northeastern US and adjacent part of Canada, showing the locations of Starks Knob, the Cortlandt–Beemerville magmatic zone, the Jonestown Volcanics, and the Ordovician foreland normal fault system. Taconic allochthons: HK – Hamburg Klippe, QA – Quebec Allochthon, TA – Taconic Allochthon.

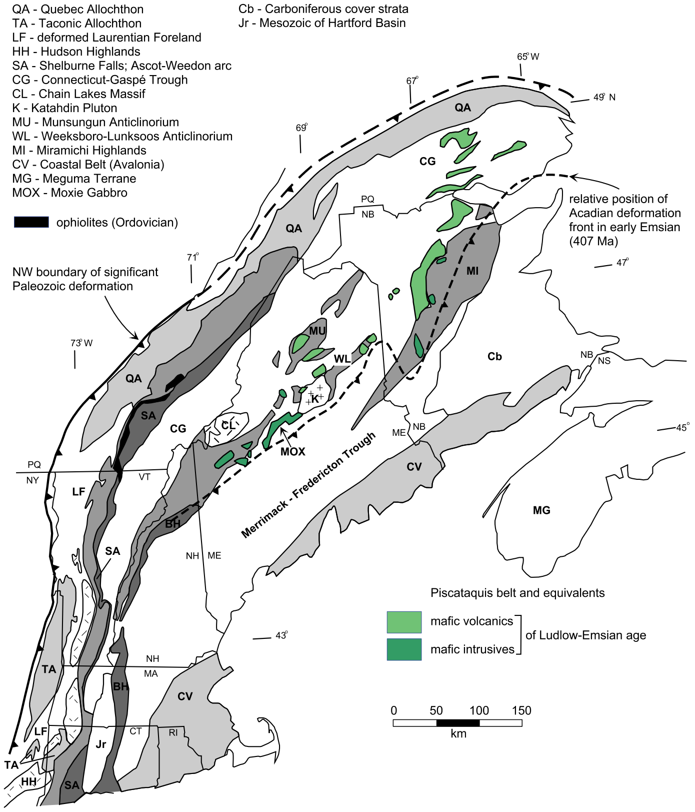

Figure 8. Map of regional elements of the mainland Northern Appalachians showing the setting of the Piscataquis magmatic belt. Adapted from Schoonmaker et al. (2011). Position of the early Emsian Acadian deformation front across Maine is from Bradley et al. (2000), speculatively extrapolated farther NE.

area (Fig. 8). Its petrogenesis has been debated and further information is contained in these references: van Staal et al. (1998, 2009); Eusden et al. (2000); Bradley and Tucker (2002); Murphy and Keppie (2005); and Schoonmaker et al. (2005, 2011). Syn-sedimentary normal faults, which are oriented parallel with slightly younger Acadian thrust fabrics nearby, occur in sedimentary strata just below the volcanic rocks (Schoonmaker et al. 2005; Schoonmaker and Kidd 2013). The dyke-like Moxie Pluton, a major gabbroic body dated at ca. 406 Ma (Bradley et al. 2000), which cuts some of the Acadian thrust fabrics in foreland basin sedimentary rocks, has a similar strike-parallel orientation. The volcanics are within marine strata, and some show pillowed form. Locally subaerial eruption may have occurred (Boucot et al. 1964), but a well-exposed section near the west margin of the Katahdin Pluton (Fig. 8) contains all these volcanics in deeper water clastic rocks deposited just above the Silurian–earliest Devonian shallow marine shelf strata (Schoonmaker et al. 2011).

Starks Knob (New York)

Starks Knob is a small remnant block of pillow lavas interpreted to have been erupted into the outer part of the Laurentian passive margin just before the arrival and collision of the Taconic accretionary thrust complex (Landing et al. 2003). This block was tectonically transported to its present position within the mélange of that accretionary complex (Fig. 7), now lying above the Laurentian foreland of New York State (Landing et al. 2003). The volcanic rocks contain only interstitial limestone, indicating shallow marine eruption; the regional clast association in the mélange is only with the Laurentian passive margin and adjacent continental rise (Kidd et al. 1995), and the fossil age (Landing et al. 2003) is consistent with eruption in the Ordovician just before collision began. Syn-collisional normal faults oriented parallel to the regional Taconic thrust fabric are present in the adjacent foreland and have been interpreted to be related to extension of the lower plate during the Taconic collisional event (Bradley and Kidd 1991).

Jonestown Volcanics (Pennsylvania)

The Jonestown Volcanics are located within the outcrop of the Hamburg Klippe (Fig. 7), a Taconic thrust sheet remnant (Lash 1986), and are interpreted on the basis of the detailed mapping of Ashcroft (2002) to form a separate out-of-sequence thrust sheet remnant above the transported sedimentary strata of the Hamburg Klippe (Fig. 9). The Jonestown Volcanics consist of basaltic pillow lavas, and diabase (dolerite) (Fig. 10); the only sedimentary material clearly associated with the volcanics, like Starks Knob, is limestone (Fig. 11). The limestone has not been fossil dated, but is inferred to be mid-

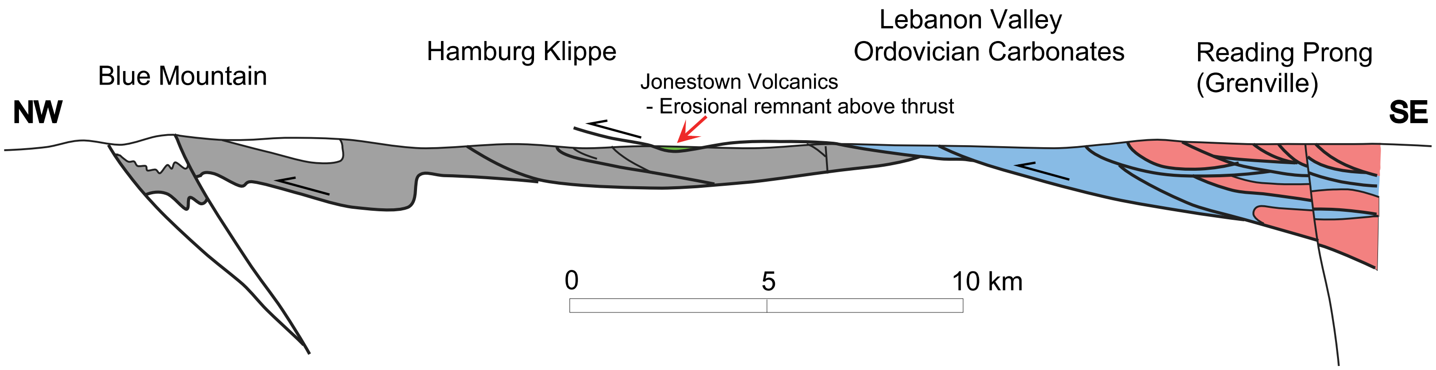

Figure 9. Generalized cross section (from Berg et al. 1980) of the Great Valley–Hamburg Klippe (grey), Ordovician carbonate rocks (blue) and Grenville crystalline rocks of the Reading Prong (red). The section shows the interpretation that the Jonestown Volcanics and associated limestone (green) are an erosional remnant of one of the thrust sheets of Ordovician carbonate rocks in the Lebanon Valley. No vertical exaggeration. Location of section line shown on Figure 7.

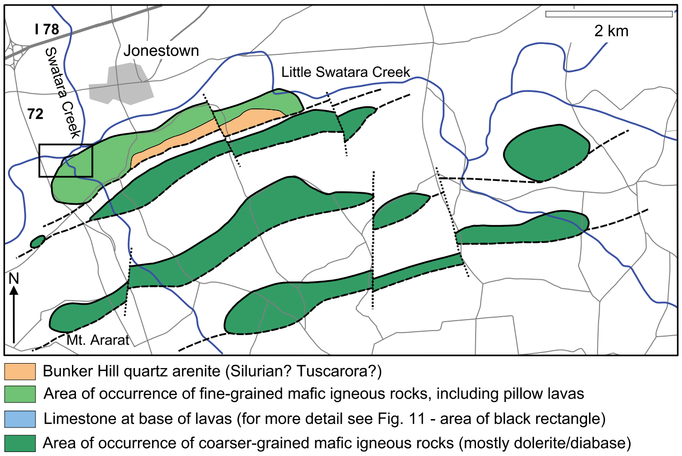

Figure 10. Map of the Jonestown Volcanics showing the extent of mafic igneous rocks from outcrop mapping (Ashcroft 2002). Black rectangle is area of detailed geological map (Fig. 11). Inferred faults affecting the volcanics shown by thick lines: solid – early thrusts, folded; dashed – later thrust faults; dotted – cross faults. Uncoloured area – bedrock sedimentary strata of the Hamburg Klippe structurally underlying the volcanic rocks. Quartz arenites of the Bunker Hill ridge are inferred to overlie the Jonestown volcanic rocks unconformably and to be of Silurian age.

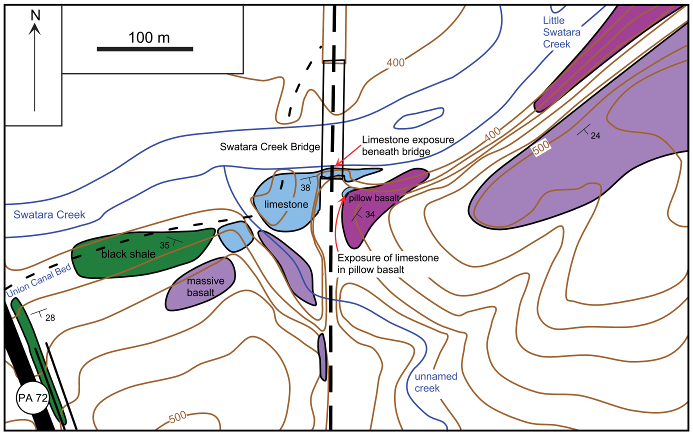

Figure 11. Geological outcrop map of the vicinity of the abandoned Reading Railroad bridge over Swatara Creek, south of Jonestown, PA. The locality of the pillow basalt containing limestone is shown. Contour interval 20 feet. From Ashcroft (2002).

Ordovician based on lithological resemblance to the Annville Limestone in the nearest passive margin-derived thrust sheet in the Lebanon Valley to the southeast (Ashcroft 2002). Quartz arenites of the Bunker Hill Ridge (Fig. 10) are inferred to overlie the Jonestown volcanic rocks unconformably, and to be of Silurian age. Local evidence for contemporaneous extensional stress orientation is lacking in the volcanic rocks, although there are hints that lower plate foreland normal faulting (Shanmugan and Lash 1982), like that better documented in New York and Quebec (Bradley and Kidd 1991), occurred in the platform strata to the northwest. We think that the Jonestown Volcanics and Starks Knob had similar sites of eruption on the outer Laurentian shelf (see geochemical characterization below), and that both had Taconic (Ordovician) thrust-emplacement histories.

Morel Sills and Ghost Dykes (Wopmay Orogen)

The Coronation Supergroup exposed in the Wopmay Orogen is the origin of the model first presented by Hoffman (1987) of foredeep sedimentation and magmatism. There, a basement and rift sequence on the northwest margin of the Slave Craton is overlain by a shallow marine passive margin sequence. This passive margin sequence is swamped by overlying, thick greywacke turbidites and other clastic rocks that form a collisional foreland basin fill. The Morel Sills (Fig. 12) intruded the passive margin and foredeep sedimentary section and were emplaced just prior to foreland-directed thrusting. Hoffman (1987) noted a lack of evidence for pre-collisional normal faulting besides that associated with pre-passive margin continental rifting, but Hildebrand and Bowring (1999) and Hildebrand et al. (2010) concluded that the substantial (~200 km) margin-parallel distribution of the sills reflects extension perpendicular to the margin, and to the collisional thrusts and fold hinge lines.

The ca. 1884 Ma Ghost dykes, a series of NNE-trending mafic dykes, intruded the Slave Craton south of the main part of the Wopmay Orogen (Fig. 12), and are sub-parallel with it (Frith 1993). These dykes have been correlated, based on position, orientation, and geochemistry, with the Morel Sills (Hoffman 1987; Hildebrand et al. 2010). Although there are presently no very precise isotopic ages for the Morel Sills, precise

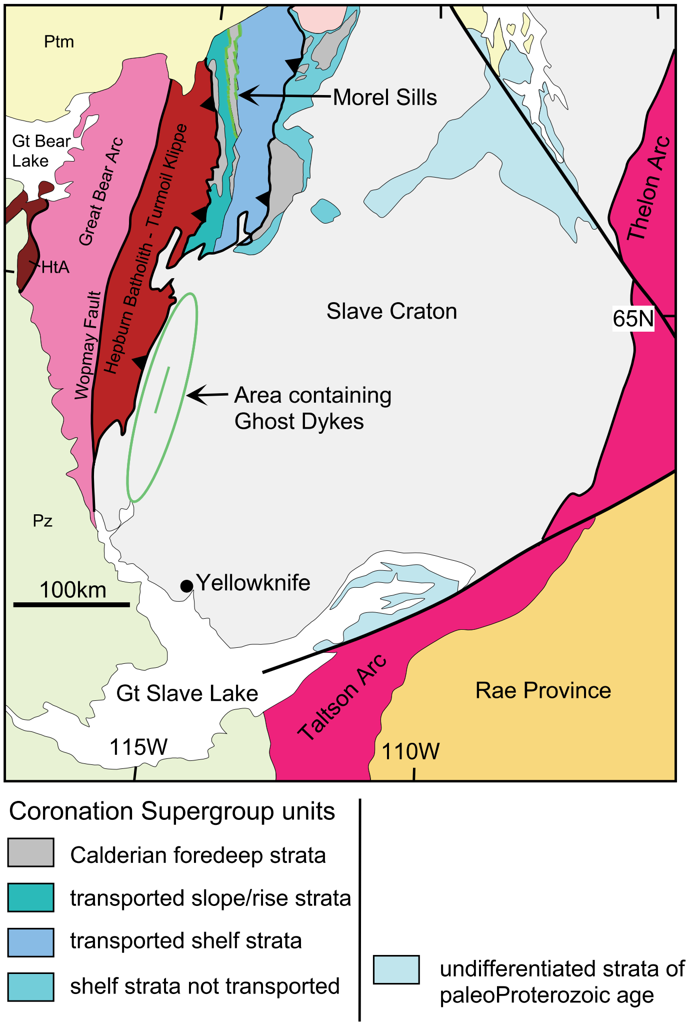

Figure 12. Location and orientation of the Morel Sills and Ghost Dykes in the Calderian (Wopmay) Orogen and adjacent Archean Slave Craton. Map simplified after Hoffman (1987, 1988); Frith (1993); Hildebrand et al. (2010). HtA – Hottah Arc, Ptm – Mesoproterozoic cover, Pz – Paleozoic cover.

dates for the Ghost dykes of ca. 1884 Ma were reported by Buchan et al. (2009). Hildebrand et al. (2003) and Davis and Bleeker (2007) concluded the Ghost dyke swarm was related to lower plate breakoff during the convergence and collision of the Slave Craton with an arc during the Wopmay Orogeny.

Molson Dykes (NW Superior Craton Margin)

The ca. 1883 Ma Molson Dykes are a series of NE-striking, nearly vertical mafic dykes that occur in the NW margin of the Superior Province, in a zone about 150 km wide adjacent to and parallel with the Thompson Belt, part of the larger Circum-Ungava (Trans-Hudson) Orogen (Fig. 13). Hoffman (1988) suggested that they were emplaced in a foredeep basin position during lower plate flexure and convergence on this margin. Their orientation is parallel to the regional orogenic trend in the adjacent Thompson Belt and craton margin, and their age is now very well constrained as in the same range as orogenic shortening and magmatism in the Thompson Belt (age compilation and discussion in Minifie 2010; see also Heaman et al. 2009) showing that these extensional structures developed parallel with the trench or thrust strike direction, and coeval with the orogenic shortening event.

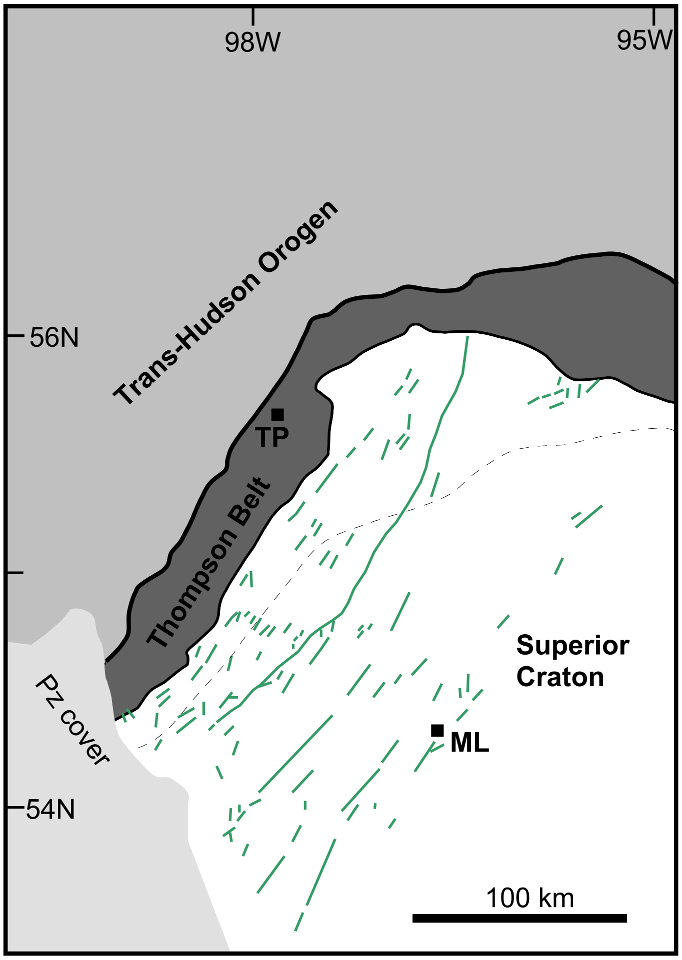

Figure 13. Distribution of the Molson Dykes (green lines) in the Superior Craton adjacent to the deformed rocks of the Proterozoic Thompson Belt. Dashed grey line – SE border of Pikwitonei granulite. ML – Molson Lake, TP – Thompson. Adapted from Minifie (2010).

Flaherty Formation (Belcher Islands, Canada)

The Proterozoic Flaherty Formation of the Belcher and Sleeper Islands in Hudson Bay (Fig. 14) are a series of mafic lavas above a rift and passive margin stratigraphic sequence that includes older subaerial volcanic rocks overlain by arkose and shallow marine carbonate rocks that pass up into argillite, shale, and iron formation (Legault et al. 1994). The Flaherty Formation is dominated by pillows and contains interbedded volcaniclastic sedimentary rocks indicating a subaqueous eruptive environment (Ricketts et al. 1982; Legault et al. 1994). The overlying sedimentary rocks are euxinic shale and turbidites. Hoffman (1987) interpreted this to be a foredeep sequence nearly identical to that seen in the Wopmay Orogen (the magmatism here equivalent to the Morel Sills). Two U–Pb ages of 1870 Ma (M. Hamilton *in* Minifie 2010) have been obtained from the Haig Sills, which occur both in the Belcher and Sleeper Islands, and are thought to be the intrusive equivalents to the volcanics. The regional distribution of the Flaherty Formation and Haig Sills and their magmatic correlatives in the Chukotat Group in the Ottawa Islands and Cape Smith Belt (Hynes and Francis 1982; Hynes et al. 1994; Dunphy et al. 1995; Baragar 2007, 2008), over a distance of hundreds of kilometres along the Superior Craton margin, implies a thrust-parallel extensional structure association.

GEOCHEMISTRY

We have selected and compiled 330 geochemical analyses of volcanic and shallow intrusive mafic rocks including basalt, basalt-andesite, alkaline basalt, and foidite from the foreland magmatic settings described above (Fig. 15). These are presented in several commonly used trace element discrimination diagrams to distinguish between plume-influenced and slab detachment types. Sources of the original analyses are listed in Table 1; refer to these sources for the analytical methods used.

Although some analyses are of young, relatively pristine rocks unaltered by weathering or metamorphism, many older ones are not, so only immobile trace elements, generally stable during weathering and low-grade metamorphism (Pearce 1996), are used for comparison purposes. All rocks presented here have been reported as having experienced greenschist facies metamorphism or less, except for the rocks from the Piling Group (discussed below) that reached amphibolite facies and for which there may be less confidence that the original immobile element concentrations have remained significantly unchanged since magmatic emplacement.

Discrimination diagrams have been shown to work over a range of degrees of partial melting of the mantle source in natural examples (e.g. Shervais 1982; Pearce 1996) in that immobile element ratios in magmas are not significantly changed unless there are high differences in degree of partial melting from one source. If significant differences in partial melting occur within a suite then a transdiscriminant pattern (suite samples plot across tectonic field boundaries) may result. They also permit discrimination in the face of compositional changes induced by some degree of fractional crystallization, as long as the samples chosen are basaltic in composition (see Pearce 2014).

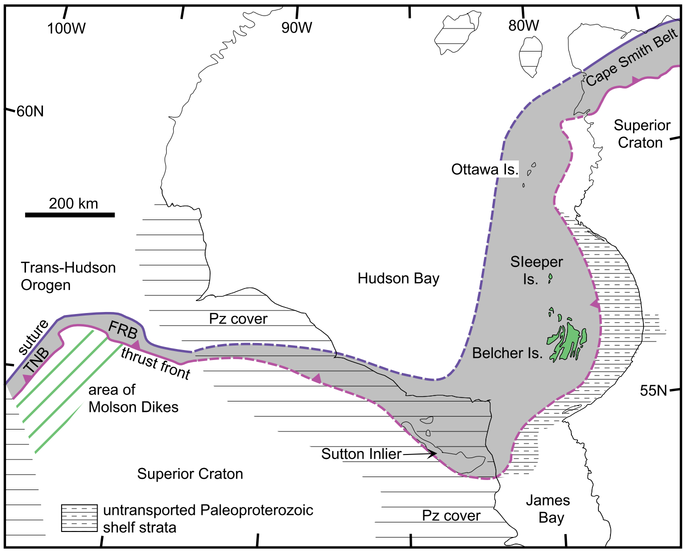

Figure 14. Location of the Belcher and Sleeper Islands in eastern Hudson Bay, within the fold and thrust belt of Paleoproterozoic age on the north side of the Archean Superior Craton. FRB – Fox River Belt, Pz – Paleozoic cover, TNB – Thompson Belt.

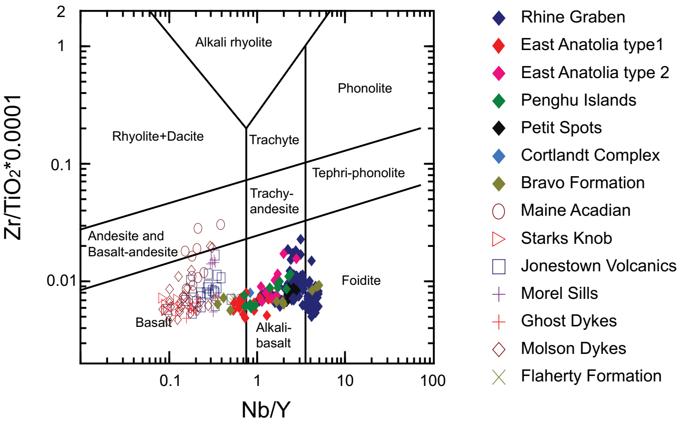

Figure 15. Classification diagram of Winchester and Floyd 1977.

Normalized Diagrams

The chondrite- and MORB-normalized diagrams illustrate some important differences between the Rhine and Maine types. First, Rhine-type volcanic rocks are significantly more enriched in LREEs than the Maine-type indicating a more enriched mantle source (or a lower degree of partial melting); the flatter Maine-type patterns indicate a more depleted mantle source (or a higher degree of partial melting; Fig. 16). The Rhine-type patterns on the MORB-normalized diagram (Fig. 17A) are consistent with those shown by the chondrite-normalized diagram. Second, many of the Maine-type samples on the MORB-normalized diagram display Ta–Nb (or just Ta for the Flaherty Formation) negative anomalies (Fig. 17B). The Ta–Nb negative anomaly, typically associated with supra-subduction zone environments, and evident in the Devonian Maine rocks may be the result of partial melting of a subduction-modified sub-continental mantle (Dostal et al. 1989; Hon et al. 1992; Keppie and Dostal 1994; Schoonmaker et al. 2011). In contrast, all but one of the Starks Knob samples lack sufficient Th to be analyzed, so do not show an anomaly (Fig. 17C). The very low Th concentrations in the Starks Knob samples indicate that the sub-continental mantle at its eruption site was not exposed to a prior supra-subduction event. The Jonestown samples show significant scatter, two of them suggest a Ta negative anomaly, but there is no corresponding anomaly for Nb (Fig. 17C). When the Starks Knob and Jonestown samples are removed from the MORB-normalized diagram, the remaining Maine-type samples show a more uniform pattern with distinct Ta–Nb negative anomaly (Fig. 17D). This raises the possibility that the Starks Knob and Jonestown rocks (both formed on the Laurentian margin, with Grenville basement) experienced a somewhat different history than those in Maine and those in Proterozoic orogens in Canada. Third, Ti/Yb

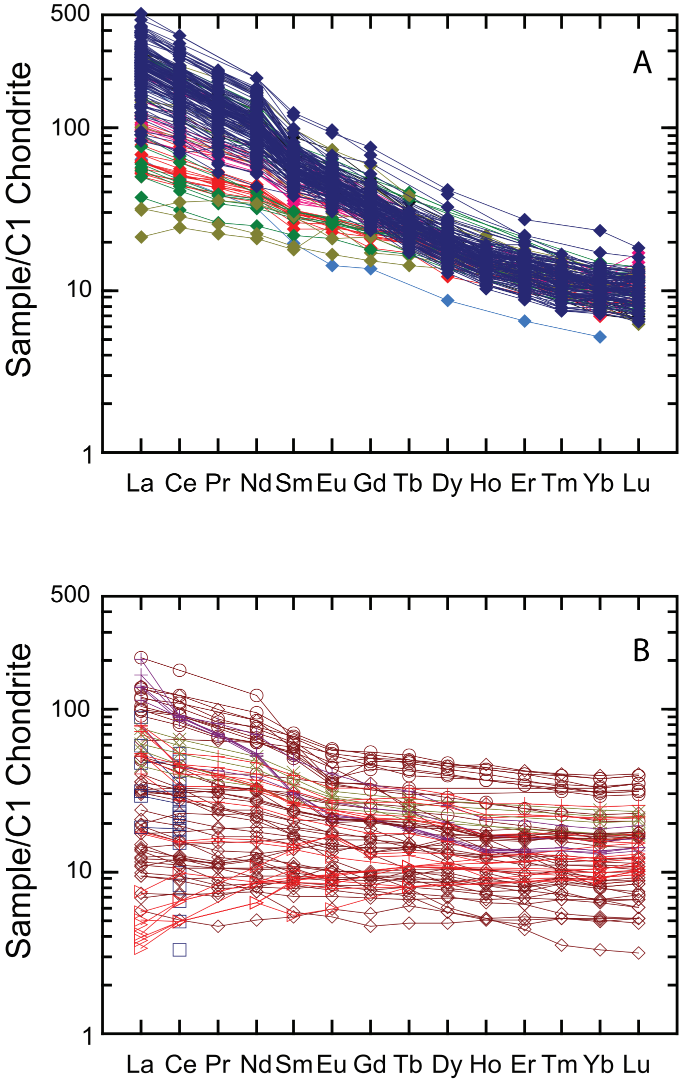

Figure 16. Chondrite-normalized diagrams: A – Rhine-type, B – Maine-type. See Figure 15 for symbol legend.

ratios (normalized) are higher in the Rhine-type rocks than those in the Maine-type rocks (3.33 vs. 1.24, respectively).

Tectonic Discrimination Diagrams

Several tectonic discrimination diagrams are presented to illustrate correlations and differences between the suites and to infer possible processes involved. What is clear is that there is a nearly complete separation of Rhine- and Maine-type foredeep rocks (Figs. 18–23) in all of these diagrams.

Nb–Zr–Y, Nb/Y–Zr/Y, and Hf–Th–Nb Diagrams

The Nb–Zr–Y diagram of Meschede (1986) discriminates between various MORB types and plume-influenced tectonic settings based on the concentration of Nb relative to Zr and Y (Fig. 18). In lavas derived from enriched mantle, Nb concentrations are high, whereas lavas from depleted mantle (MORB and arc environments) have lower Nb concentrations. The separation between Maine and Rhine types indicates they are partitioned between these different mantle types. Less obvious in this diagram is that the Zr/Nb ratio is higher in the Maine-type rocks than in the Rhine-type rocks (15.7 vs. 3.26, respectively).

The Nb/Y–Zr/Y diagram (Fitton et al. 1997) is designed to discriminate between MORB and plume-influenced lavas based on Nb concentrations, serves a similar purpose to Meschede's diagram, but more clearly separates the Maine and Rhine types where the Rhine types have more enriched concentrations of Zr and Nb relative to Y. Significant variation in Zr/Y ratios evident in the plot, specifically the Acadian Maine samples, was attributed to systematic analytical bias in the compiled datasets used (Schoonmaker et al. 2011).

Wood's (1980) diagram (Fig. 20) makes use of similar processes (depletion of Nb in depleted mantle) as the other Nb–Zr–Y diagrams, but uses the ratio Nb to Hf to discriminate between volcanic rocks derived from enriched and depleted mantle. Low Nb concentrations relative to Hf are characteristic of volcanic rocks from depleted mantle whereas high concentrations are characteristic of an enriched mantle source for volcanics. Rocks that are enriched in Th, typical of subduction zones or from mantle sources that have been otherwise enriched in Th (e.g. previously subduction-modified), plot down to the left, away from the mantle source fields. Similar to the Nb–Zr–Y diagrams, in this the mantle sources between Maine (depleted) and Rhine (enriched) types are nearly completely separated (some Molson dykes from Heaman et al. (2009) have Nb or Hf concentrations below detection limits).

Ti–V Diagram

The Ti–V diagram (Fig. 21) of Shervais (1982) is generally used to identify arc environments based on the difference in behaviour of V depending on fluid content of the mantle source. V becomes more incompatible when fluid contents are high, such as occurs in supra-subduction zones that generally have Ti/V ratios below 20. In alkaline rocks, Ti/V ratios are high, above 50. Continental tholeiite may have Ti/V ratios below 50. In this diagram there is a strong separation of Maine- and Rhine-type rocks although a significant number of the Rhine samples plot at Ti/V ratios slightly below 50. Most of the Maine-type suite has Ti/V ratios between 20 and 50, where MORB, back-arc basins, and continental tholeiites typically plot, although a significant number of the Molson dykes plot in the arc field.

Ti–Zr–Y Diagram

Pearce and Cann's (1973) diagram (Fig. 22) discriminates between within-plate settings and MORB and volcanic arc environments. Within-plate magmas include plume or hotspot types and result from higher relative concentrations of Ti and Zr to Y. MORB and volcanic arc magmas have lower relative amounts of Ti and Zr. The Rhine-type rocks almost exclusively plot in the within-plate field, consistent with their patterns on the MORB-normalized diagram (Fig. 17), whereas the Maine-type rocks plot across the MORB and arc fields.

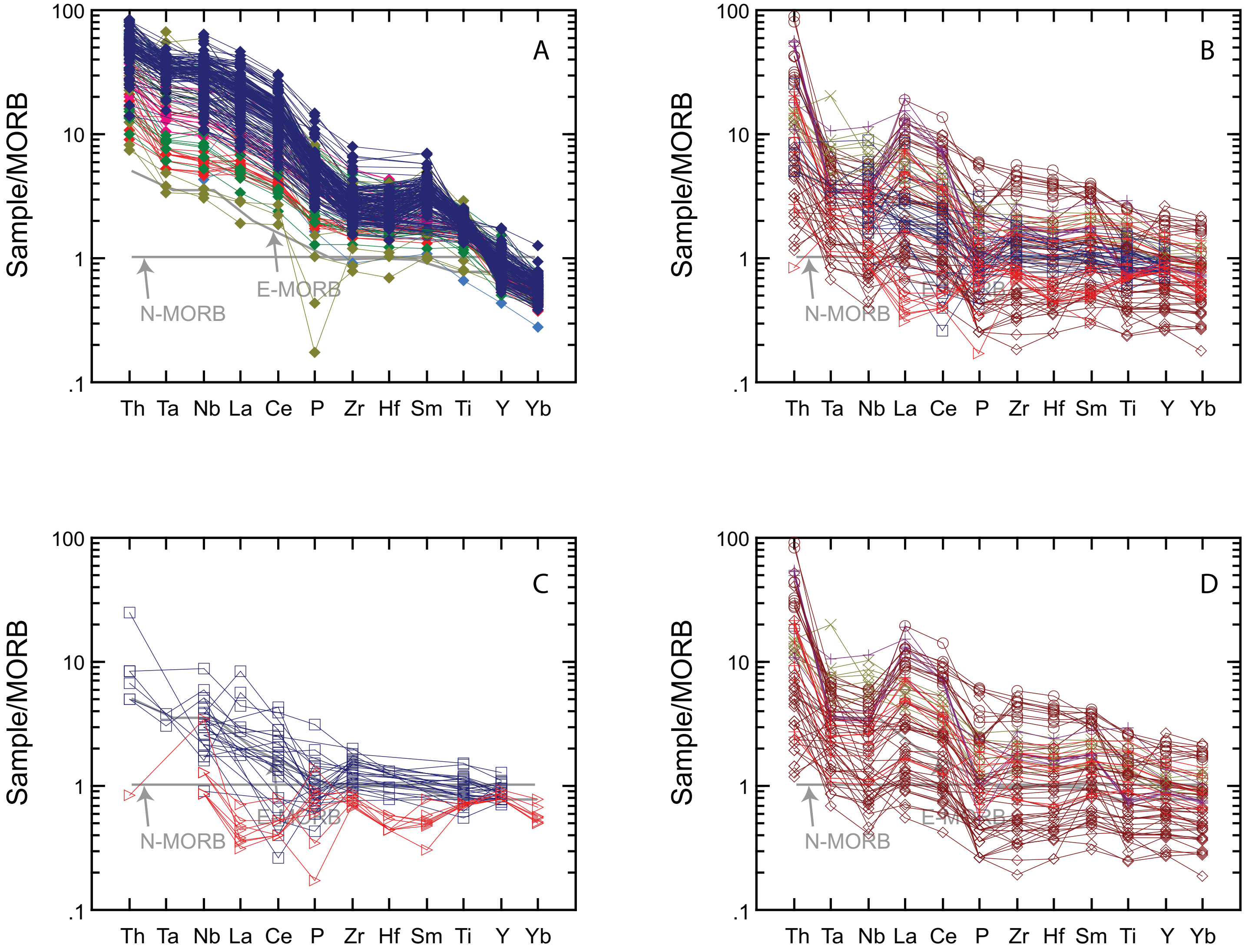

Figure 17. MORB-normalized diagrams: A – Rhine-type, B – Maine-type, C – Starks Knob and Jonestown samples only, D – Maine-type with Starks Knob and Jonestown samples removed. See Figure 15 for symbol legend.

TiO_2/Yb–Nb/Yb Diagram

The TiO_2/Yb–Nb/Yb diagram (Fig. 23) of Pearce (2008) is useful for the purposes of this paper as it discriminates between magmas from deep mantle and shallow mantle sources. During melting of shallow spinel peridotite, Ti and Yb enter the melt equally but garnet in deep mantle retains Yb (Pearce 2008, 2014), so Ti/Yb ratios are higher in lavas from deep mantle sources, relative to those from shallow mantle sources. The Rhine and Maine types in the selected example suite are completely separated in this diagram, in both TiO_2/Yb and Nb/Yb ratios.

DISCUSSION

Magma Sources and Tectonic Associations

From the striking chemical separation of the Rhine and Maine types it is probable that these two types of foreland magmatism were generated under substantially different conditions and result from different processes. Additionally, the degree of partial melting for the Rhine types is inferred to be less than the Maine types; the Rhine types have significantly lower Nb/Y (or Nb/Yb) and Zr/Y ratios than the Maine types (Figs. 16, 17, 18, 22, 23). High Hf concentrations in Figure 20 and generally higher Y concentrations relative to Cr (not figured) also support this conclusion (see Pearce 1982). While there are internal variations in element concentrations of the two types (e.g. the overall trends in the Figs. 18, 20, and 21), the internal trends do not correlate between the groups suggesting that variations in partial melting cannot explain the differences between the two types. The lack of apparent intermediate suites (see especially Fig. 23) also supports the idea that the differences in partial melting do not explain these differences.

Two main tectonic processes have been proposed by previous workers in these areas to explain the origin of these suites: plume (or at least sub-lithospheric mantle upwelling) influence, and slab detachment. In some of these examples, different authors have put forward these competing hypotheses for the

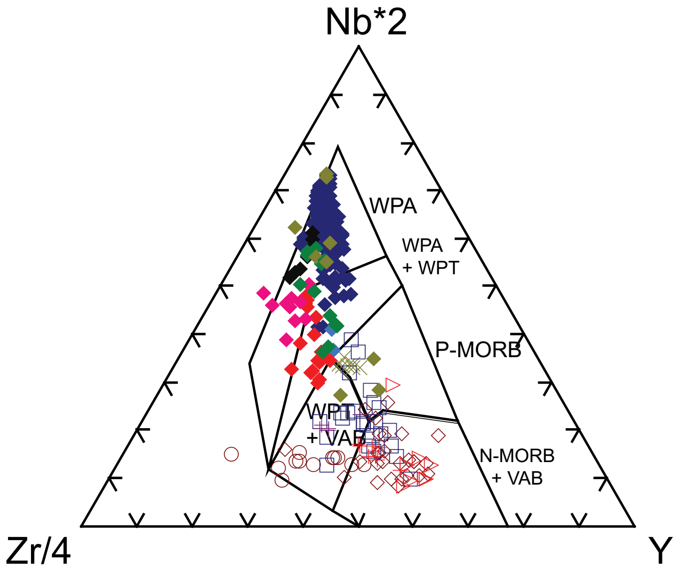

Figure 18. Nb–Zr–Y diagram of Meschede 1986. See Figure 15 for symbol legend.

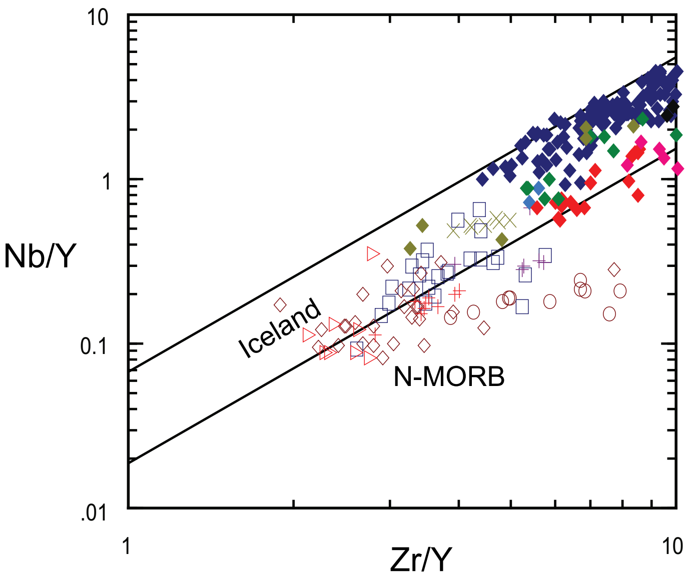

Figure 19. Nb/Y–Zr/Y diagram of Fitton et al. 1997. See Figure 15 for symbol legend.

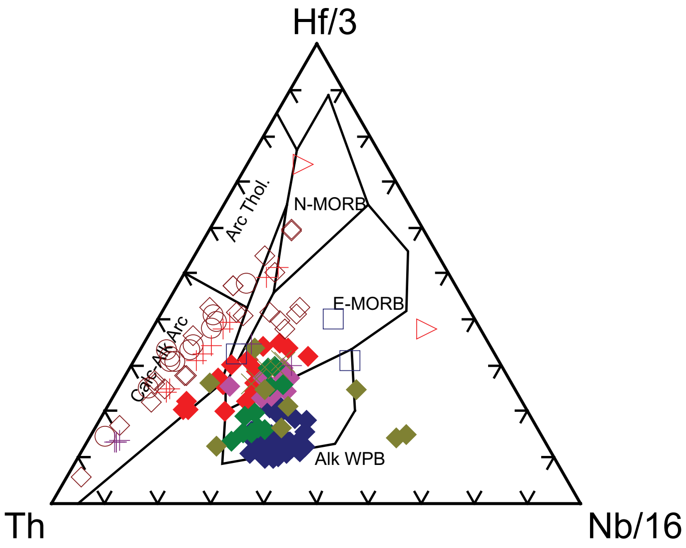

Figure 20. Hf–Th–Nb diagram of Wood 1980. See Figure 15 for symbol legend.

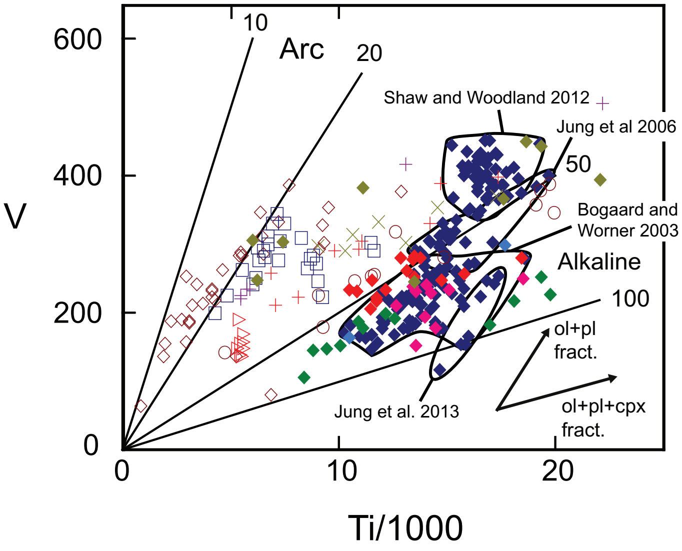

Figure 21. Ti–V diagram of Shervais 1982. See Figure 15 for symbol legend.

same setting, particularly in the case of the Rhine Graben.

Multiple hypotheses have been proposed for the origin of magmas erupted in the Rhine Graben including partial melting of metasomatized asthenospheric mantle, partial melting of the base of the lithosphere (thermal boundary layer), and partial melting of mantle plumes (Bogaard and Wörner 2003; Haase et al. 2004 and references therein; Jung et al. 2006; Shaw and Woodland 2012; Jung et al. 2013). In some of this work, largely based on isotopic ratio differences, the Westervald–Eifel area is generally considered to have formed primarily from a mantle plume source, whereas the Vogelsberg area formed from a thermal boundary layer source at the base of the lithosphere. Our compiled dataset contains samples from both these areas that show no separation based on trace element concentrations. Importantly, the TiO_2–Yb–Nb concentrations (Fig. 23) indicate rocks from both areas were derived from garnet peridotite, whereas Haase et al. (2004), based on isotopic ratios, concluded that the Vogelsberg rocks were sourced from spinel peridotite of the thermal boundary layer at the base of the lithosphere, although they infer that this melting occurred in the larger context of mantle plume activity.

In SE Turkey, Ekici et al. (2012) divided the Siverek Plateau lavas into two groups based on major and trace element concentrations: Group 2 lavas generally having higher concentrations of incompatible trace elements. In our plots, the Group 1 lavas plot further from the Rhine samples than do the Group 2 lavas, but both are still consistent with that group. The Karacadağ Volcanic Complex has alternatively been interpreted to have contributions from the Afar plume (Krienitz et al.

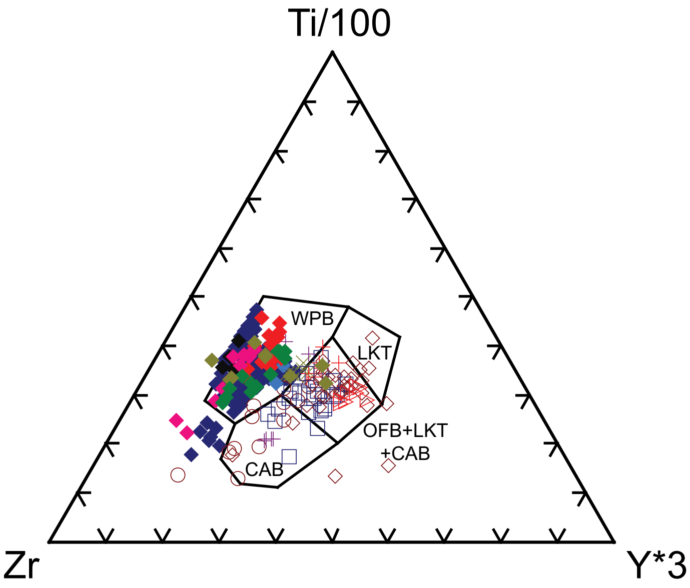

Figure 22. Ti–Zr–Y diagram of Pearce and Cann 1973. See Figure 15 for symbol legend.

2009) or a separate mantle upwelling (Keskin 2003; Ekici et al. 2012), and isotopic studies give conflicting interpretations regarding the role of mantle plumes in northern Arabian Peninsula volcanism. Ekici et al. (2012) reported Pb isotope ratios that do not match Afar plume compositions, while Krienitz et al. (2009) concluded that an Afar contribution is consistent with part of a mixed magma source. Ekici et al. (2012) argued for Maine-style magmatism as the origin of Karacadağ volcanic rocks, with lithospheric thinning of the margin resulting from tension from the subducting Tethyan oceanic lithosphere to the north, and Keskin (2003) similarly invoked a slab breakoff mechanism, although the Karacadağ Plateau is peripheral in his model. Evidence against this mechanism is a reported lack of appropriately oriented extensional deformation in the area (Camp and Roobol 1992), and the fact that there are young, directly associated extensional structures in the area of this magmatism, oriented at a high angle to the nearby thrust belt (Şengör and Kidd 1979; Pearce et al. 1990). Perhaps the earliest magmatism here was through fractures controlled by slab-pull stresses (Ekici et al. 2012), and converted to the now dominant convergence-controlled fractures for the later eruptions. The early volcanic rocks, however, are not known to include examples falling within the fields of Maine-type compositions, although some of the Group 1 lavas of Ekici et al. (2012) do plot closer to those fields. Perhaps the later part of a transition to Rhine-type magmas is preserved here.

Near Taiwan, the mid–late Miocene basalt of the Penghu Islands are interpreted (Chung et al. 1994; Wang et al. 2012) to have formed from asthenospheric mantle, both from lithospheric extension and from mantle upwelling. The amount of lithospheric extension of the crust required to bring asthenosphere into the melting regime following thinning of the lithospheric mantle would likely produce much greater extension of the upper crust than is evident (Chou and Yu 2002) west of Taiwan for the 16–8 Ma time interval of the volcanism. We have strong doubts that the Penghu Islands volcanics ought to be regarded as foreland basin magmatism, based on the coherent set of mid–late Miocene ages, including the fossil ages of interbedded sedimentary rocks, and their consistency with the dissected and planated topography of the volcanic field exposed in the islands, where no evidence of young constructional volcanic landforms is visible. At the rate of plate convergence across the Manila Trench, presently 90 mm/a in southern Taiwan opposite the Penghu Islands (DeMets et al. 2010), the accretionary toe of the subduction system would have been nearly 300 km away from the East China passive continental margin only 3 M.y. ago, and much farther at 8 M.y. (Fig. 5). Even with the slower convergence rate for the last 8 M.y. given by Sibuet et al. (2002), the distance from the trench at 8 Ma would have exceeded 500 km. Stratigraphic and other geological evidence indicates that the diachronous collision began at about 5 Ma (Teng and Lin 2004; Huang et al. 2006). Nevertheless, because they have been previously suggested to be foreland magmatism, have both good geochemical and structural data sets, and because they provide a useful demonstration of the limits of discrimination possible from geochemical compositions, we included the Penghu volcanic rocks (if only as an object lesson) in our suite of possible examples. The geochemical characteristics of the magmas indicate that if they are included as foreland magmatism, they would belong to the Rhine-type group. We think that an independent mantle upwelling is a more likely explanation than others for the properties and localization of the Penghu Islands magmatism whether or not they have a relationship to the Taiwan foreland.

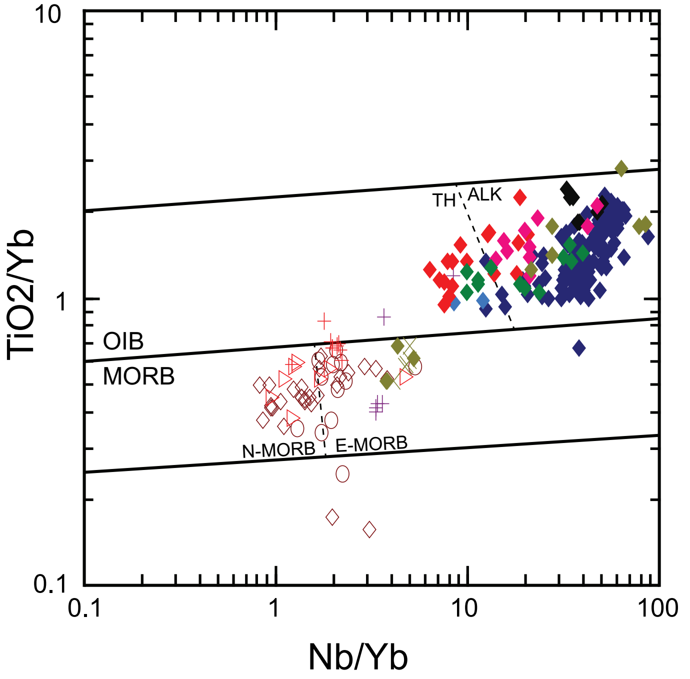

Figure 23. TiO_2/Yb–Nb/Yb diagram of Pearce 2008. See Figure 15 for symbol legend.

The Japan Trench petit-spot area is similar in geochemical characteristics to the other Rhine-type occurrences, but it currently has rather weak evidence of the associated extensional structures. The overall distribution of the volcanic rocks does not show any preferred distribution along the belt of outer trench slope (trench-parallel) normal faulting, which suggests it is not associated primarily with those faults. Hirano et al. (2006) and Hirano (2011) suggested an origin from fracturing caused by lithospheric fore-bulge flexure, which should trend SW–NE parallel with that feature. We think the WNW–ESE orientation of the envelopes to two of the three volcanic areas, and the same alignment of spots in the area of older volcanic rocks (group 3, Fig. 6; Hirano et al. 2006), do not support this hypothesis. The WNW–ESE alignments that are evident, if not prominent, rather suggest that magmas used extensional fractures produced by maximum compressive stress in the lithosphere in the direction of, and resulting from, convergence at the Japan Trench. At 4 M.y. ago, the older group (3 – Fig. 6) would have been in the position where the younger group (2) is presently located, and we note that this age progression, although with intermittent expression here, is the same as from Pacific plate motion over better known, larger hotspots (e.g. Hawaii). The other group (1) is admittedly not accommodated by this suggestion, unless the area affected by mantle upwelling is 400 km or more across.

The one ancient Rhine-type structure, the Cortlandt Complex–Beemerville zone in the New York Taconic thrust belt, has properties similar to its modern counterparts. It is of interest that it occurs spatially between the two Maine-type Taconic examples (Jonestown, Starks Knob), which we think were erupted through the outer Laurentian passive margin (with inferred Grenville crust and lithosphere) before their tectonic transportation, and that the Cortlandt magmas were also emplaced through that type of lithosphere after the Taconic foreland thrusts had been emplaced over it. The strong contrast in the geochemistry of the Cortlandt magmas with the two older Taconic examples is striking, and also is suggestive that quite different processes generated the two types of foreland magmatism.

For the Maine-type examples, it is significant that for those where the orientations of contemporary extensional structures are known (Maine Acadian, Starks Knob, Ghost Dykes, Molson Dykes) or can be inferred from asymmetric regional extent (Morel Sills, Flaherty Formation–Haig Sills), the extensional fault and fracture orientations parallel the trench or thrust front, consistent with a slab pull or detachment mechanism.

Currently there is debate concerning the subduction polarity of the Acadian Orogeny in Maine. The west-dipping model requires the Piscataquis Volcanic Belt and associated magmatism to have occurred in a far back-arc region (van Staal et al. 1998) and to have been caused by shallow subduction (van Staal et al. 2009), and consequently not an example of foreland magmatism. In contrast, Bradley et al. (2000), Bradley and Tucker (2002), and Schoonmaker et al. (2005, 2011) have argued for an east-dipping subduction, placing Piscataquis belt volcanism in the foreland region of the lower plate, with emplacement slightly preceding the NW-migrating orogenic front. Discussion of these interpretations, and others (Eusden et al. 2000), was made by Schoonmaker et al. (2011). Here, we emphasize one inconsistent consequence of the west-dipping interpretation. In the flat slab region of the Andean orogenic belt of Argentina, the crust of the Precordillera has undergone significant thickening and thrusting involving basement. Current thickness of the Precordillera crust exceeds 60 km (Ammirati et al. 2013) and given current erosion rates in the Precordillera that approach 100 m/M.y. (Walcek and Hoke 2012), this suggests that the Maine Acadian should have exhumed significantly buried metamorphic rocks if it had experienced a Precordilleran-type thickening. The Acadian of central and northern Maine and Gaspé only caused low-grade metamorphism of the rocks now exposed (e.g. Osberg et al. 1985) suggesting that such thickening did not occur and that back-arc magmatism caused by flat slab subduction is an unsatisfactory interpretation for the origin of Piscataquis Belt volcanism.

It is clear from numerous studies that magmas derived from partial melting of sub-continental lithospheric mantle can be heterogeneous and can also be influenced by prior subduction-related events during arc or microcontinent accretion. These prior events result in more depleted sub-continental mantle that can also have subduction geochemical signals (e.g. Pearce et al. 1990; Cloos et al. 2005). This geochemical pattern is characteristic of foreland magmatism of all the Maine-type examples, and so we infer for this type a slab-pull or detachment mechanism and shallow asthenospheric decompression partial melting, perhaps accompanied by some lithospheric partial melting.

Other Examples

Bradley (2008, his table 2) identified more occurrences of probable foredeep magmatism in his discussion of ancient passive margins but, as far as we are aware, those additional to the ones we discuss are mostly not at present as well-documented, nor are sufficient geochemical analyses available for many of them.

One that has recently been well-characterized in its geological setting and geochemistry is in the approximately 1900 Ma Piling Group, which starts with a series of quartzitic, calc-silicate, and carbonate metasedimentary rocks of medium metamorphic grade that directly overlie Rae Craton basement in the Trans-Hudson Orogen north of Hudson Bay (St-Onge et al. 2009; Rainbird et al. 2010). These metasedimentary rocks are overlain by a series of alkaline to tholeiitic pillowed basalt and associated mafic sills, and interlayered subaqueous volcaniclastic sedimentary rocks (Partin et al. 2014) affected by upper greenschist-facies metamorphism (Bravo Lake Formation). Overlying the volcanic rocks is a series of graded fine-grained sandstone and mudstone that locally contains conglomeratic beds in channels (Rainbird et al. 2010). This section suggests a passive margin stratigraphy that subsequently underwent subsidence concurrent with mafic volcanism. The occurrence of zircon of external origin in the overlying sandstone and subsequent deformation suggests an orogenic foreland setting as the Rae Craton margin was involved in collision during the Trans-Hudson Orogeny (Partin et al. 2014). Most of the Piling Group samples plot with the main group of Rhine-type rocks in the geochemical diagrams, although three of them overlap into the field of Maine-type rocks, but still relatively close to the Rhine-type field. Overall, these three show rather low concentrations of LREE, as well as Nb (Figs. 17A, 18A), so it is not clear whether they resulted from a difference in petrogenetic process or from mobilization of multiple elements during amphibolite-facies metamorphism. The orientation of extensional structures accompanying Bravo Lake volcanism has not yet been documented; if it is possible to determine this from the deformed and metamorphosed remains, we predict that faults and fissures (dykes) should be of Rhine-type, formed at a high angle to the thrust fault fabrics.

Another occurrence, which we considered for inclusion in the example set, is the late Devonian–earliest Mississippian section in the Roberts Mountain Allochthon in Nevada. This is clearly recording (Burchfiel and Royden 1991) an accretionary complex–passive continental margin overthrusting event (Antler Orogeny), probably from an arc–continent collision with much slab roll-back, and there are mafic volcanic rocks in the deep continental rise and slope lower plate section of late Devonian age. However, modern analyses of these late Devonian volcanics are few (3 by Madrid 1987). We chose not to include this example in the selected set because of the paucity of adequate geochemical data, and also from the absence of clear evidence of the orientation of associated extensional strain. The geochemical data from the three samples of volcanics of late Devonian age (Madrid 1987) suggests this is a Rhine-type alkalic suite, from which we would again predict faults or dykes of the same age to be developed at high angles to the thrust transport direction. Clearly, there is an opportunity here to investigate fully and characterize these volcanics better, and perhaps even to test the hypothesis offered in this paper, as with the other possible examples identified by Bradley (2008).

New Guinea

Cloos et al. (2005) have documented in detail the Neogene arc–continental margin collision in New Guinea and the resulting slab breakoff event. Magmatism associated with the laterally propagating slab breakoff event is mostly confined to the orogen, with only a small area of volcanism just crossing the southern thrust boundary in the eastern (younger) part of the system. The New Guinea magmatism therefore is in contrast to most of the examples discussed in this paper, being largely not located in the foreland basin and, where it does slightly emerge into the northern edge of the basin, in occurring later than much of the sedimentary fill and the active thrust loading of that basin. Because of these differences, and the focus of this paper on magmatism located in and emplaced during the filling of collisional foreland basins, we chose not to include it among the examples. In general, the mafic members of the suite in Papua (Mackenzie 1976) have properties that mostly resemble (Schoonmaker et al. 2005) the Maine-type suites of this paper, consistent with the demonstration of Cloos et al. (2005) that they originated dominantly from decompression melting during the slab breakoff process. However, some occurrences of more alkaline types (e.g. the Porgera Intrusive Complex, Richards et al. 1990), and others in western New Guinea (Housh and McMahon 2000) show that this was not the only source of these magmas and that a minority have Rhine-type compositions, probably derived from locally enriched lithosphere.

Secular Variation?

One curious feature of our selected example set is the skewed distribution in long-term geological history. The Rhine-type set contains four of Neogene–Recent, and one of Paleozoic age, whereas the Maine-type set consists of no modern, two Paleozoic, and three Proterozoic items. We think this might be significant, especially for the Maine-type, although the small overall number of items in our selection hardly permits a firm conclusion. However, the widespread occurrence of the Maine-type in extensive segments of the early Proterozoic orogens of Canada contrasts strongly with their definitive absence from extensive lengths of Phanerozoic orogens and, apart from the Maine Acadian, very minor volume magmatism in the Taconic example. Following Hofmann (1987) we think that it is plausible that a long-term secular change has reduced the likelihood of Maine-type magmatism in the foreland margins of collisional orogens. A possible cause might be reduction of upper mantle conductive heat transfer into continental lithosphere through time, and/or a longer average time interval from rifting to collision (Hoffman 1987) based on declining mantle heat generation rate and consequent slower average plate motion (e.g. Burke et al. 1976). Both of these would provide on average a thicker (and consequently stronger) lithosphere under passive continental margins at collision, less likely to rupture early in the process for younger collisional events. Alternatively, perhaps there was an unusual coincidence of circumstances for the early Proterozoic of the Canadian cratonic-margin orogens, if the magmatism was caused by one or more 'superplumes' (Ernst and Buchan 2004; Minifie 2010) but with magmatism localized by slabs ready to break off on margins near to or already involved in the collisional events.

Mantle Plumes?

Some authors have suggested mantle plumes are the cause of and occur under the area of Rhine Graben volcanism (Hoernle et al. 1994; Goes et al. 1999), and also for SE Turkey (Keskin 2003; Krienitz et al. 2009; Ekici et al. 2012). We think the trace- and rare earth element compositional evidence shows clearly for all the Rhine-type examples that the primary source is sub-lithospheric and sub-asthenospheric. The magmatism is localized in areas of a typical scale of up to a few hundred kilometres across, like some active volcanic hotspots demonstrated to have deep mantle plume-sourced magmatism, from compositional (^{3}He anomaly) and/or seismic tomographic evidence (e.g. Hawaii). The Rhine Graben magmatism overlies a plume-like seismic anomaly in the upper mantle (Ritter et al. 2001), inferred by Goes et al. (1999) to extend to the lower mantle. We suggest that upper mantle convection is likely to be involved in generating these Rhine-type foreland magmatic occurrences, but it has not been demonstrated whether any of the others might also have a deep mantle plume connection.

Table 2. Foreland magmatism examples, and New Guinea, ordered by time of interval of magmatism (vtime) relative to start of collision (continental crust entering under the accretionary toe), or subduction age (for petit-spots). Estimated on basis of stratigraphic relationship to foreland basin clastic rocks, and numerical ages where known, or estimated; for the Precambrian examples, estimated by comparison to the younger examples, presuming comparable convergence rates. Refer to Figure 1 for relative position in a foreland basin profile section.

Example	R-type	M-type	Tectonic setting for time of volcanism	vtime M.y.
Rhine Graben	X		non-marine foreland basin and platform	35 to 50
Cortlandt	X		collisional belt (non-marine foreland basin)	~15
Karacadağ	X		collisional non-marine foreland basin	0 to 15
New Guinea		X	collisional thrust belt and orogen interior	7 to 15
Flaherty/Molson		X	marine foreland basin over shelf strata	?~5 to 10
Piscataquis (Maine)		X	marine foreland basin over shelf strata	~5 to 10
Morel/Ghost		X	marine foreland basin on or near shelf break	?~0 to 5
Starks/Jonestown		X	on continental shelf inside flexural bulge	~ –5 to 0
Japan petit spots	X		ocean floor outer trench slope to outside flexural bulge	(–8 to 0)
Penghu	X		on continental shelf, well beyond flexural bulge	–11 to –3

Timing of Magmatism Relative to Start of Collision

For the examples of foreland magmatism, if they are listed by order of the age of magmatism relative to the initiation of collision, or age at subduction of the volcanic rocks for the Japan petit spots (Table 2), the pattern emerges of the Maine-type being concentrated near this time, with the Rhine-type before or after. The concentration in time of the Maine-type may be because, if slab detachment occurs at all, it takes place soon after collision starts (see Cloos et al. 2005).

CONCLUSIONS

Contemporaneous magmatism in modern convergent or collisional foreland settings is readily recognized, but in ancient settings recognition relies on the presence of underlying passive margin sedimentation and overlying or contemporaneous deeper water sedimentary rocks, turbidites and flysch, and the association with collisional deformation. The several modern and ancient examples of foreland magmatism identified using those criteria fall strikingly into two distinct chemical groups defined by their trace element compositions: a more enriched alkaline group and a less enriched tholeiitic group. These two groups likely reflect two different processes that can occur in thrust forelands during arc or continental collision. The alkaline group is sourced from the sub-asthenospheric mantle and is inferred to result primarily from upwelling convection of plume-type geometry. The more tholeiitic group resulted from extension of the lower plate experiencing slab-pull forces and in some cases lithospheric detachment, with consequent melting of upwelling asthenospheric mantle. In either case, incorporation of melts from lithospheric mantle can occur, from intrusion or detachment, and in places (Maine) this can show evidence of previous modification by subduction processes. The geochemical results are quite sufficiently distinct to permit discrimination of such foreland magmatic rock suites from each other in ancient examples. However, they cannot be separated only by the geochemistry from magmatic products of other tectonic environments where similar compositions can be generated. While there may be in general lesser amounts of partial melting and magma volumes in the Rhine-type examples, the minor element geochemistry shows that the two types are not a result of differing degrees of partial melting of a single mantle source type.

For those foreland settings where coeval extensional structures reveal the extensional stress orientation during basin development, Maine-type magmatism is accompanied by normal faults parallel to the thrust front or trench. We think it is most implausible that the small amount of extension induced by lithospheric flexure of a few degrees or less, localized entirely in and widely distributed across the outer part of an antiformal bend, will lead to any surface magmatism. The examples of Maine-type foreland magmatism and the associated outer slope normal fault and dyke systems are evidence that they result from whole-lithosphere extension induced by slab pull. Rhine-type basin orientations are more variable, although several of our examples (Rhine Graben, Karacadağ, Cortlandt) have fissures or dykes and normal faults nearly perpendicular to the thrust front or trench, reflecting the orientation of the maximum compressive stress in the foreland crust imposed by the active plate boundary convergence. Oblique orientations could result either from oblique plate convergence (Japan petit spots), or from extension using older inherited fractures in the local crust (Penghu Islands?) and/or from stress fields modified by regional continental escape tectonics (Burke and Şengör 1986).

It is possible that there has been a long-term secular decrease in the occurrence of the Maine-type foreland magmatism since the early Proterozoic, and this aspect of foreland magmatism needs further investigation.

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SERIES

Geoscience Medallist 1. Understanding the Holocene Closed-Basin Phases (Lowstands) of the Laurentian Great Lakes and Their Significance*

C.F.M. Lewis

Geological Survey of Canada Atlantic
Natural Resources Canada
Bedford Institute of Oceanography
Dartmouth, Nova Scotia, B2Y 4A2, Canada
E-mail: michael.lewis@canada.ca

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SUMMARY

The Laurentian Great Lakes are a chain of five large water bodies and connecting rivers that constitute the headwaters of the St. Lawrence River. Collectively they form one of the largest reservoirs of surface freshwater on the planet with an aggregate volume of >22,000 km^3. Early interpretations of the postglacial lake history implicitly assumed that the Great Lakes always overflowed their outlets. A study of Lake Winnipeg which concluded that lack of water in a dry climate had dried that lake for millennia led to re-evaluation of the Great Lakes water-level history. Using the empirical information of glacio-isostatic rebound derived from ^{14}C-dated and uptilted Great Lake paleo-shorelines, a method of computation was developed to test the paradigm of continuous lake overflow. The method evaluated site and outlet uplift independently, and low-level indicators such as submerged tree stumps rooted beneath the present Great Lakes were found to be lower than the lowest possible corresponding basin outlet. Results confirmed the low-level, closed-basin hydrological status of the early Great Lakes. This status is consistent with paleoclimatic inferences of aridity during the early Holocene before establishment of the present patterns of atmospheric circulation which now bring adequate precipitation to maintain the overflowing lakes. In a sense, the early to middle Holocene phase of dry climate and low water levels is a natural experiment to illustrate the sensitivity of the Great Lakes to climate change in this era of global warming, should their climate shift to one much drier than present, or future major diversions of their waters be permitted.

RÉSUMÉ

Les Grands Lacs Laurentiens sont une chaine de cinq grandes étendues d'eau connectées par des rivières, constituant la source du Fleuve St-Laurent. Collectivement, ils forment un des plus grands réservoirs d'eau douce de surface de la planète avec un volume total de plus de >22,000 km^3. Les premières interprétations de l'histoire postglaciaire des lacs supposaient implicitement que les Grands Lacs débordaient à leurs exutoires. Une étude du Lac Winnipeg, qui concluait qu'un déficit en eau durant un épisode de climat aride avait desséché le lac pendant des millénaires dans le passé, a mené à la réévaluation de l'histoire du niveau de l'eau des Grands Lacs. En utilisant des données empiriques du relèvement glacio-isostatique, dérivées de littoral anciens surélevés datés au ^{14}C, une méthode de calcul a été développée pour tester le paradigme d'une décharge lacustre continue. La méthode a évalué le soulèvement des sites et des exutoires indépendamment, et il a été constaté que les indicateurs de bas niveau tels que des troncs d'arbres submergés, enracinés en dessous des Grands Lacs actuels, étaient en fait sous le niveau de l'exutoire correspondant le plus bas. Les résultats confirment le bas niveau et le statut de basin hydrologique fermé des Grand Lacs dans le passé. Ce statut est cohérent avec des évidences paléoclimatiques d'aridité au début de l'Holocène, avant l'établissement des modes de circulation atmosphérique actuels qui apportent des quantités de précipitation adéquates au maintien des

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décharges lacustres. Dans un sens, la période climatique aride du début et du milieu de l'Holocène, et les bas niveaux d'eau constituent une expérience naturelle qui illustre la sensibilité des Grands Lacs aux changements climatiques, pertinent dans le contexte actuel de réchauffement global, surtout s'il s'avérait que leur climat devienne plus aride que présentement, ou que des diversions majeures des eaux soient permises.

INTRODUCTION

The Laurentian Great Lakes in eastern North America are a chain of five large water bodies totalling 244,160 km^2 in surface area with a land drainage area of 521,830 km^2. These lakes constitute the headwaters of the St. Lawrence River which drains to the Atlantic Ocean (Fig. 1). Collectively the lakes form one of the largest reservoirs of surface freshwater on the planet with an aggregate volume >22,000 km^3 (United States Environmental Protection Agency and Government of Canada 1995), similar to that of Lake Baikal in southern Siberia (Galazy 2015).

The Great Lakes today are open overflowing lakes (Fig. 2a) which receive adequate water supply to fill their basins and overflow their basin outlets into downstream rivers. The predecessor glacial lakes were also open overflowing water bodies, and the immediate postglacial (early Holocene) Great Lakes were initially interpreted in the same way, although early Holocene water levels in small lakes in eastern North America were long known to have been reduced by the dry climate (Shuman et al. 2002). Only since the late 1990s with increasing awareness of differential lake-basin warping by glacial isostatic adjustment, have the early to middle Holocene (early postglacial) Great Lakes come to be understood as closed or 'terminal' lakes (here termed *lowstands*) whose water levels were generally at lower elevations than their basin outlets (Fig. 2b). The lake basins were then isolated from the outlet rivers.

In this paper the present Great Lakes and the types of evidence used to infer low water levels below the present lake surfaces are discussed. A short review of the glacial and early postglacial Great Lakes follows to reveal that the latter were previously interpreted with an implicit assumption that they were open, overflowing water bodies. This assumption was challenged when the large Lake Winnipeg, about 500 km northwest of the Great Lakes watershed, was found to have been forced by the dry climate into a closed condition for several millennia. The remainder of the paper describes the steps which led to recognition of the early to middle Holocene Great Lakes closed-basin lowstands, and discusses their significance.

THE LAURENTIAN GREAT LAKES OF TODAY

The five Great Lakes between 41.5º and 49ºN latitude in central eastern North America today each overflow into connecting rivers which ultimately discharge to the St. Lawrence River and Atlantic Ocean (Fig. 3a). This chain of large lakes begins with the deepest (406 m maximum depth) and highest water body, Lake Superior (183 m asl), which overflows via the St. Mary's River into water bodies in the basins of lakes Michigan (282 m deep), Huron (229 m deep) and Georgian Bay (168 m deep), which all sit at a common level of 176 m asl. These lakes then overflow via the connecting St. Clair and Detroit rivers, and Lake St. Clair, to Lake Erie (64 m maximum depth) at 172 m asl. Lake Erie then discharges over the 52-m high Niagara Falls via the Niagara River to Lake Ontario (244 m maximum depth) at 74 m asl. The Lake Ontario overflow supplies the St. Lawrence River with an approximate mean discharge of 7000

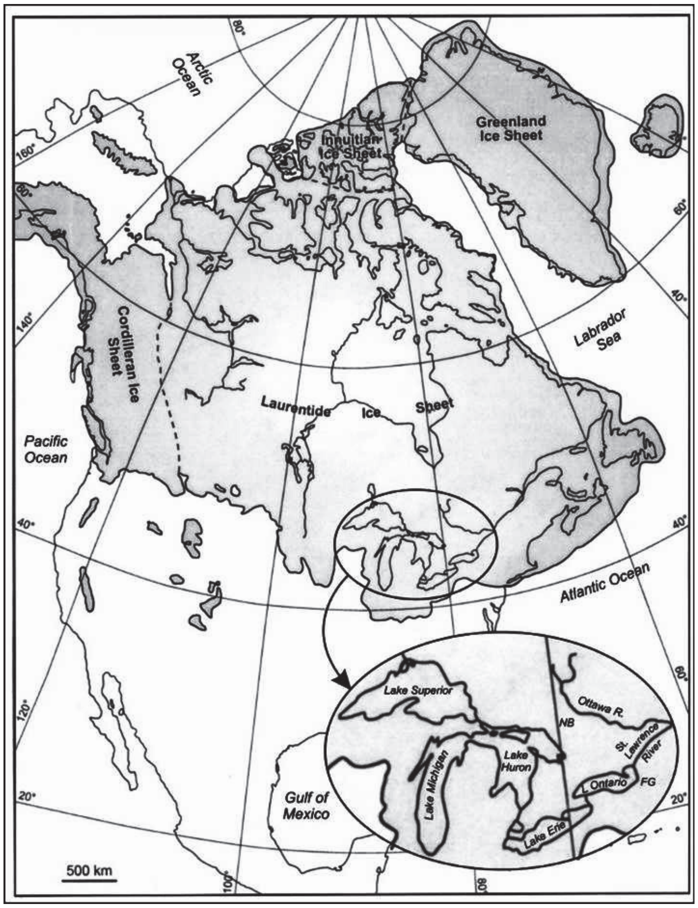

Figure 1. Map of North America showing the Laurentian Great Lakes (within the oval) draining northeastward via the St. Lawrence River to the Atlantic Ocean. Shaded area portrays the North American ice sheets at their maximum extent about 21,000 calendar years ago. From Lewis et al. (2010).

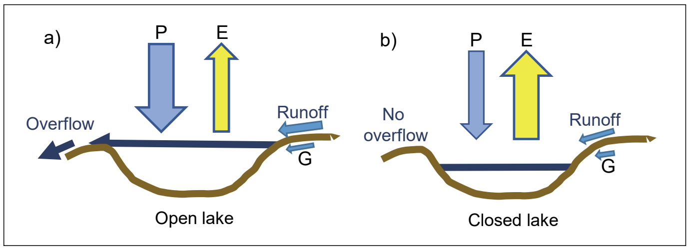

Figure 2. Schematic diagrams illustrating the types of water bodies that have occupied the Great Lake basins. P = precipitation, E = evaporation, G = groundwater. a) Open overflowing lake in which water supply by precipitation, runoff, inflowing rivers, and groundwater exceeds water loss by evaporation, and excess water overflows the basin outlet to supply a downstream river. b) Closed or terminal lake in which water loss by evaporation exceeds water supply by precipitation, runoff, inflowing rivers, and groundwater with the result that water level falls below the basin outlet and is isolated from a downstream river.

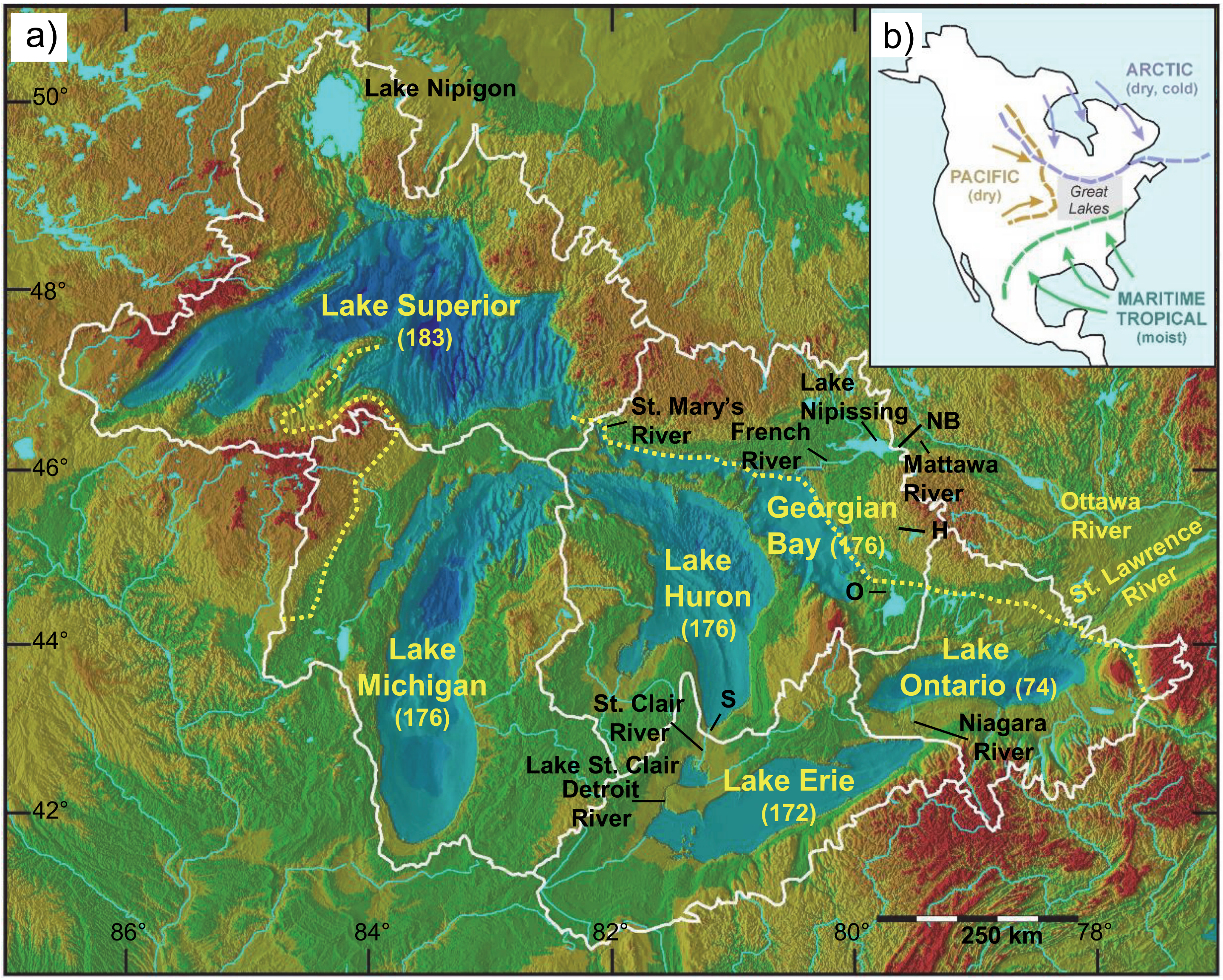

Figure 3. The Laurentian Great Lakes today. a) Shaded-relief map of the Great Lakes basin illustrating lake watersheds (white lines), lake elevations in metres, and generalized bathymetry. Areas north of the yellow dotted line near Georgian Bay, and west of the yellow dotted line near Lake Superior are underlain by harder rocks of the Precambrian Shield, and areas south of these dotted lines are underlain by softer Paleozoic sedimentary rocks. H = Huntsville, NB = North Bay, O = Orillia and S = Sarnia. Adapted from a relief map prepared by P. Gareau in Lewis et al. (2005). b) Map of North America showing the three main air masses whose periodic incursions over the Great Lakes influence their water supply. Adapted from Bryson and Hare (1974).

m^3s^{-1} (Mortsch et al. 2000). Also of importance is the Nipissing–Mattawa lowland northeast of Georgian Bay in the area of North Bay, Ontario, comprising the present Lake Nipissing and the French and Mattawa rivers, which drained the upper Great Lakes to valleys of the Ottawa and St. Lawrence rivers until about 6000 years ago (Fig. 3a).

The lakes occupy basins that were excavated during multiple glaciations, and are mostly underlain by the relatively soft Paleozoic sedimentary rocks that surround and overlap the harder metamorphic rocks of the Precambrian Shield (Fig. 3a). The Lake Superior basin was mainly excavated from Precambrian sedimentary and volcanic rocks which infilled an ancient mid-continent rift valley developed ca. 1.1 billion years ago (Hough 1958; Sutcliffe and Bennett 1992; Stein et al. 2015).

Water is supplied to each lake by direct rainfall and snowfall (precipitation), by runoff from adjacent land surfaces, and by inflow from upstream rivers and lakes. Apart from overflow, water is lost from the Great Lakes by evaporation from water surfaces (United States Environmental Protection Agency and Government of Canada 1995). Groundwater contributions to tributary streams of the Great Lakes range from 48 to 79% of their flows. Although total groundwater volume in the Great Lakes watersheds is estimated in the order of 4900 km^3, similar to the Lake Michigan volume (International Joint Commission 2010), groundwater input to the lakes is not well known.

Atmospheric circulation brings three major air masses over the Great Lakes (Fig. 3b). Incursions of Pacific and Arctic air are dry and enhance evaporation from the lakes. Incursions of moist subtropical air masses from the Gulf of Mexico and adjacent Atlantic Ocean deliver most of the precipitation in the Great Lakes region. Over all the Great Lakes, this water supply currently averages about 87.4 cm/yr (Croley and Lewis 2006), or less than 3% of the water volume stored in the Great Lake basins. Shifts in the relative periods of time that these contrasting moist and dry air masses overly the lake watersheds can change the water supply to the Great Lake basins, and affect their water balances significantly.

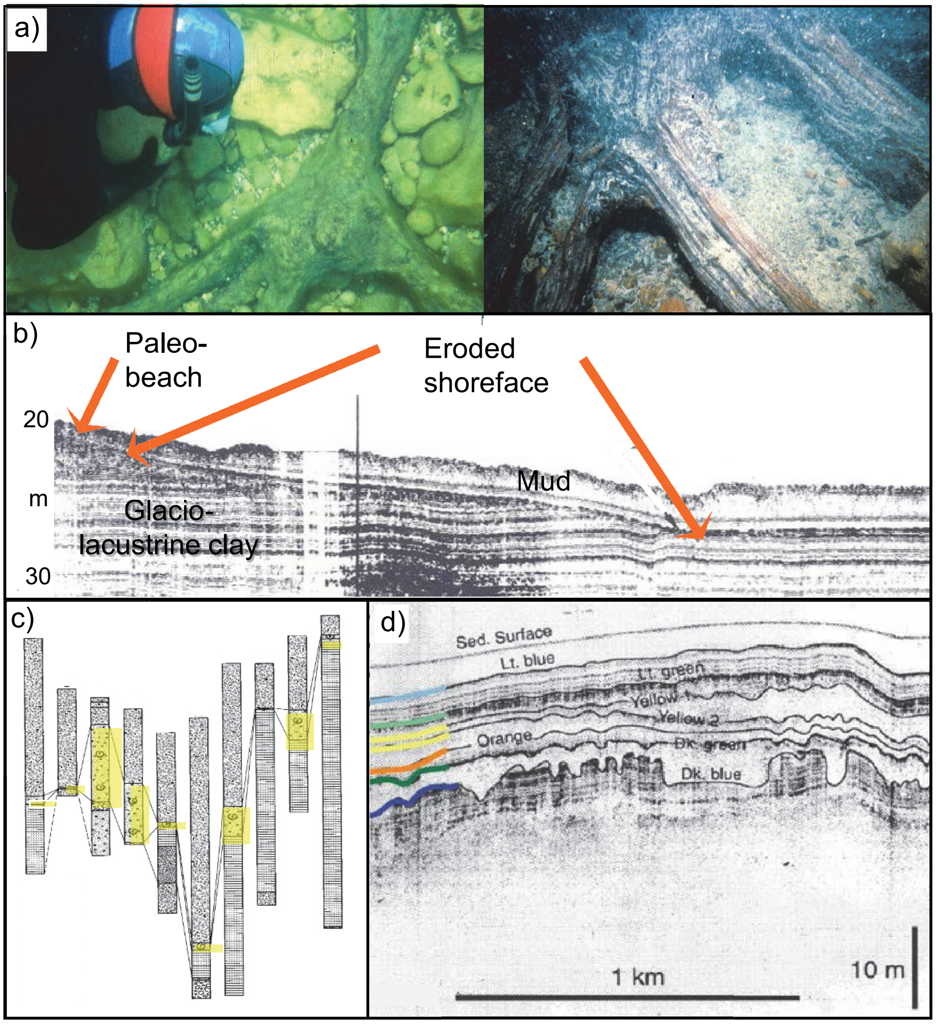

Figure 4. Some evidence indicating lake lowstands. a) Submerged tree stumps rooted in lake floor in Fathom Five National Marine Park between Lake Huron and Georgian Bay. Photos courtesy of S. Blasco. b) Seismic profile of mud-buried beach and shoreface beneath eastern Lake Erie. Adapted from Coakley and Lewis (1985). c) Shallow-water silt and sand with mollusc shells (yellow zones) in cores 3.5 to 11 m long under deep-water mud in Lake Ontario. From Anderson and Lewis (1985). d) Sedimentary unconformities revealed as acoustic reflections in a seismic profile from northern Lake Huron; the most obvious is the lowermost boundary, labelled dark blue. From Moore et al. (1994).

TYPES OF EVIDENCE FOR LOWSTANDS

The most convincing evidence of former low lake levels below the present water surfaces comes from tree stumps that are rooted into the lake floor in growth position (Fig. 4a). The two illustrated stumps are from a set of tree stumps in Fathom Five National Marine Park on the submerged Niagara Escarpment between Lake Huron and Georgian Bay in water depths from 3 to 43 m, which range in age from 7200 to 9600 ^{14}C years BP (Blasco 2001). Other sets of rooted tree stumps are: the Olson Forest in Lake Michigan offshore of Chicago, where stumps are dated at 8100 and 8400 ^{14}C years BP in 24 m water depth (Chrzastowski et al. 1991); two tree stumps in the Straits of Mackinac in 37 m water depth dated at 9800 and 8200 ^{14}C years BP (Lewis et al. 2005, their Table II); and the Sanilac Forest in southern Lake Huron, which ranges in age from 7900 to 6600 ^{14}C years BP in 13 m water depth (Hunter et al. 2006). A rooted spruce dated 7960 ^{14}C years BP was found in southern Lake Huron also, at 35 m water depth, on a submerged cross-lake ridge (O'Shea et al. 2014).

Other evidence for lowstands includes a seismic profile of a mud-buried beach and shoreface in 21 m water depth in eastern Lake Erie (Fig. 4b; Coakley and Lewis 1985), and shallow-water silt and sand with shells under deep-water mud in Lake Ontario at water depths ranging from 20 to 90 m (Fig. 4c) (Anderson and Lewis 1985).

Striking evidence for lowstands is provided by sedimentary unconformities documented in seismic reflection profiles, for example, from northern Lake Huron (Moore et al. 1994). These unconformities, seen in the seismic profile (Fig. 4d) as highlighted reflections labelled dark blue to light blue, signify lowstand wave erosion of previously-deposited sediment in an offshore basin. The yellow to light blue lowstands were dated in sediment cores and ranged from 10,000 to 7800 ^{14}C years BP (Rea et al. 1994a).

Overall, 223 pieces of dated evidence of former lake levels were considered, of which 221 are radiocarbon-dated and two are based on paleomagnetic secular variation (Lewis et al. 2007, 2012; Brooks et al. 2012; Anderson and Lewis 2012; Lewis and Anderson 2012; O'Shea et al. 2014). Additional ages were estimated by correlation of offshore pollen assemblages to onshore dated assemblages. Other indicators of low lake levels such as deeply incised tributary streams, submerged deltas, submerged terrestrial peat deposits, and lowstand unconformities were recognized by Coakley and Lewis (1985), Moore et al. (1994), Karrow et al. (2007), Kincare (2007), Lewis and Anderson (2012), and Lewis et al. (2012).

THE GLACIAL GREAT LAKES

The Great Lake basins were completely covered by the Laurentide Ice Sheet at its maximum extent about 21,000 years ago (Fig. 1). A continuous succession of evolving meltwater lakes began to appear starting in the southern Lake Erie basin about 14,500 ^{14}C BP or 17,600 cal BP (Calkin and Feenstra 1985; Fisher et al. 2015), and continued to develop for about 9000 years during the oscillatory retreat of the ice margin until eventually ice receded northward out of the Lake Superior watershed.

Wave-formed coastal features, such as shorebluffs of the glacial lakes (Fig. 5a), were recognized as shorelines of former water bodies as early as 1818 (Calkin and Feenstra 1985). In the period prior to 1950, when radiocarbon dating became commonplace, at least 48 different investigators produced multiple papers describing the shoreline features and interpreting their origin. The number of new researchers grew to peaks of 7 and 11 per decade in 1890–1899 and 1900–1909, respectively (Fig. 5b). During the 19th century the shoreline features were described without there being a clear consistent concept of their origin. Only towards the close of the 19th century and the beginning of the 20th century were these features recognized as traces of glacial lakes linked to the former ice sheet (Calkin and Feenstra 1985). Mapping the lake shorelines across moraines permitted the correlation of the moraines to aid in the construction of former ice margin positions and reveal the pattern of recession of the former ice sheet.

Early Strandline Diagrams, Uplift, and Isobase Maps

Mapping and correlation of individual glacial lake shorelines also revealed that these formerly level water planes were uplifted towards the north with increasing amplitude. Profiles of the uplifted shorelines were displayed in classic strandline diagrams of elevation versus distance in the direction of maximum uplift (Fig. 5c), as shown in the work of J.W. Goldthwait (1910a). Contour lines joining points of equal elevation over the uplifted water planes were plotted in map form to produce isobase maps. Isobases were drawn on the deformed water planes of former high-level lakes, for example, glacial Lake Algonquin in the Huron and Michigan basins (Fig. 5d) (Goldthwait 1910a). Shorelines were found to rise in elevation towards the NNE mainly in the direction of ice retreat with older shorelines raised more than younger ones – leading to an understanding of isostatic crustal depression under the load of the former ice sheet, and that recovery (uplift) was differential – faster and of greater amplitude in the direction of thicker and longer-lasting ice. As was learned from later studies, the recovery was prolonged – continuing through time, up to and including the present, but at decreasing velocity (Gutenberg 1933; Mainville and Craymer 2005), and including the lesser effects of both water loading and a component of forebulge subsidence near the former ice sheet margin (Clark et al. 1994, 2007).

Understanding of the retreat of the ice margin and the succession of proglacial lakes developed rapidly in the early 1900s, and a major synthesis was published in 1915 by F. Leverett and F.B. Taylor in a 529 page monograph of the United States Geological Survey.

Recognition of Glacial Lake Phases Below Present Water Levels

A theoretical basis for predicting the occurrence of lowstand water levels below the surfaces of the present Great Lakes emerged in 1936 when G.M. Stanley completed mapping the post-Main Lake Algonquin series of lake levels southeast of Georgian Bay. In the Leverett and Taylor (1915) synthesis, the profiles of this series of glacial lake levels converged southward toward a single outlet in the southern part of the Huron basin (Fig. 6a). In their interpretation, an ice margin had blocked and supported the northern parts of these lakes and progressive differential uplift over time had caused shorelines to form at successively lower elevations on the emerging land surface while their outlet remained in the south.

However, Stanley's mapping (Stanley 1936) showed that the successive shorelines were nearly parallel in the strandline diagram (Fig. 6b) which implied that the succession of lowering lakes was rapidly drained eastward to the Ottawa River valley by the opening of lower northern outlets. The projected water planes of the lakes would have passed southward many tens of metres below the water surface of the present Georgian Bay and Lake Huron. This interpretation was demonstrated generally to be true by J.L. Hough in 1962, and the scenario of glacio-isostatically depressed outlets in the northern sectors of Great Lake basins was generally regarded as an explanation for lowstand lake evidence (Hough 1962). In other words, the lakes were still regarded as open, overflowing systems, but the outlets were inferred to be at significantly lower elevations than today.

Study of the Great Lakes region continued in the years following 1950, and with the benefit of ^{14}C-dated chronology, these studies further refined the early interpretations and syntheses. Notable post-1950 syntheses were published by J.L. Hough in 1958 in his book *Geology of the Great Lakes*, and by P.F. Karrow and P.E. Calkin acting as editors and authors in the 1985 book *Quaternary Evolution of the Great Lakes* published by the Geological Association of Canada. Later contributions were made by J.T. Teller in 1987 in a volume of the Decade of North American Geology series, by P. Barnett in 1992 in the Ontario Geological Survey book *Geology of Ontario*, and by Larson and Schaetzl in 2001 in the *Journal of Great Lakes Research*, among others.

By 1990, the glacial Great Lakes were understood to have been open overflowing lakes supplied with abundant meltwater from the retreating ice sheet. Changes in water levels were mainly attributed to outlet erosion or the opening and closing of topographically lower outlets and drainage routes by oscillations of the ice margin during the general deglaciation. Outlets and drainage routes also changed as crustal isostatic rebound progressed at differential rates across this wide area.

OVERFLOWING POSTGLACIAL GREAT LAKES

Until the late 1980s, efforts to extend the history of water levels into postglacial time in the Great Lake basins used an

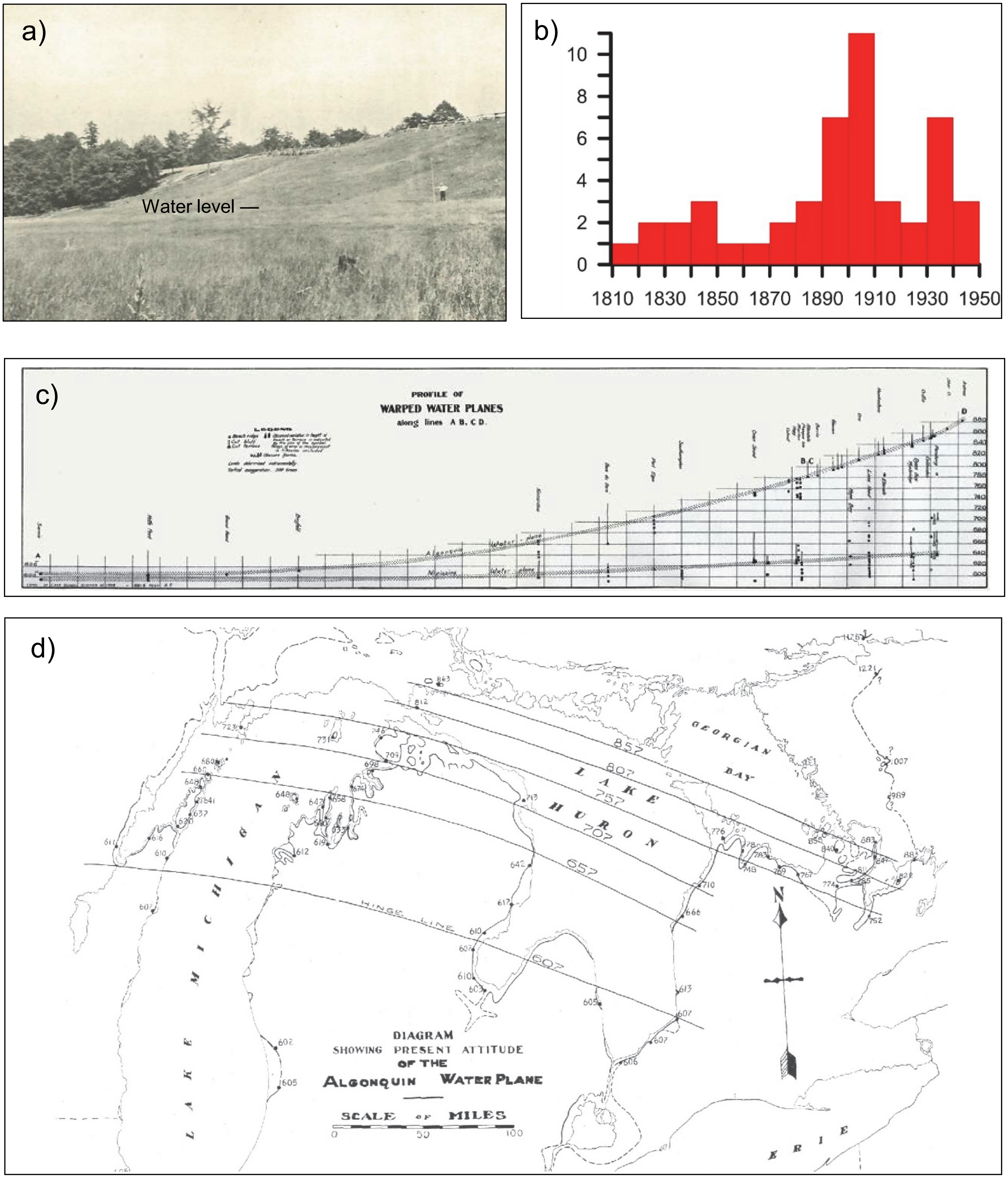

Figure 5. The glacial Great Lakes. a) Glacial lake shorebluff and nearshore terrace near Kettle Point on Lake Huron, Ontario, published by J.W. Goldthwait (1910a). b) Histogram of numbers of new authors per decade writing about the predecessor Great Lakes between 1818 and 1950 based on citations in Goldthwait (1910a, b), Hough (1958), and Karrow and Calkin (1985). c) Strandline diagram (elevation vs. distance) showing rises of 83 m for glacial Lake Algonquin (upper) and 15 m for the younger Nipissing Great Lake (lower) over 264 km in a NNE direction between Sarnia and Orillia, Ontario (Fig. 3). From Goldthwait (1910a). d) Contours of equal elevation or isobases drawn on the inferred waterplane of glacial Lake Algonquin (basins of lakes Huron and Michigan) (Goldthwait 1910a).

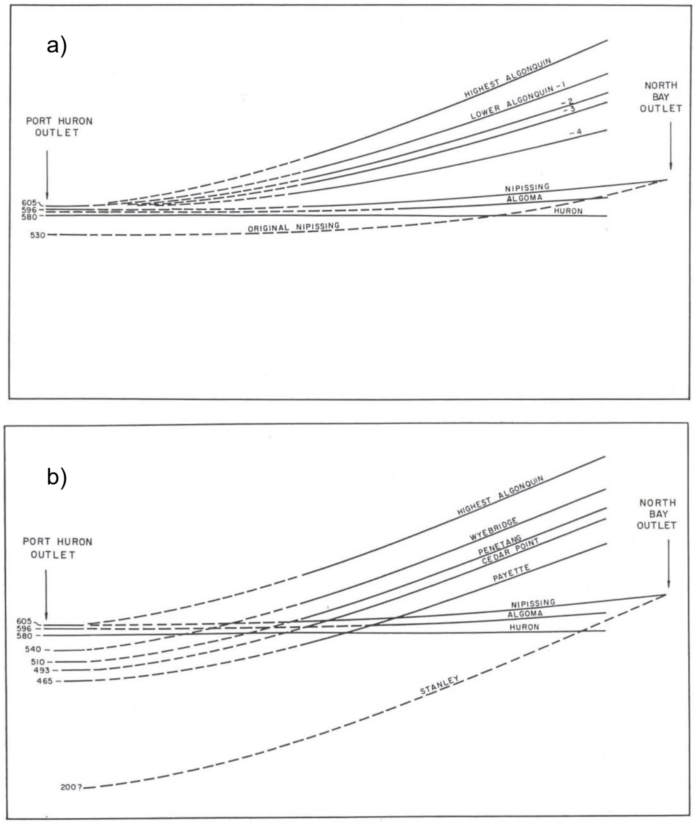

Figure 6. Recognition that 'lowstand' lakes could be caused by glacio-isostatic differential depression of outlets in northern sectors of the Great Lake basins. a) Leverett and Taylor (1915) synthesis of Post Algonquin glacial lakes in Huron and Georgian Bay basins. From Hough (1958). b) G.M. Stanley's (1936) revised synthesis of the Post Algonquin waterplanes. Elevations in feet. From Hough (1958).

implicit assumption that the postglacial lakes *always* overflowed their outlet sills, just as the Great Lakes do today, and as they did during deglaciation when they were supplied with abundant meltwater. Although a few indicators of past water levels lower than those of today were known, they were either ignored or considered explicable by lake outlets being relatively lower in the past due to differential glacio-isostatic depression. Two examples of this paradigm of interpretation are described from the literature.

Pausing Isostatic Rebound to Accommodate the Paradigm

In a 1962 milestone paper, J.L. Hough found a lowstand unconformity in the sediment sequence beneath northwestern Lake Huron which he believed was the evidence of the low water level as predicted by G.M. Stanley in 1936. Hough named the lowstand 'Lake Stanley' in honour of Stanley's insight. Hough reconstructed Lake Stanley with an overflowing outlet at North Bay, Ontario. The uptilted slope of the reconstructed Lake Stanley water plane was not as steep as the gradient of the earlier glacial Lake Algonquin paleosurface. Hough estimated that 25% of post-Algonquin uplift had been achieved by the time of Lake Stanley. His reconstruction met a problem, and he wrote "*In attempting to prepare a reconstruction of the outline of Lake Stanley … it was found that Lake Stanley could not have drained northeastward from Georgian Bay.*" (In other words, it was lower than the North Bay outlet.) He went on "*Therefore the concept of rates of uplift was revised.*" Hough proposed that much of the uplift was delayed until the time when Lake Stanley existed. In other words, to conform to the general assumption of overflowing lakes, Hough proposed a halt in uplift so that the North Bay outlet remained low enough to allow overflow from Lake Stanley. Although the evidence of a closed-basin lowstand was within his grasp, the paradigm that lakes always overflowed their outlets was too strong to overcome (Lewis et al. 2007).

Erie Lowstand Lake – Too Low to Overflow

In 1985, the present author with John Coakley (Coakley and Lewis 1985) attempted to fit a known trend of a submerged beach beneath eastern Lake Erie onto the strandline diagram of glacial lake shorelines in the region. The submerged beach trended up to the NNE as did the profiles of the earlier glacial lake water planes, but it projected to a position below the bedrock sill at the head of the Niagara River near Buffalo. Assuming that this low shoreline had to be part of an overflowing lake the authors declined to interpret the situation by writing "*Clearly, more information is needed before the significance of such features can be assessed further.*" Again, the assumption of overflowing lakes was too strong to allow serious consideration of a closed-basin phase in Lake Erie.

CORRECTING THE IMPLICIT ASSUMPTION – THE LAKE WINNIPEG STUDY

The alternate interpretation of closed-basin large lakes in eastern North America became a reality when the Geological Survey of Canada and partners in Manitoba undertook a major study of Lake Winnipeg (Todd et al. 2000; Lewis et al. 2001). Lake Winnipeg is oriented with its long axis S to N, approximately in the direction of greater postglacial isostatic rebound (Fig. 7). It is generally less than 20 m deep, but its area is large, similar to that of Lake Erie. It overflows at the northern end of its basin into the Nelson River which drains to Hudson Bay. Like its predecessor glacial lake, Lake Agassiz, its basin has been warped upward to the NNE by differential crustal rebound (Johnston 1946; Teller and Thorleifson 1983).

After two seasons of field research and study of sediment architecture in hundreds of kilometres of seismic profiles, and investigation of sediment properties in more than 30 cores of both Lake Winnipeg and underlying Lake Agassiz sediments, it became clear that dry climate had greatly affected this water body. A strong unconformity, marked AU, between the Lake Winnipeg and Lake Agassiz sediments, was evident in seismic profiles in most areas of the lake (Fig. 7b). The surface of the Lake Agassiz sediments is dry and crumbly beneath the overlying Winnipeg sediments.

Pollen studies in the region revealed that a dry grassland climate had existed around most of the lake basin, shown in Figure 7a by the brown and red lines marked 6.5 (^{14}C ka), through most of early and middle Holocene time (Anderson and Vance 2000). Also, the basal ages of the Lake Winnipeg sediments south of the northern North Basin are all around 4 ^{14}C ka (Fig.

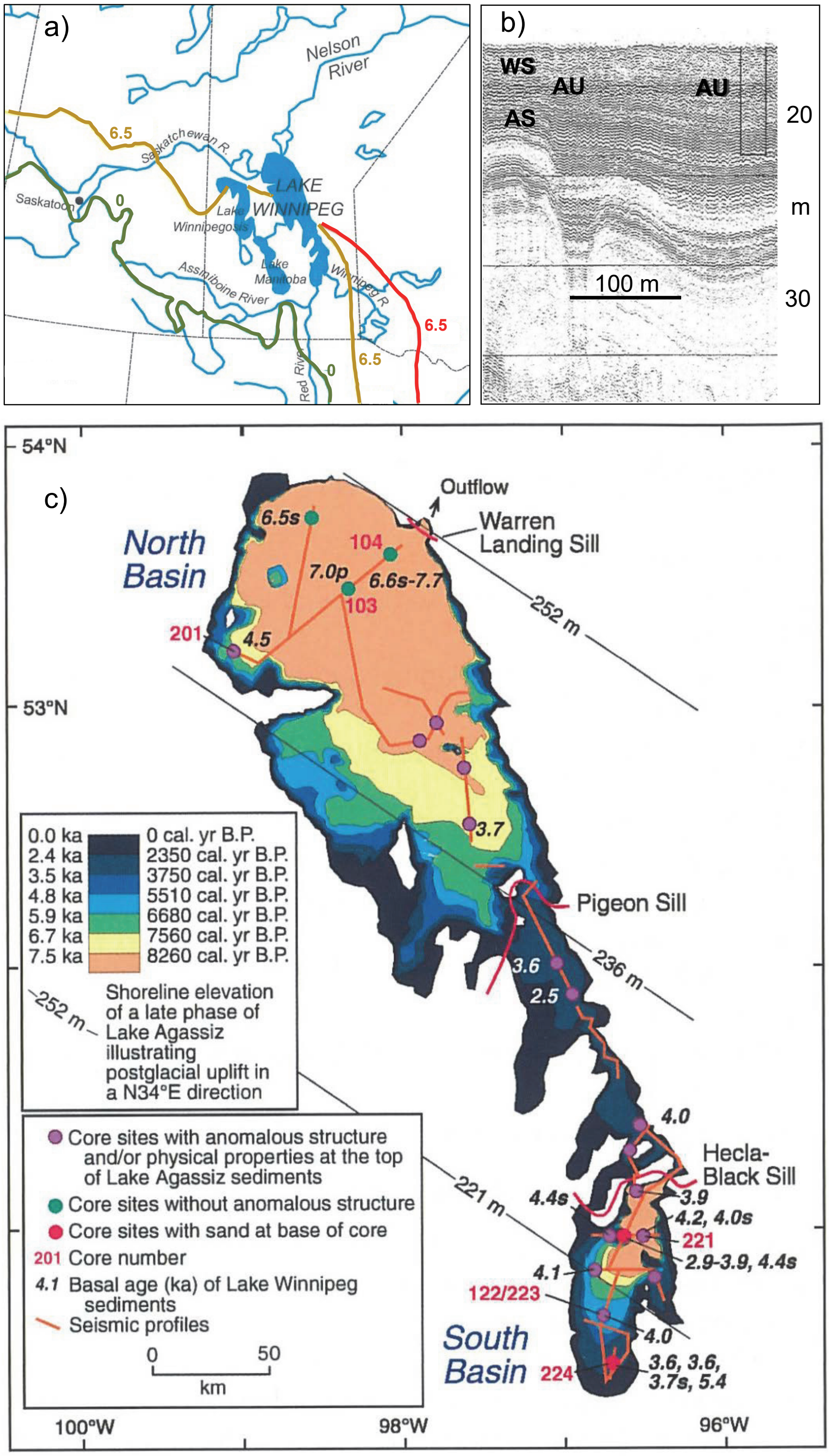

Figure 7. Lake Winnipeg, Manitoba. a) Location of Lake Winnipeg and the outflowing Nelson River. Also shown are the major inflowing rivers, and the northern and eastern boundaries of grassland (brown line) and parkland (red line) biomes at 6.5 ^{14}C ka compared with their present position (green line). From Anderson and Vance (2000). b) Typical seismic profile in Lake Winnipeg showing the Agassiz Unconformity (AU–AU) between Lake Winnipeg sediments (WS) and underlying Lake Agassiz (AS) sediments; black rectangle demarcates a core location. From Todd et al. (2000). c) Map of Lake Winnipeg showing areas that would have been inundated had it always been an overflowing lake; the colour-coded date of inundation applies to the lake area between the southern boundary of the indicated colour and the lake outlet or internal sill. Numbers beside core sites are the ^{14}C ka ages of basal Lake Winnipeg sediments. From Lewis et al. (2001).

7c), revealing that Lake Winnipeg sediments had not begun to accumulate until the late Holocene, even though the basin had been isolated from Lake Agassiz since the end of the early Holocene. A new analysis of uplift showed that had the lake always overflowed its fast-rising northern outlet, as it does today, the lake water would have back-flooded the basin several millennia earlier than the ages found for the basal Lake Winnipeg sediments. For example, the yellow area in Figure 7c would have been inundated by about 7 ^{14}C ka, yet the basal Winnipeg sediments there are only 3700 ^{14}C years old.

REASSESSMENT OF THE POSTGLACIAL GREAT LAKES

With the revelation that Lake Winnipeg had been a closed-basin lake for several thousands of years, a reassessment of the Great Lakes history in the time domain was begun by applying the method pioneered in the Lake Winnipeg study. The method computed independently the elevations of potential outlets and the elevations of sites that preserve evidence of lowstand lake levels through time. If a site with evidence for low water levels was ever *below* the corresponding basin outlet, the lake would then have been in closed-basin status (Lewis et al. 2005).

Since Andrews in 1970 showed that the uplift versus age curve of glaciated arctic sites was well-described by a negative exponential expression, a similar function was sought to fit uplift in the Great Lakes basin using available upwarped shorelines of known age, as shown in the two sketch maps of their isobases (contours joining shoreline sites of equal elevation) in Figure 8a, b.

Relative uplift, *U*, versus age, *t*, is described by the expression

$$U = A * (\exp^{(t/\tau)} - 1) \qquad (Eq.\ 1)$$

This expression from Peltier (1998) depends on two parameters: *A* is a site-specific amplitude factor, and τ is the relaxation time of the uplifting process. *Tau* (τ) is the period in years for which decelerating uplift is reduced by 1/e or 1/2.7183 or 36.8% in successive periods.

Upwarped shorelines of three high-level former lake phases of different age support the negative exponential expression for describing uplift through time – the Iroquois, Main Algonquin, and Nipissing Great Lake phases. The shoreline of glacial Lake Iroquois in the Lake Ontario basin formed about 13,500 cal BP, as lake levels fell when ice began retreating and lower outlets opened from the central St. Lawrence Lowland (Muller and Prest 1985; Anderson and Lewis 2012). Similarly, the shoreline of glacial Main Lake Algonquin formed throughout the basins of Lake Michigan, Lake Huron, and Georgian Bay about 12,500 cal BP as lake levels fell when lower outlets opened to the Ottawa River valley (Karrow et al. 1975). The shoreline of the postglacial Nipissing Great Lake, the last high stage of the upper Great Lakes, formed throughout the basins of lakes Superior, Michigan, and Huron and Georgian Bay between about 6000 and 4500 cal BP when drainage through the rapidly uplifting Nipissing–Mattawa lowland was gradually transferred to southern outlets (Eschman and Karrow 1985; Thompson et al. 2011). At two sites on the isobase maps (Fig. 8a, b), C and D between Lake Ontario and Georgian Bay, uplift of C relative to D was evaluated from extended isobases of these three former lake phases. As shown in Figure 8c, in the plot of relative uplift versus age, uplift for these three shorelines (solid red symbols) describes an exponential function reasonably well with relaxation times between 3000 and 5000 years, a wide range that indicates that uplift computations would not be overly sensitive to the τ parameter.

The relaxation time parameter was evaluated in transects where the ratio of uptilted slopes of two dated paleo-shorelines was known (Fig. 8d). A value of 3700 ± 700 years was obtained for τ from 20 transects (Lewis et al. 2005).

The exponential expression with τ evaluated allowed computation of isobase values at any age from known isobase values of a dated water plane. This property was used to convert water-plane isobase values of different ages to 10.6 ^{14}C ka or 12,500 cal BP, the age of glacial Main Lake Algonquin (Karrow et al. 1975). The Algonquin-age values were contoured to produce a surface of reference uplift throughout the entire Great Lakes basin (Fig. 8e). The uplift is relative to the area southwest of the Lake Michigan basin which was adjacent to the margin of the Laurentide Ice Sheet at its maximum extent, and south of glacial Lake Wisconsin (Fig. 8a, b). Then, for any site in the Great Lakes basin, the appropriate amplitude factor, A, was computed as

$$A = U_{ref}/(\exp(12500/3700) - 1) \qquad (Eq.\ 2)$$

where U_{ref} is given by the reference uplift surface (Fig. 8e) for the site in question. The original elevations E_t for the site at any time t cal BP were calculated as

$$E_t = E_p - A * (\exp(t/3700) - 1) \qquad (Eq.\ 3)$$

or in words: Site elevation at age t cal BP = Present site elevation (E_p) – Site uplift since t cal BP.

This first-order expression enabled independent computation of the original elevations of outlet sills and sites with dated evidence for low (or high) water level in any basin for any age t cal BP. The lake level inferred from low water evidence could then be compared with outlet elevation through time. In this way, a quantitative estimate was obtained for the periods of time when water levels were below outlet elevations and lakes were in closed-basin status. The graph of elevation versus age (Fig. 8f) illustrates the typical trajectory of an uplifting lake-level indicator or an outlet sill with time.

DISCOVERING THE CLOSED LOWSTANDS

The original elevations of dated lowstand evidence and the uplift history of corresponding basin sills were computed and plotted on graphs of original elevation versus age for the Great Lake basins (Lewis et al. 2005, 2008). Closed-basin conditions were recognized in the Great Lakes (Lewis and King 2012), and results are summarized below.

Lake Ontario Water Level History

On the graph of original elevation versus age for the Lake Ontario basin (Fig. 9a) (Anderson and Lewis 2012), the water level history was inferred from the plotted array of lake-level evidence, and is shown by the thick blue line. Water levels descend on the right through the post-Iroquois glacial lake phases to a plateau between 12,900 and 12,300 cal BP or earlier, which was a near still-stand (a period of little relative movement of water level and lake basin) while the lake was at the same level as the Champlain Sea in the St. Lawrence Valley, as shown in the map of reconstructed shorelines (Fig. 9b). The black lines illustrate the rising sills of Lake Ontario (Fig. 9a). Clearly the blue line or lake level of early Lake Ontario fell below the outlet sills from about 12,300 to about 8300 years ago, defining a 4000-year period of closed-basin lowstand conditions. The lake lowstand reconstruction in Figure 9c for 10,500 years ago shows the lowstand shoreline well offshore from the present shoreline (black line).

A mud-buried paleo-barrier beach in the western end of the basin is shown in Figure 9d by the successive clinoform reflections in the seismic profile. The uplift history of the beach on the graph (labelled Grimsby-Oakville barrier beach in Fig. 9a) indicates that it was at lake level more than 12,300 years ago, and was likely built during the near still-stand at that time. The isotopic composition of shelly fauna (ostracodes and clams) in offshore sediment cores revealed an increase in $\delta^{18}O_{lakewater}$ after 12,900 cal BP from ~–14‰ to –9‰, signifying loss of glacial meltwater and hydrologic closure of Lake Ontario (Hladyniuk and Longstaffe 2016), consistent with the water level history in Figure 9a.

Lake Erie Water Level History

In the Lake Erie basin similar analyses of lowstand evidence and outlet sills plotted on a graph of original elevation versus age revealed a 6000-year period of closed-basin conditions, the longest in all of the Great Lakes, from about 12,500 to 6500 years ago (Fig. 10a) (Lewis et al. 2012). The lake level was defined in the central basin by its rise from the early Holocene lower limit of an offshore wave-cut terrace to middle Holocene buried lagoon sediments at the upper limit of the terrace at Rondeau Park (Fig. 10b). In the eastern basin the lake level was defined by a succession of dated mollusc shells in a

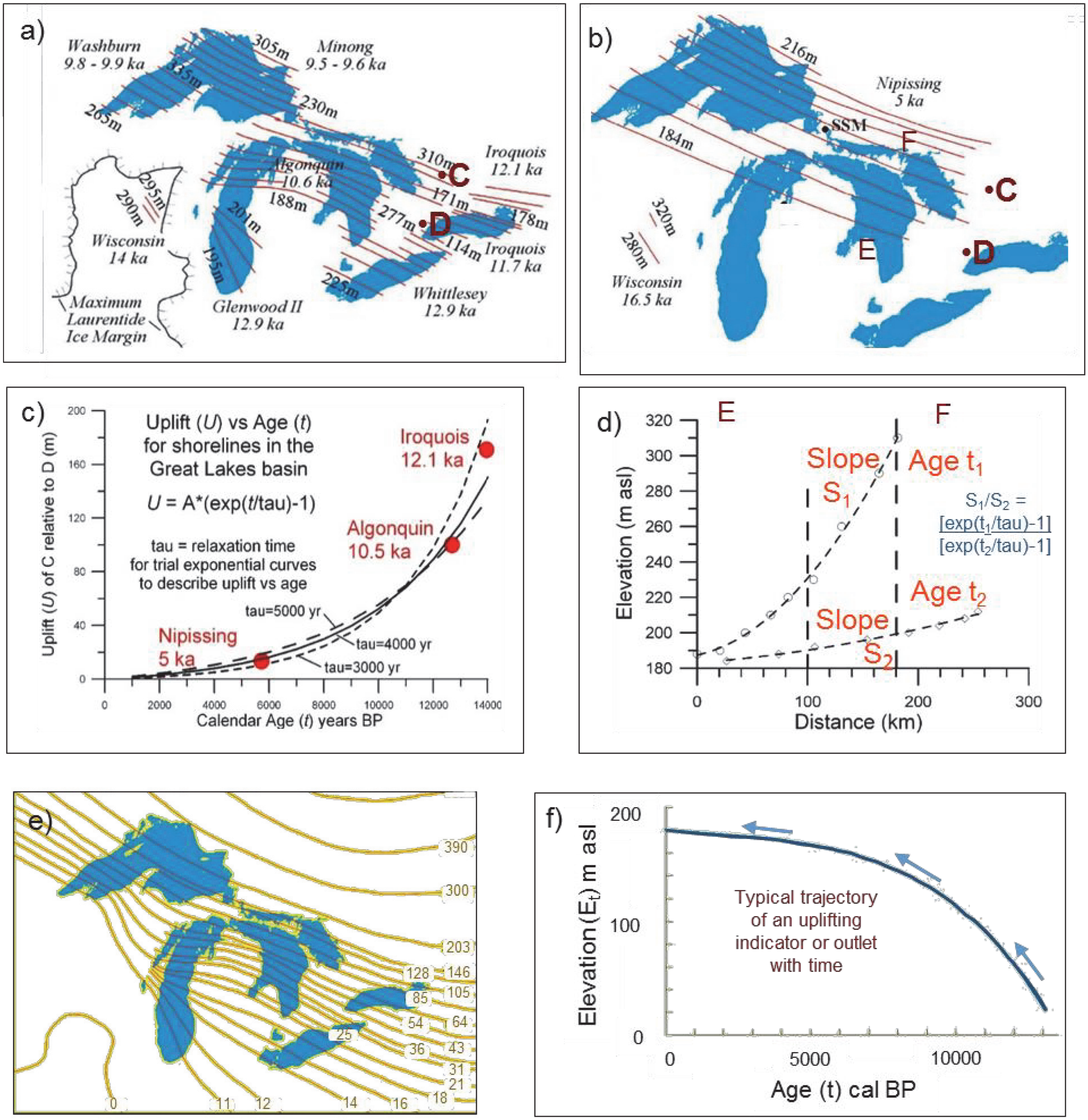

Figure 8. Computation of the original elevations of lowstand evidence and basin outlet sills independently. a–b) Sketch maps showing the age and isobase elevations of principal paleo-lakes in the Great Lakes region. From Lewis et al. (2005). c) Relative uplift of two locations, marked C and D (Fig. 8a b) versus age based on the differences in isobase values at C and D for the dated waterplanes of the Iroquois, Algonquin, and Nipissing paleo-lakes. From Lewis et al. (2005). d) Plot EF of elevation versus distance for isobases of two dated paleo-lake waterplanes (the higher Lake Algonquin and the lower Nipissing Great Lake shorelines) on the transect EF in Figure 8b; the ratio S_1/S_2 shows how τ, uplift relaxation time, is related to the shoreline slopes and ages. e) Reference uplift surface in metres describing glacial isostatic rebound throughout the Great Lakes basin since 12,500 cal BP, age of glacial Main Lake Algonquin, relative to the 0 m contour southwest of the Lake Michigan basin. From Lewis et al. (2005). f) Typical trajectory of an uplifting lake-level indicator or an outlet with time. See text for further explanation.

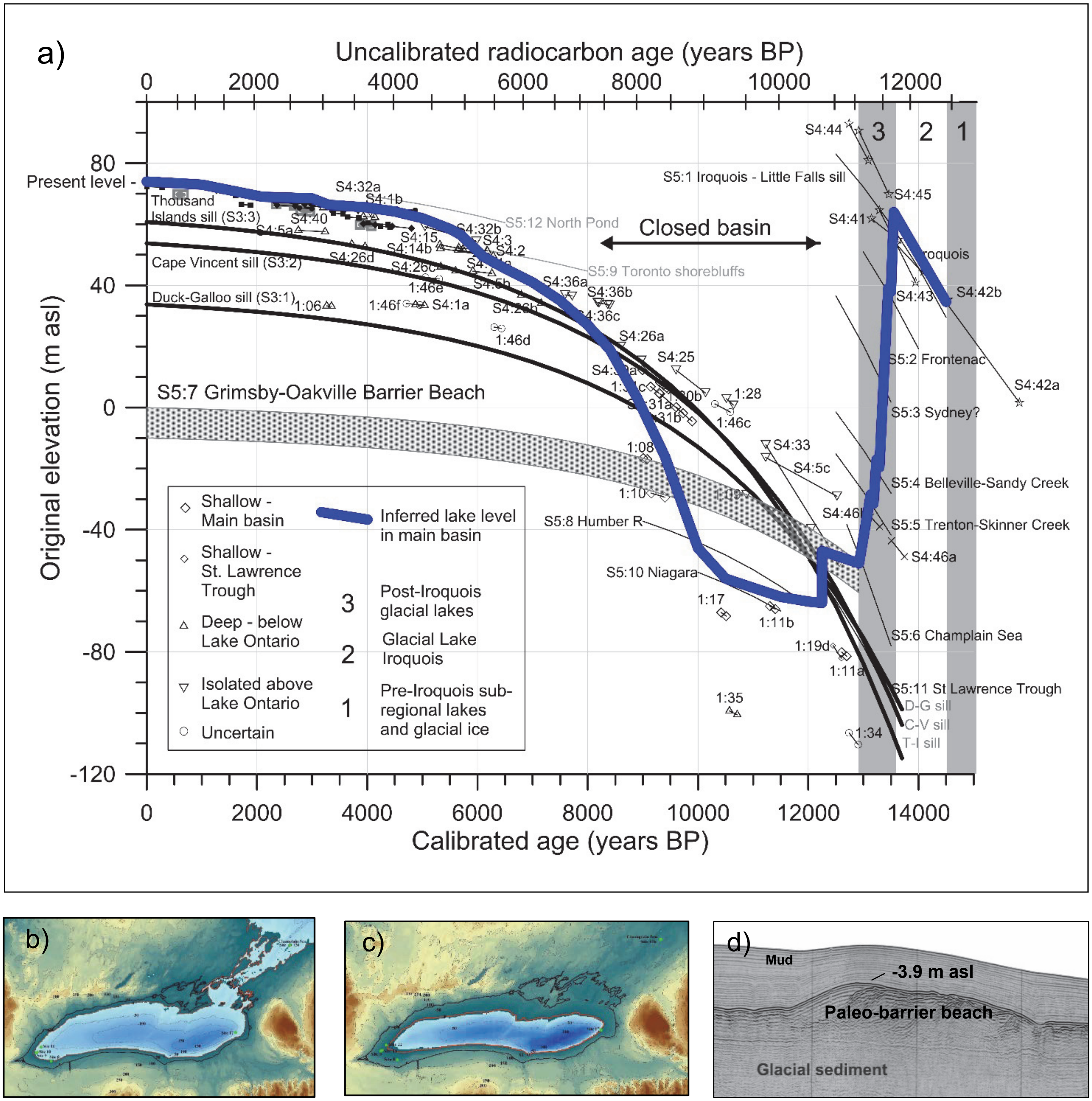

Figure 9. Lake Ontario basin water level history. a) Graph of original elevation versus age for an array of evidence of former water levels and the sills of the Lake Ontario basin (black lines). Inferred lake level is shown by the thick blue line. b) Map of reconstructed shorelines at 12,500 cal years BP showing confluent levels of early Lake Ontario and Champlain Sea in St. Lawrence River valley. Present Lake Ontario shore in black line. c) Map showing reconstructed shoreline of closed-basin Lake Ontario at 10,500 cal years BP. d) Seismic profile of a mud-buried paleo-barrier beach (Grimsby-Oakville Barrier Beach in Fig. 9a) in the western Lake Ontario basin, probably constructed during a near still-stand 12,900 to 12,300 cal years BP. Parts (a), (b) and (c) from Anderson and Lewis (2012), part (d) from C.F.M. Lewis unpublished data.

core of the mud-buried paleo-Nanticoke beach sediments. Between 12,500 and 6500 cal BP lake level was as much as 16 m below the outlet sills in the Niagara River. During this closed-basin phase, a map reconstruction of lowstand shorelines for 8500 cal BP (Fig. 10b) shows that Lake Erie was reduced to separate pools of water in its sub-basins.

Early and middle Holocene sediments in Lake Erie, from about 12,000 to 5000 cal BP, are consistent with a strongly

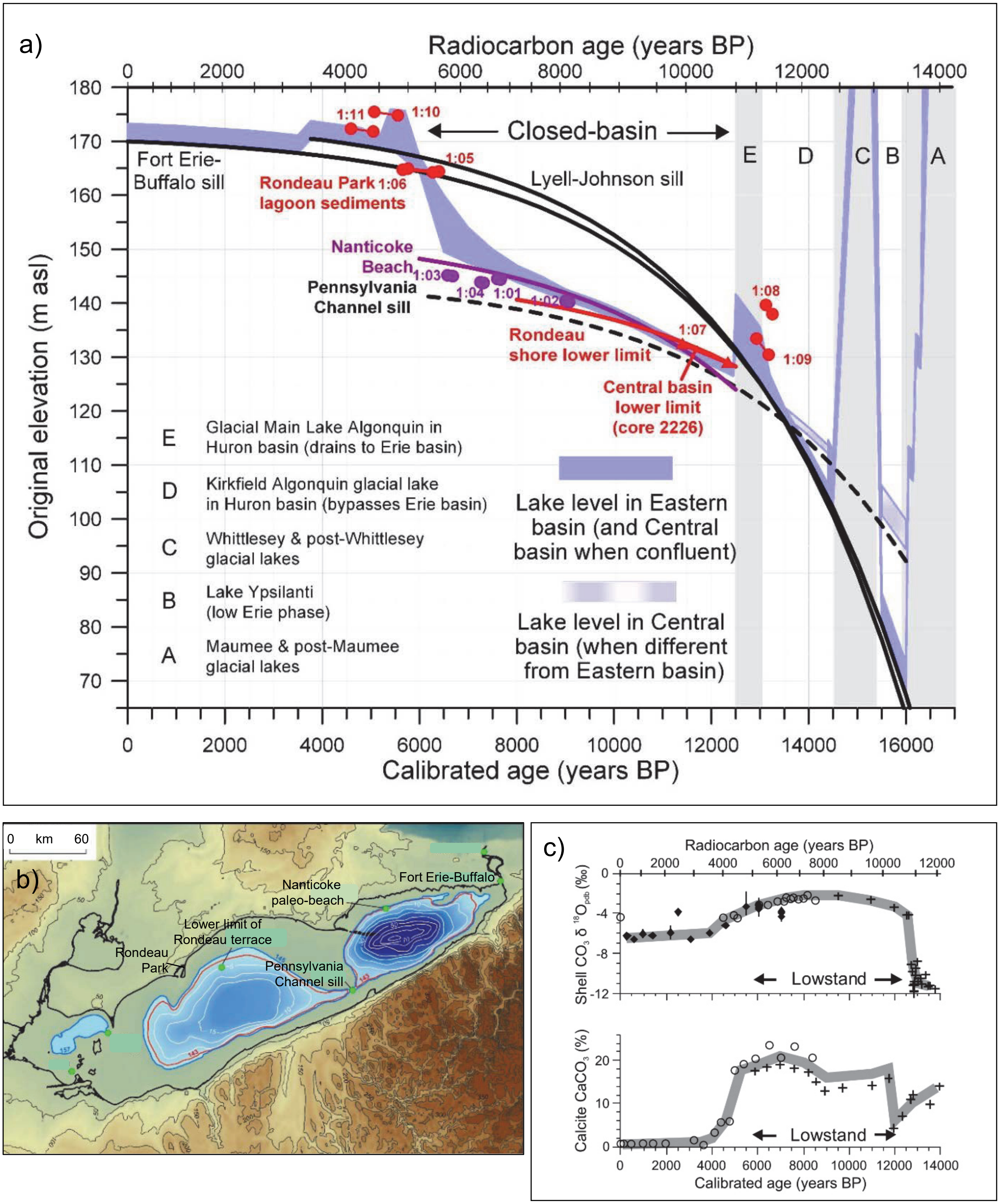

Figure 10. Lake Erie basin water level history. From Lewis et al. (2012). a) Graph of original elevation versus age for evidence of former lake levels and the outlet sills (black lines) of the Lake Erie basin. Inferred lake level is shown by the thick blue line. Key radiocarbon-dated evidence (site evidence numbered 1:11, as in Lewis et al. 2012, for example) is indicated by red and purple circles (red for evidence near Rondeau Park, and purple for evidence at Nanticoke paleo-beach, Fig. 10b); the circles at ends of lines bracket 2-sigma age ranges. b) Map showing shorelines of reconstructed closed-basin Lake Erie at 10,500 cal years BP. c) Sediment properties in offshore Erie basin sediments differentiate the lowstand (~12,000 to ~5000 cal BP) and open-lake (~5000 cal BP to present) conditions. Mollusc and ostracode δ^{18}O isotopic composition are shown in the upper graph and mineral calcite content is shown in the lower graph.

evaporative, calcite-saturated lowstand environment (Fig. 10c). The lowstand sediments are characterized by a highly positive δ^{18}O composition of ostracode and molluscan fossils, shown in the upper graph, and a high mineral calcite content, shown in the lower graph (Fig. 10c; Lewis et al. 2012).

Lake Huron and Georgian Bay, Lake Michigan, and Lake Superior Water Level History

In late glacial and early Holocene time, the overflow outlet for the Michigan, Huron and Georgian Bay basins was at North Bay, Ontario, via the Nipissing–Mattawa lowland. The uplift history of the elevation interval between the outlet sill and the full-discharge level at North Bay is shown in Figure 11a by the pale green band of rising original elevations while the water level history is portrayed by the thick blue line through the lake-level indicator data (Lewis and Anderson 2012). These data include complementary evidence of Georgian Bay lowstands in basins of the French River (Brooks et al. 2012), and in Georgian Bay (McCarthy et al. 2012). Tree stump data, always above the inferred lake level, are shown by the solid-coloured downward-pointing triangles, and their locations are plottted in Figure 11b. The lake-level history defines five lowstands with four below the North Bay outlet. Lowstands in solid blue line (Fig. 11a) are based on evidence in the Huron basin and are considered phases of low Lake Stanley. Lowstands shown with blue dots are based on evidence in the Georgian Bay basin and are named 'Lake Hough' after J.L. Hough. These lacustrine lowstands are largely contemporaneous with terrestrial evidence of dry climate and drought in eastern upper Michigan, USA, between the Lake Michigan and Lake Superior basins (Loope et al. 2012). Lowstands marked B, C_3, and D in Figure 11a are correlated with the Lt. Blue, Lt. Green1, and Lt. Green2 offshore sediment unconformities in the northern Lake Huron basin (Fig. 4d), marked by brown lines above the X-axis of Figure 11a.

The approximately 2500-year period of closed lowstands from about 11,000 to 8500 years ago was interrupted by at least four highstands. These lakes, collectively named 'Lake Mattawa,' would have overflowed the basin outlet valley at North Bay into the Mattawa and Ottawa River valleys. Currently they are variously attributed to outburst floods of surface water from glacial Lake Agassiz, meltwater from the Laurentide Ice Sheet (Breckenridge and Johnson 2009), or possibly, from unknown reservoirs. Recent dating of Lake Agassiz beaches in the Red River Valley (Fig. 7a) (Lepper et al. 2013), and boulders in outlet discharge channels north of Lake Superior (Kelly et al. 2016) suggests that the 10.7 cal BP Early Mattawa lake (Fig. 11a) could have been caused by rapid drainage from the Campbell beach level of Lake Agassiz through the basins of lakes Nipigon and Superior to the Lake Huron basin. Also, the Lake Mattawa phase about 9300 cal BP has been attributed to erosion of the morainic dam across the eastern Lake Superior basin and drainage of the impounded glacial Lake Minong (Yu et al. 2010; Lewis and Anderson 2012).

As measured in benthic ostracode fossils, the δ^{18}O isotopic composition of the Lake Mattawa highstand water was most similar to that of evaporated water or precipitation and runoff (Rea et al. 1994a, b; Dettman et al. 1995). It was more positive than that for the lowstand water which was quite negative, typical of glacial meltwater. Although more research is in order, the current data suggest the highstand lakes were filled with outburst floods from upstream stratified Lake Agassiz and the Superior basin lake during summers when the surface waters had undergone evaporation and mixing with summer precipitation and runoff (Buhay and Betcher 1998; Birks et al. 2007). The lowstand bottom waters, in which ostracodes lived, were possibly dominated by glacial groundwater, which drained from porewater in adjacent watersheds as base levels were lowered by evaporation (A. Smith personal communication 1996). The groundwater would have been charged by previous subglacial meltwater or glacial lakes. Clearly, the isotopic composition of surface waters in these Huron basin lake phases needs to be determined, as has been done for glacial Lake Agassiz (Buhay and Betcher 1998; Birks et al. 2007) to verify these suggestions.

In the Lake Michigan basin, low-level Lake Chippewa, following Lake Algonquin, was recognized by Hough (1955) on the basis of a sedimentary unconformity in which shallow-water sand and shells were overlain by deep-water clay. Hydrological closure of the basin was inferred at about 7 ^{14}C ka by Forester et al. (1994) and Colman et al. (1994) in a study of the ostracode fauna, and was confirmed later by a comparison of Holocene water level and outlet elevations in the Lake Michigan basin (Lewis et al. 2005). Multiple sites in the Lake Superior basin revealed a large drop during the Houghton phase and indicated that the water level was below the basin outlet between >9100 and 8900 cal BP (Boyd et al. 2012). Also, closed lake status is supported by a shift to more positive δ^{18}O isotopic values found in benthic ostracode fossils from the Lake Superior basin for the same period (Hyodo and Longstaffe 2012). Thus, the Superior basin lake was hydrologically closed during this period at least.

PALEOCLIMATE RECONSTRUCTIONS SUPPORT THE CLOSED-BASIN LOWSTANDS

Trends of annual temperature and humidity (moisture) obtained for the southern Ontario region from isotopic variations in terrestrial plant matter and lake sediments (Fig. 12a) show that the early Holocene climate was much colder and drier than at present, suggesting that dry Arctic air masses were initially prevalent over the Great Lakes basins followed by dry and warmer Pacific air masses (Edwards and Fritz 1986; Edwards et al. 1996). These trends are consistent with computation of the solar radiation reaching the northern hemisphere (Fig. 12b) (Kutzbach et al. 1998). During the period of the Great Lake lowstands, indicated by the grey band (Fig. 12b), summer insolation was more than 30 Watts/m^2 greater than present, signifying enhanced evaporation from summer water surfaces compared with present conditions.

Changes in the vegetative cover on land surfaces derived from pollen analyses also support an early Holocene dry climate. Pollen assemblage data have been correlated quantitatively to climate, and transfer function analyses of pollen

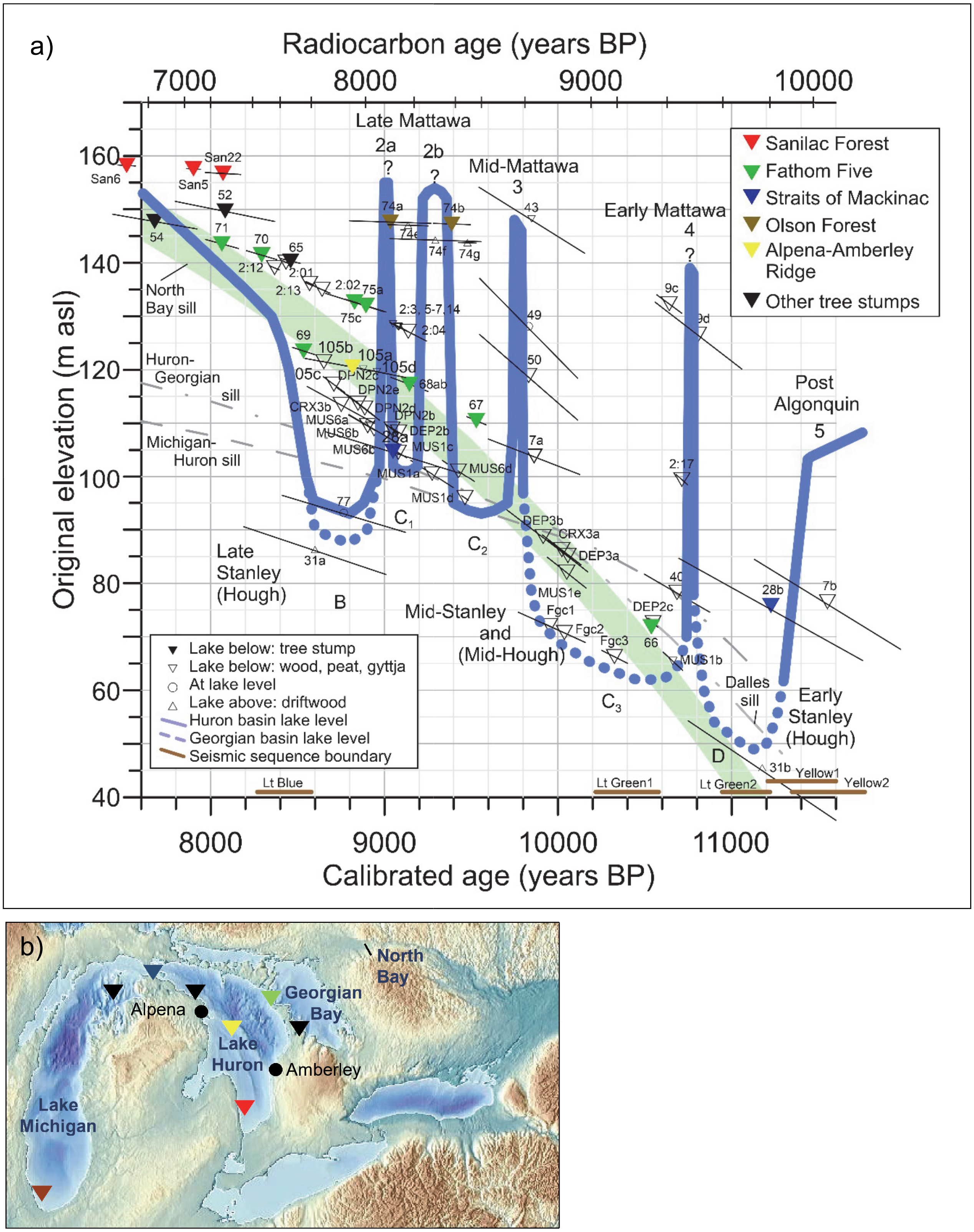

Figure 11. Huron and Georgian Bay basin water level history. From Lewis and Anderson (2012). a) Graph of original elevation versus age for evidence of former lake levels in the Huron and Georgian Bay basins and the elevation interval between outlet sill and full-discharge level (pale green band) at North Bay, Ontario. Inferred lake level is shown by the thick solid blue line in the Huron basin and by the blue dotted line in the Georgian Bay basin. b) Map showing locations of submerged tree stump data (legend on Figure 11a) and the North Bay outlet.

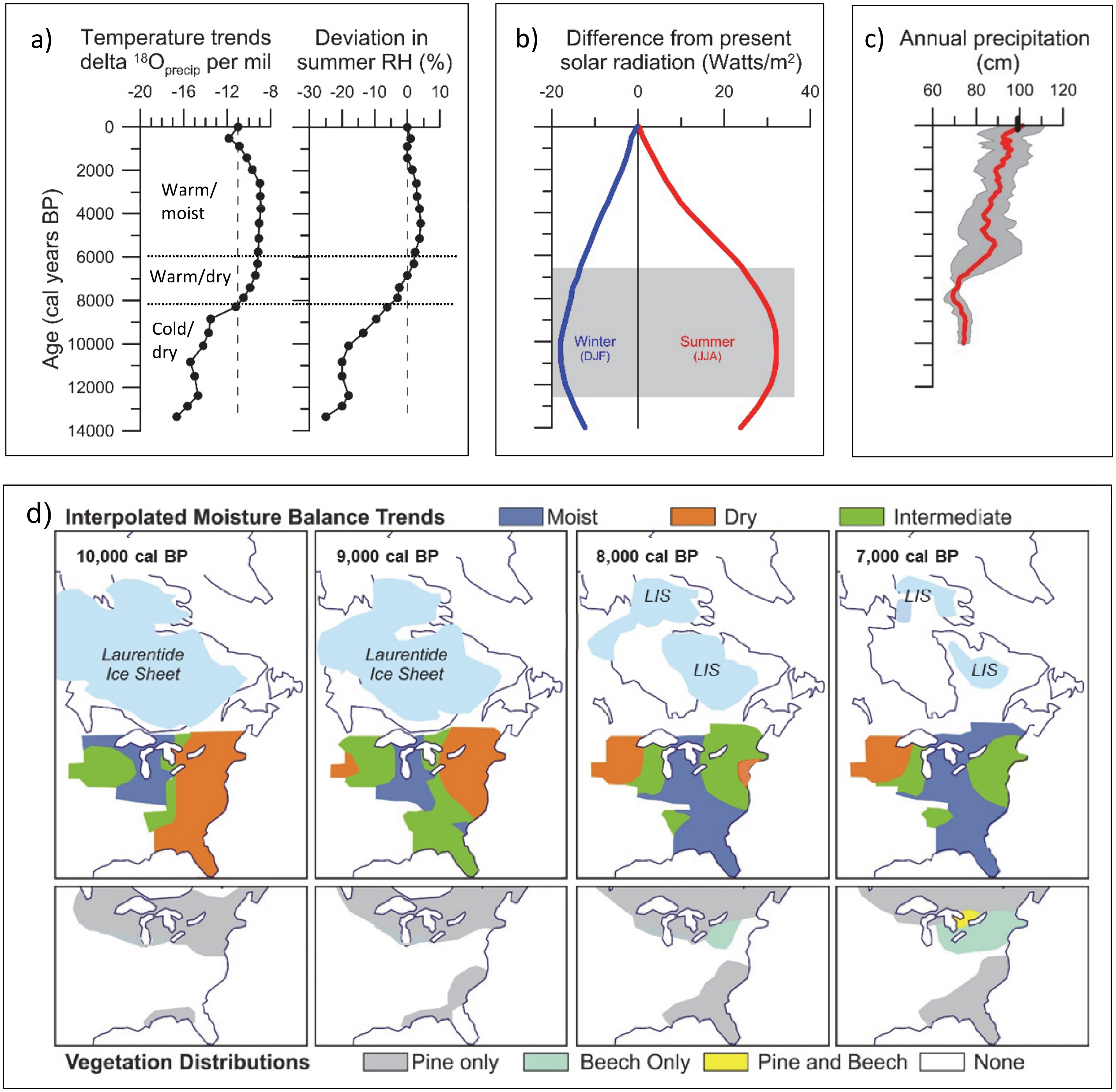

Figure 12. Paleoclimate proxy indicators. a) Mean annual temperature and summer humidity (moisture) trends in southern Ontario based on isotopic studies of terrestrial plant matter and lake sediments. Vertical dashed lines indicate present values. Data from Edwards et al. (1996). b) Solar radiation (insolation) in summer months (JJA) and winter months (DJF) for northern hemisphere. Grey band demarcates period of Great Lake lowstands. Data from Kutzbach et al. (1998). c) Results of transfer function analyses of pollen assemblage records from four small lakes near Huntsville, Ontario (Fig. 3), east of Georgian Bay showing a reduction of about 25–30 cm/yr in annual precipitation during the Great Lake lowstands; envelope of values in grey, and average values in red. Black line across X axis indicates present average precipitation. Data from McCarthy and McAndrews (2012). d) Early Holocene changes in moisture balance trends in small lake levels/areas and the relative presence of dry-tolerant pine and moisture-loving beech for the diminishing area of the Laurentide Ice Sheet (LIS) Adapted from Shuman et al. (2002).

records from small lake basins east of Georgian Bay (McCarthy and McAndrews 2012), for example, clearly show a reduction in early Holocene annual precipitation of about 25–30 cm/yr compared with present values (Fig. 12c).

The correlation of early Holocene climate change and deglaciation is well illustrated by Shuman et al. (2002) in snapshots from 10,000 to 7000 cal BP (Fig. 12d). In the upper series of maps showing a receding Laurentide Ice Sheet, changes in small lake levels and interpolated moisture balance trends show that dry conditions (orange areas) affected the eastern Great Lakes from 10,000 to 9000 cal BP, and the western Great Lakes from 8000 to 7000 cal BP. In the lower series of maps, the changing distribution of dry-tolerant pine and moisture-loving beech illustrates the increasing moisture availability through the early Holocene. At 10,000–9000 cal BP the Great Lakes were surrounded by dry-tolerant pine, but by 8000 to 7000 cal BP, the presence of moisture-loving beech appeared around the southern Great Lake basins.

In the absence of meltwater supply, the Great Lake lowstands resulted from a major incursion of dry climate induced by the residual presence of the retreating Laurentide Ice Sheet and its overlying anticyclonic atmospheric circulation, which prevented meridional (northward) flow of moisture (Shuman et al. 2002). The presence of aeolian deflation surfaces and terrestrial sand dune activity in the Great Lakes region attests to the late Wisconsinan and early Holocene dry climate, possibly aided by North Atlantic cool phases recorded in the Greenland ice core records (Campbell et al. 2011). The blockage of northward flows of moist subtropical air masses, likely also aided by southward shifts of strong temperature gradients and the atmospheric jet stream because of the residual ice sheet presence, enhanced the occurrences of dry Arctic air and later dry Pacific air masses over the Great Lake basins. The more frequent presence of dry air would have increased evaporation and reduced the lake levels. As the ice sheet diminished after 8900 cal BP and broke up over Hudson Bay at 8200 cal BP, northward advection of subtropical moisture increased (Shuman et al. 2002). With the increased water supply, lake levels rose and the closed-basin phases of the Great Lakes came to an end.

SIGNIFICANCE OF THE GREAT LAKE LOWSTANDS

Sensitivity to Climate Change

The Holocene lowstands outlined by this research can be viewed as a natural experiment to show that the Great Lakes are sensitive to climate change, particularly to climates drier than the present. This knowledge is important and such sensitivity may not be widely appreciated because the Great Lakes appear now to be relatively stable, as their mean monthly water levels have varied less than 2 m during the past 150 years of lake level monitoring (NOAA 2016).

From another viewpoint, Croley and Lewis (2006) have examined the question “How much climate change is required to reduce the present Great Lakes to closed-basin water bodies?” The change inputs are expressed in graphs of temperature change versus reductions in precipitation. The resulting changes in water level for specific lakes (Lake Superior and Lake Huron, for example, in Fig. 13) are expressed as elevation contours on the graph; the diagonally-ruled zones indicate where the lake levels fall to the outlet sills. As climate changes, contours to the left of the diagonally-ruled zones (outlet sills) illustrate the declining surfaces of the open lakes and those to the right of the same zones define the declining water surfaces when the lakes become closed. These lakes and the other Great Lakes (Croley and Lewis 2006) would become closed water bodies for large reductions in annual precipitation of 40 to 60% with present temperatures or small rises in temperature of < 2°C. In addition, evaporation and reduction of lake levels would be enhanced if wind speeds were faster (T. Croley personal communication 2010).

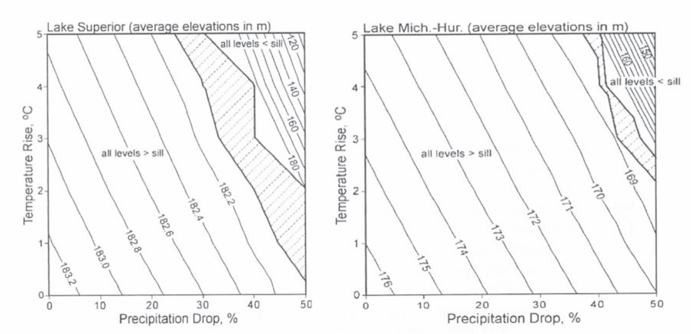

Figure 13. Climate change needed to drive the present Great Lakes into hydrological closure. These graphs of elevation contours (m asl) show how the lake surfaces decline from left to right as a function of changes in annual average values of temperature versus precipitation. Contours to the left of the outlet sills (ruled areas) indicate decline of the water surfaces while the lakes overflow their outlets, and those to the right refer to lowering of the water surfaces once the lakes are closed. From Croley and Lewis (2006).

Clearly, quite large reductions in climatic moisture to 40 to 60% of present precipitation are needed to drive the lakes into closure. This result is consistent with the conclusion of this paper that the lowstands were uniquely induced by severe dry climate related to the presence of the residual ice sheet during deglaciation.

The sensitivity of the Great Lakes water levels to past reductions in water supply implies that they would be sensitive also to future large water withdrawals and transfers to alleviate water shortages elsewhere in North America. Such a possibility should be taken into account in policy formulations regarding large water diversions from the Great Lakes.

What is the Future Outlook for the Great Lakes?

It is uncertain how climates will evolve over the Great Lake basins in this era of global warming. Kutzbach et al. (2005) explained by means of a plot of effective precipitation (P–E) versus Earth latitude, S pole to N pole, that warming is accompanied by an increase in total atmospheric vapour content in the tropics, and by an increase in poleward transport of water vapour (Fig. 14).

The boundary in the northern hemisphere, between northern areas which become wetter and southern areas which become drier, is about 42–43°N in the latitude of the southern Great Lakes for the average of seven global climate models driven by CO_2 greenhouse gas warming. However, individual climate simulations put this boundary as far south as the northern Gulf of Mexico, and as far north as James Bay. With this extent of variability, the future water supply of the Great Lakes is uncertain. Nonetheless, the early to middle Holocene phase of dry climate and closed-basin lowstands illustrates the sensitivity of the Great Lakes should their climate shift to one much drier than present, or future major diversions of their waters be permitted.

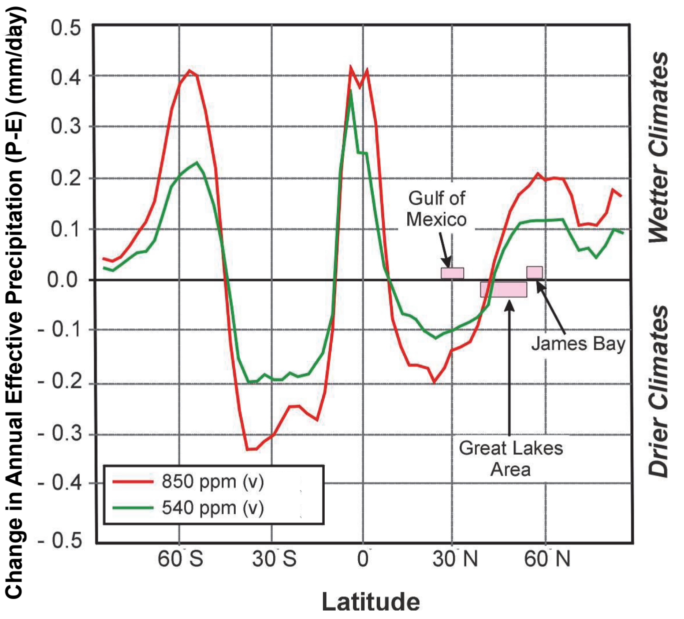

Figure 14. Future Great Lake climates. Graph of change in annual effective precipitation (precipitation – evaporation) versus Earth latitude for results from two groups of 7 climate models providing projections for the period 2089–2099, assuming either high-end (850 ppmv) or low-end (540 ppmv) greenhouse gas concentrations. The average boundary between future drier and wetter climates lies in the southern Great Lakes region, but individual model results position the boundary as far south as northern Gulf of Mexico and as far north as James Bay. Adapted from Kutzbach et al. (2005).

SUMMARY AND CONCLUSIONS

Hydrologically-closed lowstand lakes during the early to middle Holocene have been recognized in most Great Lake basins. An exponential model of glacial rebound and geological evidence of former water levels have shown that past lakes were closed when their water surfaces were lower than their corresponding overflow outlets.

The closed lowstands are the result of a past dry climate driven by the last deglaciation, and constitute an example of a severe response of the Great Lakes to a climate much drier than at present.

The recognition of the closed lowstand phases is important for

- outreach to raise awareness of the sensitivity of the Great Lakes to climate change.
- testing and validating climate-lake models by having them simulate the lowstands and thereby increase confidence in their projections of lake levels under future climates.
- policymaking that considers the implications of possible future large water diversions from the Great Lakes in the light of knowledge that the lakes have been hydrologically closed in the past and are sensitive to future changes in their water balance.

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Editor's Note:

For some years, Geoscience Canada has sought to publish papers by those who receive medals from the Geological Association of Canada for their scientific contributions. Many valuable overview papers and provocative treatments of issues in Earth Science have appeared in our Medallist Series. However, GAC is not the only geoscience organization that awards medals or recognizes excellent scientific research and in this issue it is our pleasure to extend this series to include the overview paper by Mike Lewis on the postglacial history of the Great Lakes.

Mike is the recipient of the 2015 W.A. Johnston Award of the Canadian Quaternary Association (CANQUA). The Award honours W.A. Johnston, an innovator in Quaternary studies in Canada who, in his years with the Geological Survey of Canada, developed many of the concepts of regional Quaternary studies used today. The first recipient of the Award was announced in 1987.

C.F.M. ("Mike") Lewis has worked in many areas over a long career with the Geological Survey of Canada in Ottawa and Burlington, Ontario, (Canada Centre for Inland Waters), and at the Bedford Institute of Oceanography since 1978. His central interest has been the history of the Great Lakes, a complex tale involving the interplay of the Laurentide Ice Sheet, its meltwater, isostatic rebound and shifts in the global climate. This work has revealed that these massive fresh water resources are highly sensitive, and not as perennial as we might have thought. They became shrunken, closed basins due to aridity following deglaciation, as a result of dry climate induced by the residual presence of the ice sheet north of the Great Lakes. Situated as they are in the boundary zone between differing climatic zones, the lakes remain sensitive to future anthropogenic shifts in our climate. The many lines of evidence that come together in understanding the history and perhaps the future of these iconic water bodies are explored in Mike's invited paper, based on a plenary address at the CANQUA conference in St. John's, NL, in 2015.

In future issues, we hope to honour other medal or award recipients from associated Geoscience Societies.

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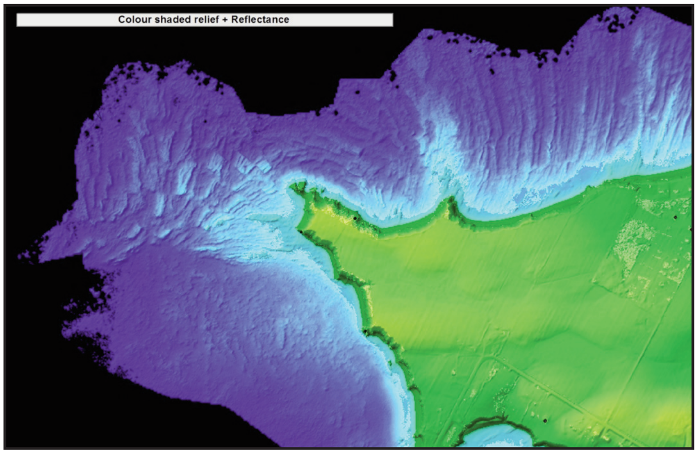

Remote Predictive Mapping 7. The Use of Topographic–Bathymetric Lidar to Enhance Geological Structural Mapping in Maritime Canada

Tim Webster, Kevin McGuigan, Nathan Crowell, Kate Collins and Candace MacDonald

Applied Geomatics Research Group
Nova Scotia Community College
Middleton, Nova Scotia, B0S 1M0, Canada
Email: tim.webster@nscc.ca

SUMMARY

An airborne topo-bathymetric lidar survey was conducted at Cape John, on the north shore of Nova Scotia, Canada, using the shallow water Leica AHAB Chiroptera II sensor. The survey revealed new bedrock features that were not discovered using previous mapping methods. A thick blanket of glacial till covers the bedrock on land, and outcrops are exposed only along the coastal cliffs and offshore reefs. The seamless land-seabed digital elevation model produced from the lidar survey revealed significant bedrock outcrop offshore where ocean currents have removed the glacial till, a significant finding that was hitherto hidden under the sea surface. Several reefs were identified offshore as well as a major fold structure where block faulting occurs along the limbs of the fold. The extension of the Malagash Mine Fault located ~10 km west of Cape John is proposed to explain the local folding and faulting visible in the submerged outcrops. The extension of this fault is partially visible on land, where it is obscured by glacial till, and its presence is supported by the orientation of submerged bedding and lineaments on both the south and north sides of Cape John. This paper demonstrates how near-shore high-resolution topography from bathymetric lidar can be used to enhance and refine geological mapping.

RÉSUMÉ

Un levé lidar topo-bathymétrique été réalisé à Cape John, sur la rive nord de la Nouvelle-Écosse, Canada, en utilisant un capteur Leci AHAB Chiroptera II. Ce levé a permis de repérer des affleurements que les méthodes de cartographie plus anciennes n'avaient pu détecter. Une épaisse couche de till glaciaire recouvre la roche en place sur le continent, et la roche affleure seulement le long des falaises côtières et des récifs côtiers. Le modèle numérique de dénivelé en continu terres et fonds marins obtenu par le levé lidar a révélé l'existence d'affleurement rocheux considérables au large des côtes, là où les courants océaniques ont emporté le till glaciaire, une découverte importante demeurée cachée sous la surface de la mer jusqu'alors. Plusieurs récifs ont été identifiés au large des côtes, ainsi qu'une structure de pli majeure, à l'endroit où se produit un morcellement en blocs le long des flancs du pli. Une extension de la faille de la mine Malagash situé ~ 10 km à l'ouest de Cape John est proposé pour expliquer les plis et les failles locaux visibles dans les affleurements submergés. L'extension de cette faille est partiellement visible sur la terre, voilée par le till, et sa présence est étayée par l'orientation de la stratification et des linéaments submergés tant du côté sud que nord de Cape John. Cet article montre comment la topographie haute résolution du lidar bathymétrique peut être utilisée pour améliorer et affiner la cartographie géologique.

Traduit par le Traducteur

INTRODUCTION

In this paper we present the results of offshore coastal mapping using airborne topo-bathymetric lidar at Cape John, Nova Scotia along the Northumberland Strait in the Gulf of St. Lawrence (Fig. 1). Traditional remote sensing mapping methods such as aerial photography and boat-based echo sounding used in the mapping of geological structures on the seabed can be difficult, time-consuming and expensive to locate. It is generally assumed that terrestrial outcrops extend underwater; Cape John is known to have outcrops along the coast but there

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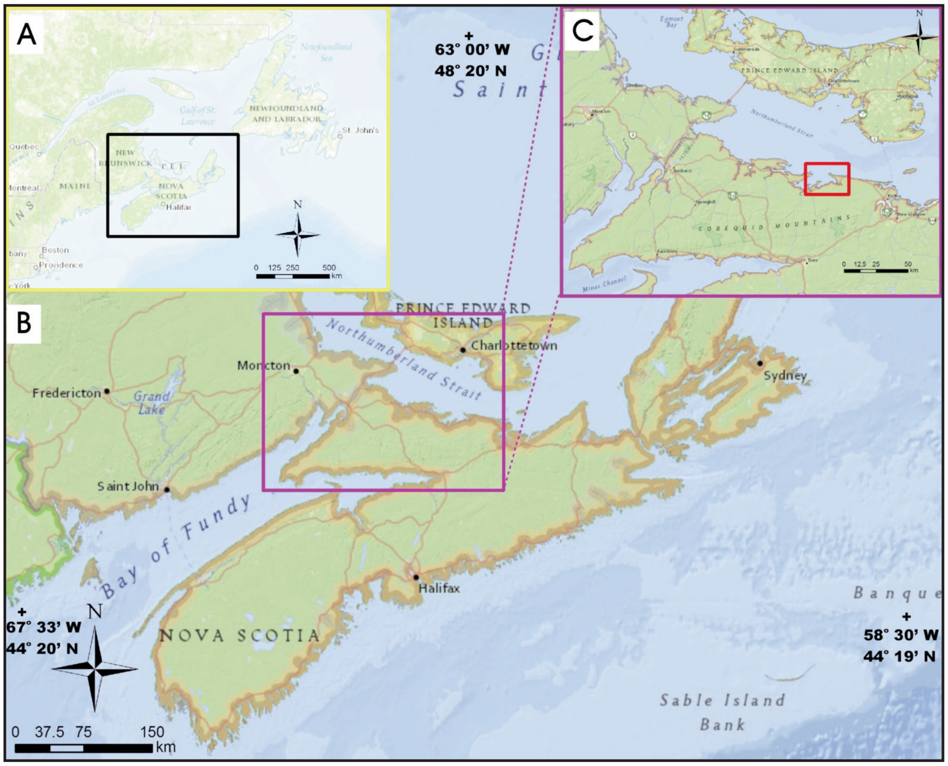

Figure 1. Overview of Atlantic Canada showing the location of the Cape John study site for the topo-bathymetric lidar survey. The black outline in A shows the location of B; C is the location of Figure 2, and the red rectangle in C outlines the area shown in Figure 3.

is little known about the distribution of geologic formations underwater, nor the fine details of the bathymetry, aside from a paper chart based on soundings from 1945 (Canadian Hydrographic Service 1945). At Cape John, the lack of outcrop on land, except for the coastal cliffs is a result of the deposition of glacial till during the last glacial period; however, the ability of an airborne sensor to accurately survey the nearshore bathymetry offers an opportunity to overcome the challenges of locating offshore exposures using traditional methods by providing detailed information on geologic structures that extend across the land-sea boundary.

Bathymetric data are traditionally collected using echo-sounding techniques in water depths greater than 10 m (Moustier and Matsumoto 1993; Clarke et al. 1996). However, these boat-based techniques are expensive and potentially hazardous in shallow water because of a limited survey field of view and the prospect of running aground. To overcome these issues, passive and active remote sensing techniques have been developed for shallow water bathymetry (Hedley and Mumby 2003; Jay and Guillaume 2014). Decker et al. (2011) have compared various methods for mapping bathymetry and water column properties from passive remote sensing. Hedley and Mumby (2003) presented a passive remote sensing technique whereby they modified a spectral unmixing method to calculate depth and substrate type from passive imagery. The technique requires pure spectral information of the substrate types very shallow and the water diffuse attenuation coefficients (Kd) for the site in the same spectral regions. Collecting Kd values during remote sensing data acquisition can be challenging, especially as these values change with conditions, such as increased turbidity or other water quality factors. Hedley and Mumby (2003) use realistic Kd values (0.15–0.25) along with random and actual spectra to test their spectral unmixing approach to mapping benthic cover, and found it to be insensitive to inaccuracies in depth estimation. Jay and Guillaume (2014) used a maximum likelihood estimation method for depth and water quality. Their method assumes that water column properties are similar for a group of at least 400 pixels having similar water clarity conditions, which is easier with high-resolution hyperspectral data.

Active remote sensing techniques for surveying depths utilize airborne topo-bathymetric lidar systems. Topo-bathymetric lidar works by emitting near-infrared (NIR) and green laser pulses from an aircraft and measuring the travel time of the pulses to and from the land, water surface, and seabed. The NIR laser pulse reflects off the land and sea surface, whereas the green laser pulse is refracted at the air-water interface, attenuated through the water column, and reflected from the seabed. Although topo-bathymetric lidar is a relatively new technology, it has been proven to be effective for mapping the fine detail of underwater bathymetry and geologic structures (Kennedy et al. 2008, 2014; Arifin and Kennedy 2011; Collin et al. 2011a, b, 2012; Coveney and Monteys 2011; Le Gall et al. 2014). The emerging uses of airborne laser bathymetry (ALB) for coastal research and coastal management are summarized in Brock and Purkis (2009). For example, Kennedy et al. (2014) used ALB (with the Laser Airborne Depth Sounder (LADS) Mk II sensor) and multibeam echo sounding to examine the erosion of granitic domes along the coast of southern Australia. Kennedy et al. (2014) concluded that coastal processes were removing debris and that the amount of erosion appeared to be related to the spacing of joints within the granite. They also calculated rugosity for the bathymetry and, in a series of offshore profiles, compared it to the jointing pattern present in the rock. Similarly, Le Gall et al. (2014) used lidar and multibeam bathymetry techniques to enhance their structural mapping of the Variscan basement off the coast of Brittany, France, allowing them to trace lineaments offshore and correlate them with geophysical maps. Covency and Monteys (2011) examined the integration of topographic lidar and ALB for coastal research along the Irish coastline. Others have studied the movement of offshore sediments, including Arifin and Kennedy (2011), who examined the evolution of large scale crescentic bars before and after hurricanes within the Gulf of Mexico, and Kennedy et al. (2008), who examined ephemeral sand waves in response to hurricane forces in the surf zone off the coast of Florida. Collin et al. (2011a, b; 2012) used the Optech SHOALS system to survey a section of the coastal zone in the Gulf of St. Lawrence in Québec, focusing on benthic habitat.

Previous research has utilized large, deep-water lidar sensors such as the LADS Mk II, SHOALS and Hawkeye systems. A new generation of commercial, relatively lightweight, shallow-water sensors are now available, including the Leica AHAB Chiroptera II, Riegl VQ-820-G, and Optech Aquarius systems, allowing surveys to be conducted in smaller aircraft and at lower costs compared to sensors designed for deeper water. At the time of this study, the Chiroptera II was the only sensor that utilizes a NIR laser in combination with a green laser to map the sea surface; the VQ-820 and Aquarius systems rely only on a green laser for their operation. Wang et al. (2015) compared a variety of waveform-processing algorithms for single-wavelength lidar bathymetry systems and pointed out that the disadvantage of such systems is the lack of a NIR channel, leading to difficulties in extracting the water surface.

The Applied Geomatics Research Group at the Nova Scotia Community College recently acquired the Chiroptera II topo-bathymetric lidar sensor equipped with the Leica RCD30 medium-format 60 megapixel digital camera system capable of RGB (red-green-blue) and NIR image acquisition and motion compensation. We surveyed the Cape John area on September 26, 2014 and present here the methods used to process the lidar and seabed reflectance data, and to construct continuous elevation models, orthophotos, and a new interpretation of the structural geology based on the lidar data. Water clarity influences how deep the green laser will penetrate, and turbidity management is important for successful surveys. Webster et al. (in press) report on the influence of variable turbidity, and on advances in topo-bathymetric lidar data-processing techniques using multiple datasets collected around the Maritimes, including Cape John.

GEOLOGICAL SETTING

Cape John, Nova Scotia is located near the southern flank of the Maritimes (Carboniferous) Basin and is part of the Appalachian orogen (Fig. 1). The late Paleozoic evolution of the Appalachian orogen was profoundly influenced by post-accretionary motion along terrane boundaries (Williams and Hatcher 1982). The contact between the two most outboard terranes, the Avalon and Meguma terranes, can be traced across mainland Nova Scotia as the Minas Fault Zone (Cobequid−Chedabucto Fault System; Fig. 2). The Cobequid–Chedabucto Fault is interpreted to have had a history of recurrent movement that records important episodes of Late Paleozoic relative motion during the later tectonic phases of the Appalachian orogen (Keppie 1982; Mawer and White 1987; Murphy et al. 2011). Upper Devonian to Upper Carboniferous sedimentary rocks occur on both the Avalon and Meguma terranes and are generally considered to represent an overstep sequence across the boundary between the two terranes. The Cape John study area is located within the Cumberland Subbasin of the Maritimes Basin.

The Cumberland Subbasin is underlain by a thick accumulation of Lower Carboniferous to Lower Permian strata assigned to the Cumberland and Pictou groups in northwestern Nova Scotia and southeastern New Brunswick (Ryan and Boehner 1994) (Figs. 2, 3). It is bordered to the north by the Northumberland Strait and to the south by the Cobequid Highlands, which in turn is bordered to the south by the Cobequid−Chedabucto Fault (Fig. 2). The internal structure of the Cumberland Basin is generalized as a broad east- to northeast-trending synclinorium that is bounded by the parallel, diapiric, Claremont and Scotsburn anticlines; major synclines in the basin include the Tatamagouche and Wallace synclines (Ryan and Boehner 1994) (Figs. 2, 3). The Tatamagouche syncline and Claremont anticline (Figs. 2, 3) are genetically related and caused by tectonically driven diapirism (halotectonic; Ryan and Boehner 1994). The axis of the Tatamagouche Syncline traverses the Cape John study area, which is underlain by Upper Carboniferous rocks of the Pictou Group, consisting predominantly of continental clastic material deposited in fluvial and lacustrine settings (Gibling and Martel 1996) (Figs. 2, 3).The Pictou Group rests either disconformably or with angular unconformity over older Carboniferous strata of the Cumberland Group (Fig. 3). Younger rocks that may have overlain the Pictou Group are not preserved.

The major structural features of the region are the Cobequid−Chedabucto Fault and related faults such as the North Fault, which forms the boundary between the Cobequid Highlands and the Cumberland Basin (Ryan and Boehner 1994) (Fig. 2). The Cobequid−Chedabucto Fault is characterized by recurrent dextral strike-slip movement between the middle Devonian and early Permian (Mawer and White 1987; Webster and Murphy 1998; Murphy et al. 2011). Late Carboniferous activity along the fault zone was responsible for polyphase deformation (Nance 1987; Waldron et al. 1989) and the generation of local pull-apart basins (Bradley 1982; Yeo and Ruixiang 1987; Murphy and Keppie 1998). The North Fault has a complex history; it includes a series of splays that displaced Upper Carboniferous strata in the basin, whereas other units overlap the fault, whose trace has been interpreted through the use of remote sensing and geophysics (Ryan and Boehner 1994). The Malagash Mine Fault is west of the Cape John study area, on the west side of Amet Sound (Fig. 3). Faulting in the Malagash area is commonly associated with salt flow (Ryan and Boehner 1994). The Cape John Fault trends north-south at the end of the Cape John peninsula (Ryan and Boehner 1994) (Fig. 3). Fault movement here is predominantly normal dip-slip with a minor strike-slip component. Reidel shear sets adjacent to the Cape John Fault collectively indicate extensional stress oriented northwest-southeast, and associated with diapirism north of Cape John (Ryan and Boehner 1994). The Malagash−Claremont anticline has a normal south limb and a faulted north limb of overturned fault blocks having high-angle reverse or thrust geometry (Fig. 3). Movement on some of these faults is difficult to constrain and some may reflect later events such as Triassic rifting, which has been documented around the Bay of Fundy (Ryan and Boehner 1994; Webster et al. 2006).

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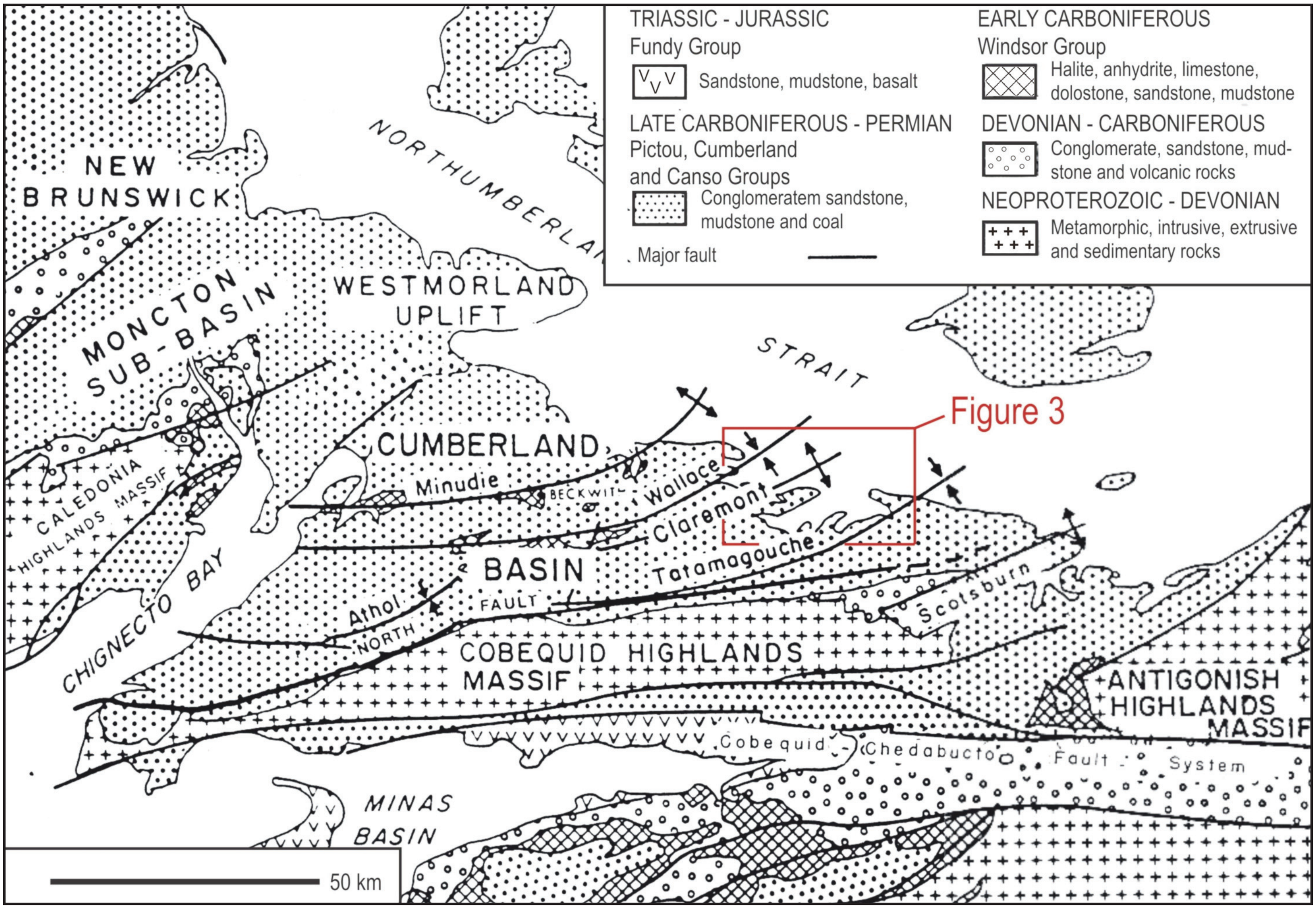

Figure 2. Regional structural setting and features of the Cumberland Basin, northern mainland Nova Scotia, after Ryan and Boehner (1994); the outline shows the extent of Figure 3.

The region was affected by fluctuations in Late Wisconsinan ice dynamics until ca. 12 ka (^{14}C yr) (Stea and Mott 1998). The earliest ice flows were eastward and southeastward from an Appalachian or Laurentide ice source ca. 75–40 ka (Caledonia ice flow phases 1A and 1B; Stea et al. 1998). The Hartlen Till was deposited by southeastward ice flow, and typically consists of 40% gravel, 40% sand, and 20% mud (silt and clay) (Lewis et al. 1998). The second major ice-flow was southward and southwestward from the Escuminac Ice Centre in the Prince Edward Island region (Escuminac ice flow phase 2, ca. 22–18 ka; Stea et al. 1998). The younger Lawrencetown Till (Stea et al. 1998) is a reddish muddy till unit that has a higher clay content than the Hartlen Till because of the incorporation of red Carboniferous sediment derived from Prince Edward Island, and typically consists of 20–30% gravel, 30–40% sand, and 30–50% mud (silt and clay) (Lewis et al. 1998). This deposit is locally known as the Eatonville–Hants Till. Ice then flowed northwestward and southward from the Scotian Ice divide across the axis of Nova Scotia (Scotian ice flow phase 3, ca. 18–15 ka; Stea et al. 1998). The study area is dominated by thick (ca. 3–5 m), red, clay-rich Lawrencetown Till.

METHODS

Topographic–Bathymetric Lidar System Specifications

The Chiroptera II topo-bathymetric lidar system incorporates a 1064 nm NIR laser for topographic returns and assisting in defining the water surface, and a green 515 nm laser for bathymetric returns (Fig. 4). The lasers utilize a Palmer scanner, which forms an elliptical pattern with angles of incidence of 14° forward and back and 20° to the sides of the flight track (Fig. 4). This scan pattern enables more returns from a single target from different angles, which reduces shadow effects and increases the number of points on vertical faces such as cliffs along the coast (Fig. 5). The elliptical scan pattern results in an increased likelihood that the target will be surveyed twice, from different angles a few seconds apart, and thus is less sensitive to ocean wave interaction whereby the air bubbles of a breaking wave will attenuate the green laser pulse (515 nm) and prevent penetration to the seabed.

The beam divergence of the topographic laser is 0.5 milliradians, and for the bathymetric laser is 3 milliradians. The topographic and bathymetric lasers have pulse repetition frequencies up to 500 kHz and up to 35 kHz, respectively. The operational altitude of the bathymetric laser is between 400–600 m above ground level and for the topographic laser is up to 1600 m above ground level. The GPS has a sample rate of 1 Hz and the Inertial Measurement Unit has a sample rate of 200 Hz for positioning. The bathymetric accuracy of the bathymetric lidar is stated to be within 0.12 m at 2 standard deviations (95% confidence interval). The topographic laser is reported to have a ranging accuracy of 0.02 cm at 1 standard deviation (68% confidence interval) and a horizontal accuracy of 0.2 m at 1 standard deviation, not including GPS-Inertial Measurement Unit error. The system is equipped with a standard 5 megapixel RGB camera capable of exposures at 1 frame per second for quality assurance purposes, and is linked to the timing of the laser points. The Leica RCD30 camera collects co-aligned RGB+NIR motion-compensated photographs that can be orthorectified using direct georeferencing. The RCD30 is capable of exposures at 0.8 frames per second with a distortion-free lens having a focal length of 53 mm, and produces images of 6732 and 9000 pixels in the across- and along-track directions, respectively. The across-track field of view is 54°, which is slightly wider than the 40° across-track lidar field of view. At 400 m altitude the RCD30 produces imagery with a 5 cm pixel resolution.

The sensor was installed in a Beechcraft A90 King Air aircraft and calibration flights were conducted at altitudes of 400 m and 1000 m. The coastal bathymetric survey was acquired at an altitude of 400 m with 30% overlap between flight lines, and a flying speed of 55 m/s, resulting in a swath 291 m wide. Bathymetric lidar spot spacing was 1.56 m in the forward lateral direction and 0.78 m in the forward and backward scan direction, producing an average point density of 1.65 points/m^2. The green bathymetric laser spot diameter on the water surface is approximately 1.2 m at 400 m altitude, and the near-infrared topographic laser spot diameter is 0.2 m. Flight lines were planned parallel to the coastline, except for one additional line perpendicular to the coastline, intersecting the parallel lines. The specifications used for this survey were selected to maximize the resolution and point density of the lidar on land and submerged areas, and the photo resolution of 5 cm was a result of the flying height of 400 m above ground level. Specifications of the sensor and typical configurations can be found on the Leica Geosystems website (http://leica-geosystems.com/products/airborne-systems/bathymetric-hydrographic-sensors/leica-chiroptera-ii).

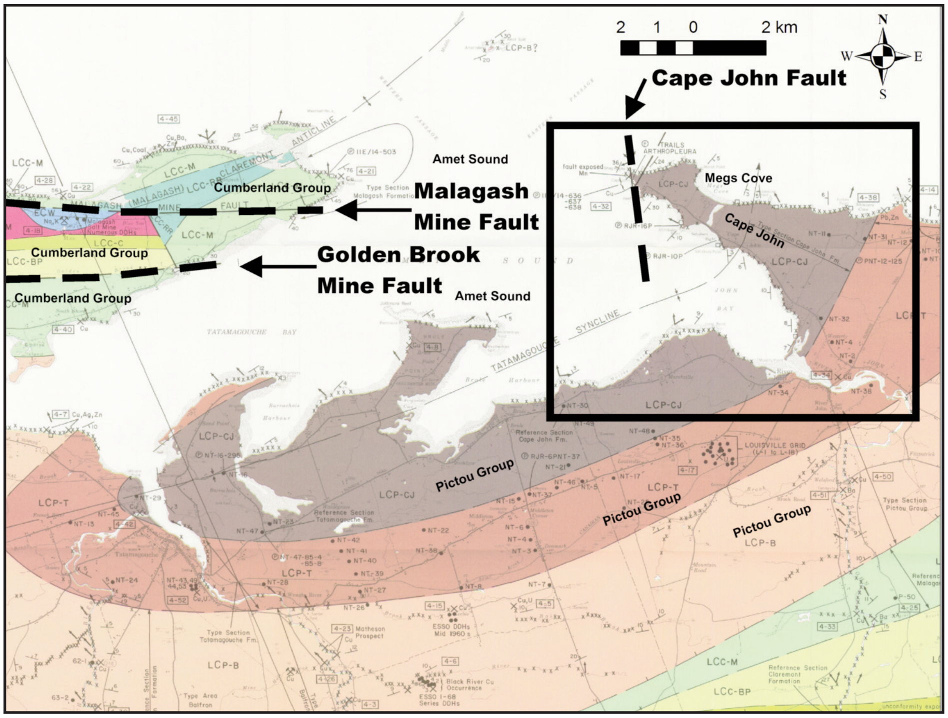

Figure 3. Geology of the Cumberland Basin, after Ryan and Boehner (1994). The black outline indicates the location of the topo-bathymetric lidar survey and the approximate extent of Figure 7. The Malagash Mine Fault, Golden Brook Fault and Cape John Fault are highlighted.

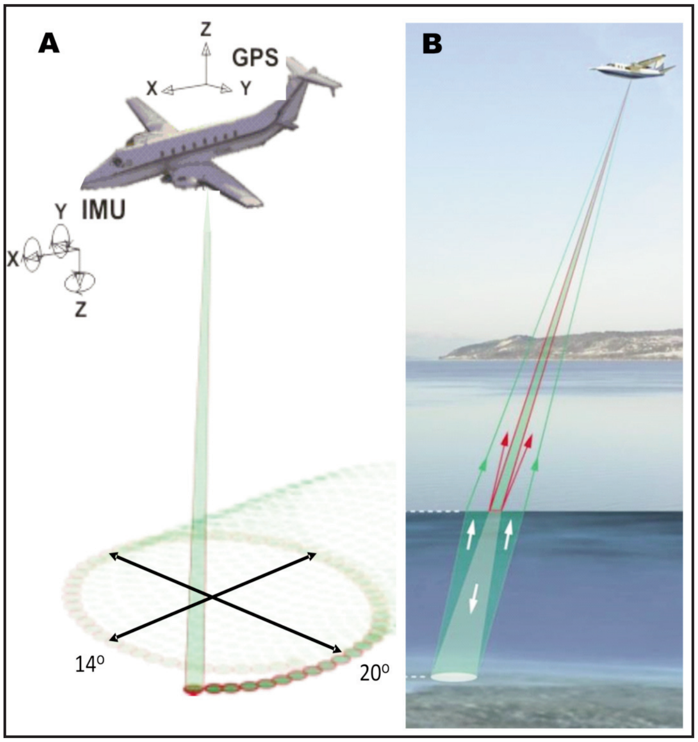

Figure 4. A. The elliptical scanning pattern of the Chiroptera II with GPS and Inertial Measurement Unit navigation system components. B. Illustration of the reflection of near-infrared topographic laser (red arrows) off the sea surface, and the green bathymetric laser (green and white arrows) penetrating the water column and reflecting off the sea bed. (Figures adapted from Leica Geosystems).

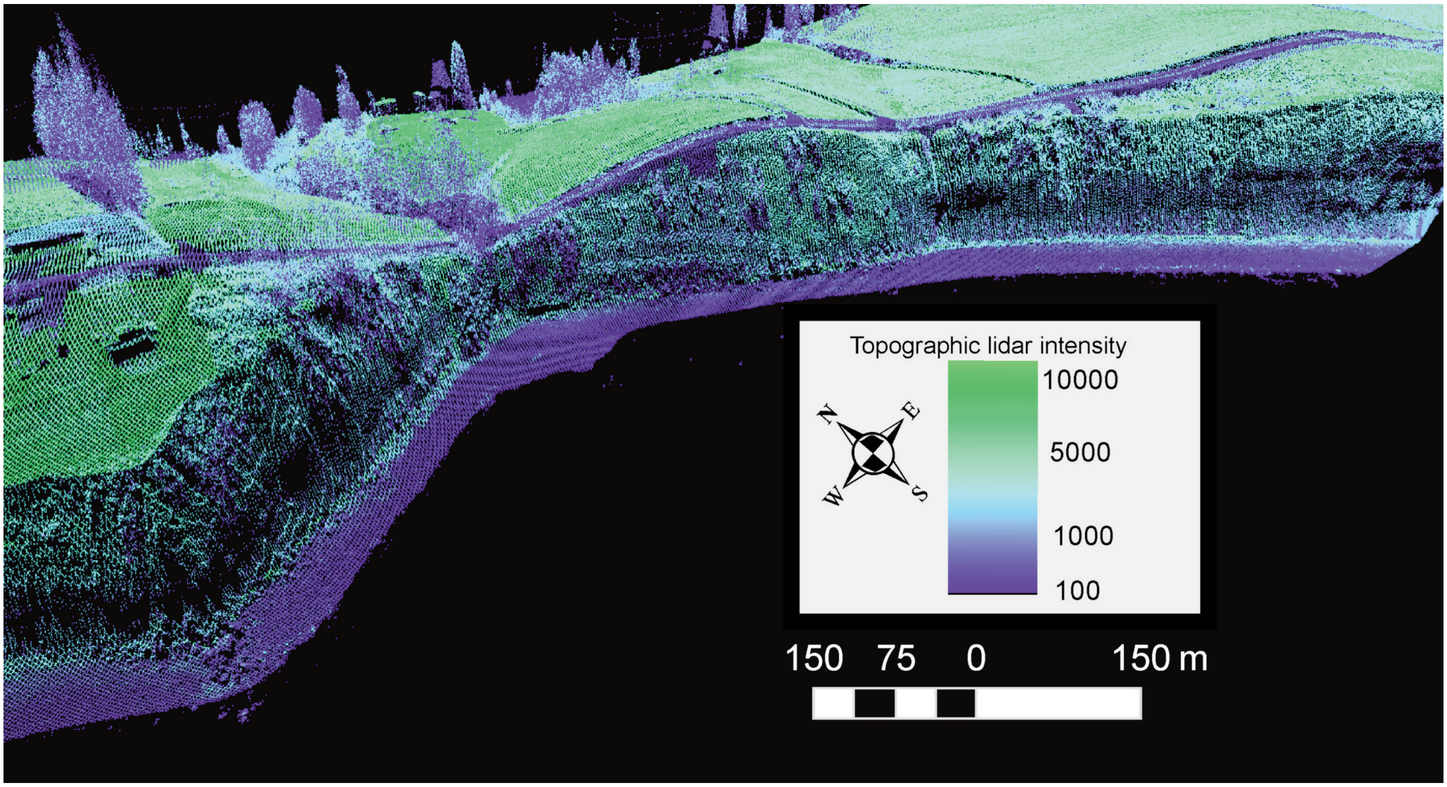

Figure 5. Example of dense point-spacing along coastal cliffs at Cape John, from the elliptical scan pattern of the Chiroptera II lidar. The colours in this perspective view represent differences in lidar intensity values from the topographic laser.

Lidar Survey

Depth penetration of the lidar sensor is limited by water clarity, as particles in the water column limit the laser's ability to travel through the water. The manufacturer suggests using a Secchi depth measurement to estimate the depth penetration of the laser under any given conditions. The Secchi depth is defined to be the depth at which a black and white Secchi disk is no longer visible as it is lowered into the water; clear water will have a large/deep Secchi depth, whereas turbid water will have a small/shallow Secchi depth. The Chiroptera II has a depth penetration limit of roughly 1.5 times the Secchi depth (Leica AHAB, personal communication 2014).

The shoreline at Cape John dominantly consists of sedimentary bedrock (red sandstone and mudstone) covered with a thick blanket of glacial till that is rich in red clay. Erosion of this material produces nearshore sediments that have a high clay content; this may cause increased turbidity when the sediments are mobilized by onshore wind and nearshore waves, preventing good laser penetration. Precipitation events can also cause runoff and increase turbidity. A weather station was installed at Cape John and the data measured there were broadcast through a cellular modem and used to monitor weather conditions remotely in order to conduct the survey during the clearest water possible.

The Cape John lidar survey was planned for September 24, 2014, but the weather data indicated that a significant storm event had occurred, accompanied by a drop in barometric pressure, wind speeds exceeding 40 km/hr from the northwest, and rainfall from September 18-22, causing the survey to be delayed. Following the storm, a high pressure system moved into the region, providing clear skies, so the survey was attempted on September 25. However, persistent winds of 20 to 40 km/hr during the time of the survey led to high turbidity levels and poor bathymetric laser returns, causing the survey to be aborted and delayed further. Good data were acquired during the second survey attempt on September 26 after suspended sediment had settled.

In-Situ Sampling

Ground-truth data acquisition is another important aspect of ALB data collection, especially since this was the first survey in the region with the Chiroptera II system. A Leica GS14 GPS system was used to set up a base station for the aircraft over a monument that was tied into the provincial High Precision Network. Real Time Kinematic GPS elevation validation checkpoints were collected along hard flat surfaces at the Cape John wharf to validate the topographic lidar, and Secchi depths were acquired along with underwater photographs of the seabed using a 1 m x 1 m quadrat (sampling area) to determine seabed cover. A Reson T-20 multibeam system was deployed in October after the ALB survey was completed so that additional depth validation points could be acquired. The vessel was also equipped with an MDL Dynascan mobile laser scanner that has a dual survey grade GPS antenna configuration for improved heading measurements and an Inertial Measurement Unit for direct georeferencing. The Dynascan supplied the real-time navigational corrections for the multibeam, and data from both sensors were acquired using QINSy™ acquisition software.

Lidar Processing

Once the aircraft GPS-Inertial Measurement Unit trajectory was processed utilizing the GPS base station, the navigation data were linked to the laser returns and georeferenced using Lidar Survey Studio™ (LSS). The lidar data were then processed within LSS, which classified the laser waveforms into discrete points (the LSS software computes the water surface from the lidar returns of both the topographic and bathymetric lasers). In addition to classifying points as land, water surface, or bathymetry, the system also computed a modelled water surface that ensured the entire surface area of water was covered, regardless of the original lidar point density. Threshold parameters were set within LSS to classify the bathymetry points from the waveforms. The point cloud can be viewed in cross-section or in a perspective view, allowing the land to be separated from the bathymetry points (Fig. 6). Once the waveforms were processed, the resultant points were displayed using a variety of attributes (flight line, elevation, intensity) within LSS, and the waveform examined with the 5 megapixel quality assurance airphoto, which was linked to the lidar scans. LAS (an open standard file format for the interchange of lidar data) version 1.2 files were exported from LSS for further classification and filtering in TerraScan™, where the separation of bathymetric points and noise was refined. As an example of the variation in files and volume of data, the raw waveform data are stored in 200 MB files, reduced to 70 MB files when converted to discrete point files in LAS format, and further reduced to 3 MB as a 2 m-resolution raster grid.

The refined, classified LAS files were then read into an ArcGIS™ LAS dataset, and Python™ scripts were written to produce a variety of raster surfaces at a 2 m spatial sampling interval. Three main data products are derived from the lidar point cloud. The first two are based on the elevation and include: 1) the digital surface model (DSM), which incorporates valid lidar returns from vegetation, buildings, ground and bathymetry returns; and 2) the digital elevation model (DEM), which incorporates ground returns above and below the water line. The elevation attribute of the lidar point cloud is relative to the WGS84 ellipsoid, since the point reference is based on the GPS aircraft trajectory. However, once the surface models (DSM and DEM) were constructed using different combinations of the point class elevations, the data were converted to orthometric heights relative to the Canadian Geodetic Vertical Datum of 1928. The geoid-ellipsoid separation model, HT2, available from Natural Resources Canada, was used for this conversion of the surface models.

The third data product is the amplitude of the lidar returns of the bathymetric laser. The amplitude values were depth-normalized by taking samples of the amplitude values of a common cover type (such as sand) over depth ranges, and using these data to establish a relationship between depth and the amplitude value; the inverse of this relationship was used to depth-normalize the amplitude data. The amplitude or reflectance of the green laser can be interpreted for seabed cover, e.g. sand, submerged aquatic vegetation, rock or potential bedrock structures. In order to easily interpret the lidar surface models, colour shaded relief models were constructed from the DSM and DEM for the study site. Figure 7 shows a DEM of the 2014 topo-bathymetric lidar survey combined with topographic lidar collected in 2006 and 2007. The missing strips of data in the southern portion of the study area (Fig. 7) occurred because fog was present during this part of the survey, which caused the lasers to reflect back towards the aircraft at close range, triggering a safety shut off. This happened on a few flight lines (Fig. 7) before it was resolved and continuous data were re-acquired.

RESULTS

Elevation Validation

GPS checkpoints collected at the end of the Cape John wharf were compared to the topographic lidar-derived elevation surface (DEM). The mean difference between the GPS elevation and the DEM was –0.02 m, with a standard deviation of 0.04 m from 13 checkpoints. The topographic sensor was well within the manufacturer's specifications of 15 cm vertical accuracy. Rough weather and technical challenges limited the quantity of depth validation data collected during the multibeam survey; therefore, more depth validation studies are planned for the future. The validation of the depths at Cape John was accomplished by qualitatively comparing the multibeam echosounder depths to the lidar bathymetry points where overlap exists. Results indicate that the lidar bathymetric points match the multibeam points within the 15 cm specification of the Chiroptera II.

Geological Interpretation

The 2014 topo-bathymetric lidar data reveal that ocean currents have eroded the glacial till cover offshore and exposed the bedrock geology around Cape John (Fig. 8). These data allow the coastal outcrops to be traced laterally and more details on the structural geology to be interpreted. The offshore structures thus revealed include bedding planes of the Cape John Formation, which generally strike northeast but curve to the north-south toward the west end of Cape John (Fig. 8B). Ryan and Boehner (1994) mapped north-northeast- and north-south-trending faults at the end of Cape John (Fig. 9); the north-northeast trending fault corresponds to where the 2014 lidar bathymetry begins to show more intense deformation (Fig. 8). Bedding appears to be folded and faulted in an arcuate shape around the point at Cape John, changing from a northeast trend to an east-west trend, then back to a northeast trend farther west. Large blocks are dextrally offset by faults, which also appear to be folded (Fig. 8B). The elevation and apparent deformation of the submerged outcrop diminishes south of the point on the west side of Cape John (Fig. 8B). Near the wharf south of Cape John bedding trends east-west, parallel to two major onshore lineaments that are expressed as subtle depressions and wetland locations (Fig. 8B, C). The lineaments are broad, low-lying, and may have been preferentially

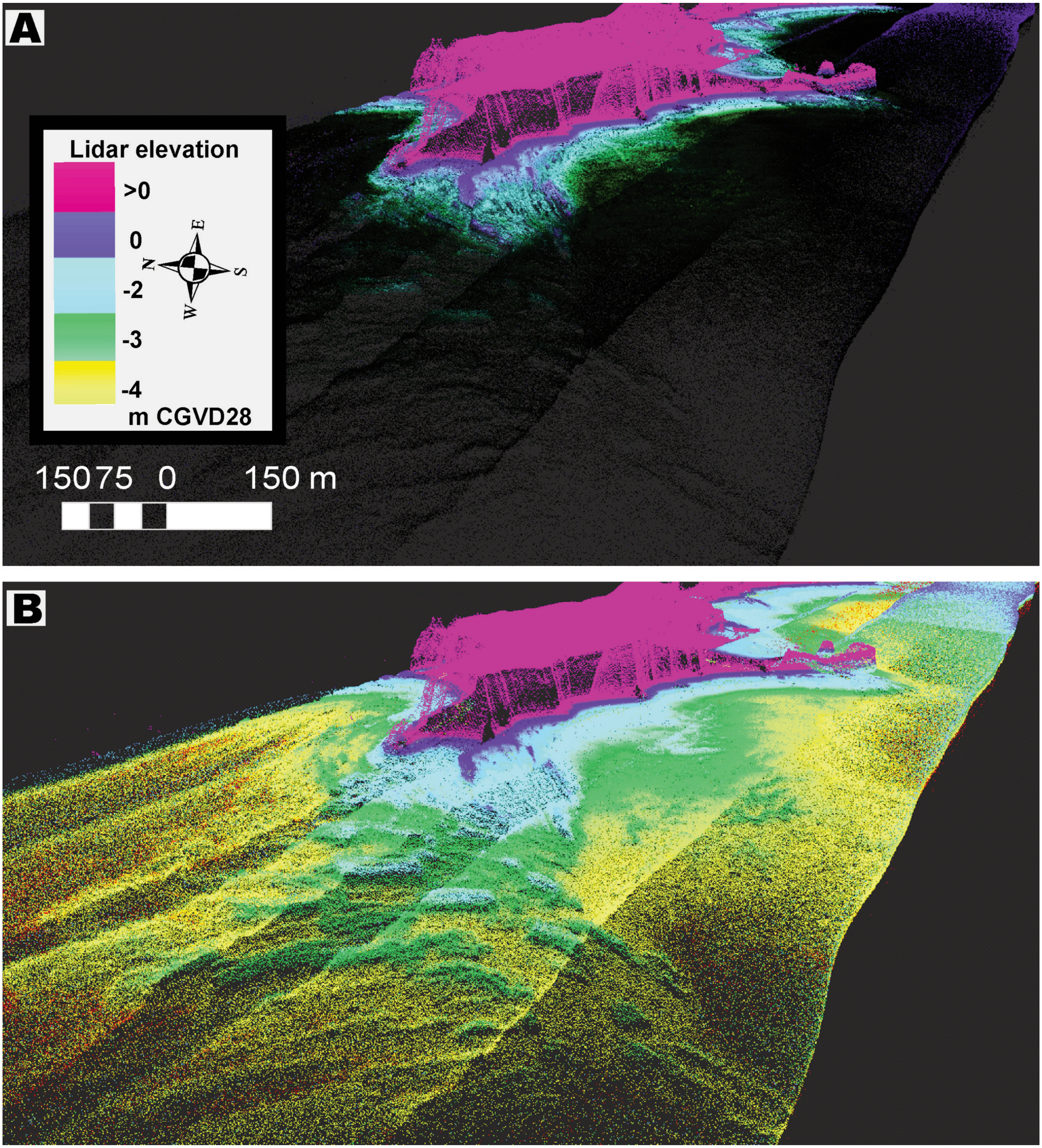

Figure 6. Point clouds for Cape John, colour-coded for elevation. A. Perspective view of the topographic laser points highlighting the exposed land. B. Perspective view of the combined topo-bathymetric lasers; the green features represent submerged, folded fault blocks.

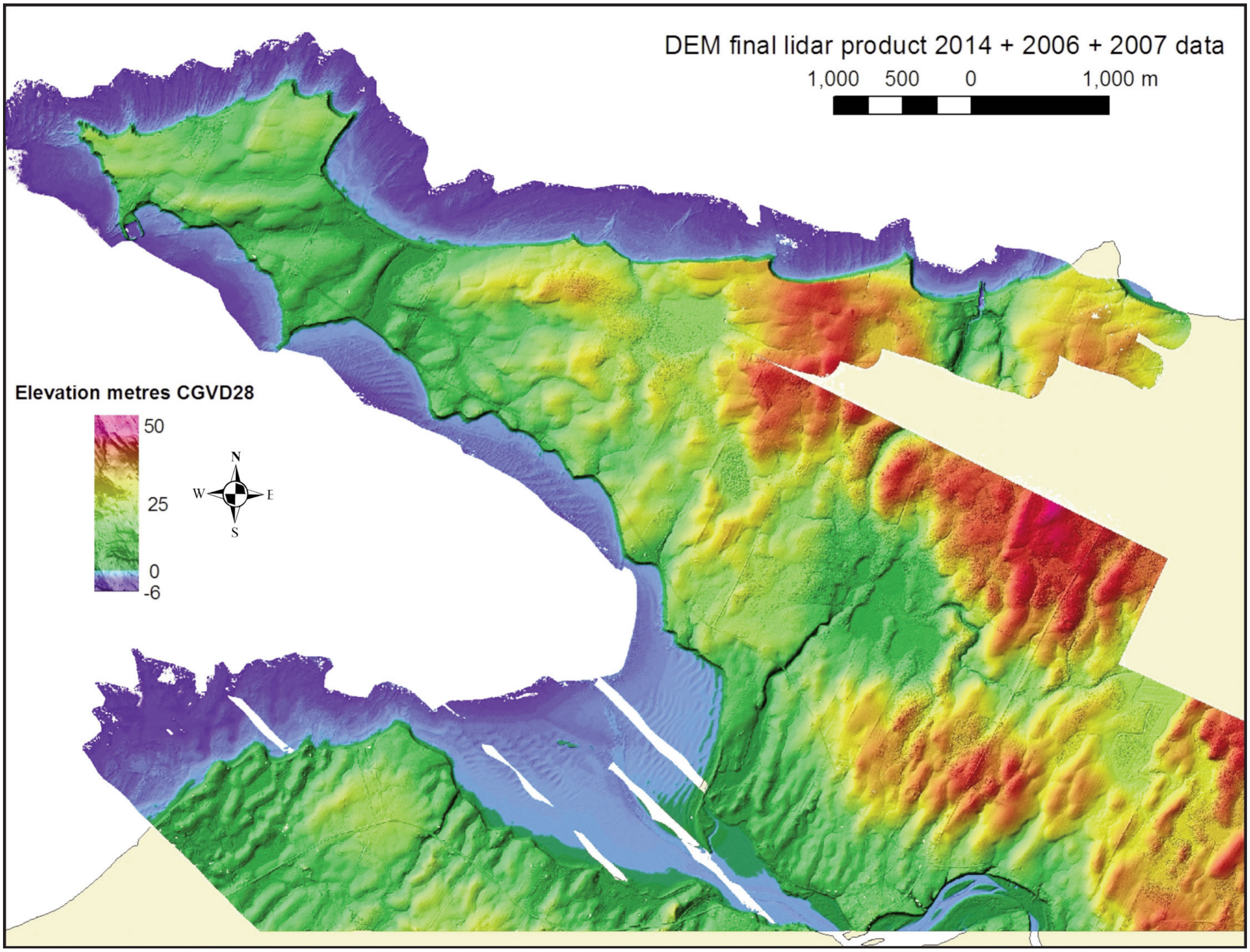

Figure 7. Colour shaded relief of topo-bathymetric lidar Digital Elevation Model for Cape John, Nova Scotia.

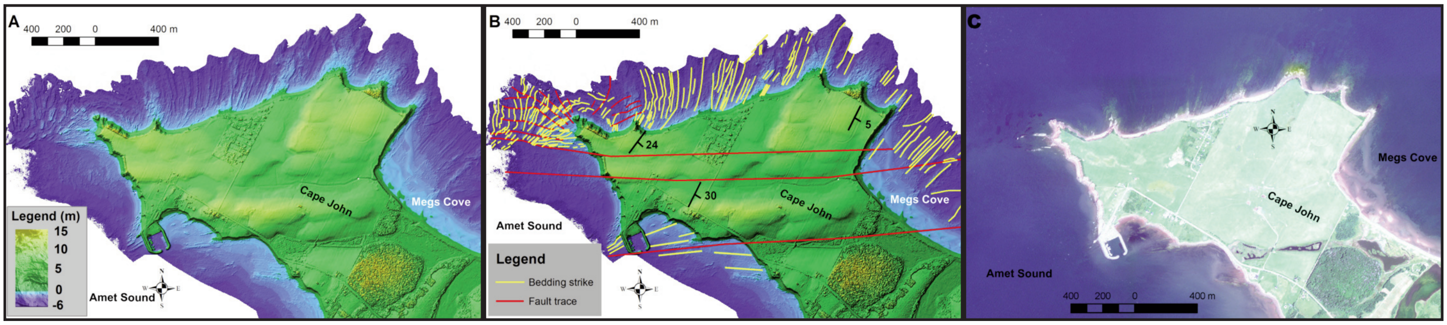

Figure 8. A. Close-up of offshore structural geology revealed by topo-bathymetric lidar Digital Surface Model (DSM). B. Map of lidar DSM with the geological interpretation of bedding attitude (yellow lines) and faults (red lines). Bedding symbols are from Ryan and Boehner (1994). C. Example of a low tide Worldview 2 image true colour composite, September 2010 (image copyright © DigitalGlobe).

eroded by glaciers. These lineaments are evident on a Worldview 2 satellite image acquired at low tide in September 2010, which was examined and interpreted for lineaments and exposed and submerged outcrop (Fig. 8C). However, the satellite image contains little information on exposed or submerged outcrops compared to what is visible in the lidar DEM (Fig. 8A, B). The lineaments are aligned with breaks in the strike of the offshore bedding planes and also with extrapolated positions of the Malagash Mine and Golden Brook faults, mapped less than 10 km to the west across Amet Sound (Fig. 9A). The

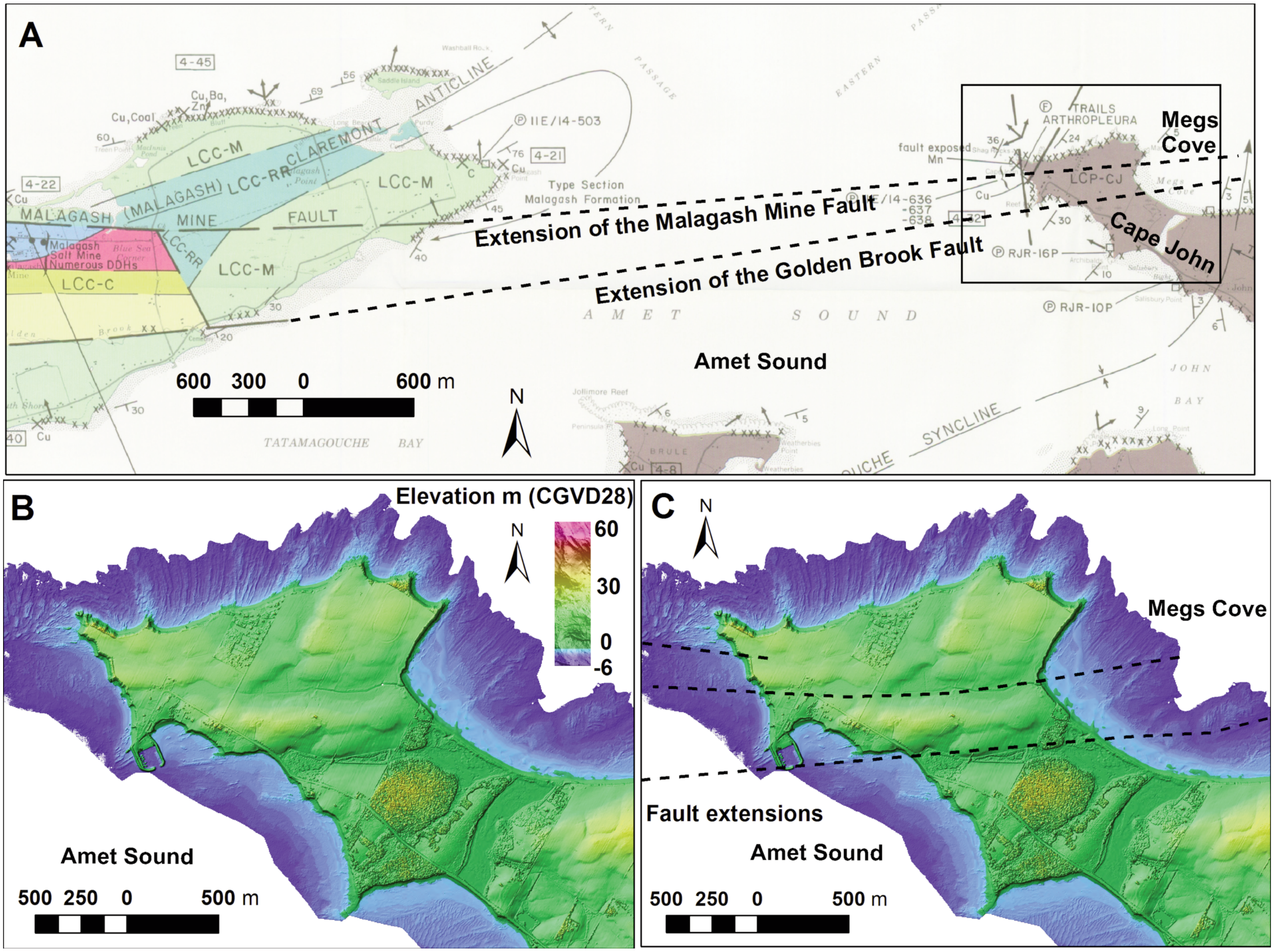

Figure 9. A. Projection of the Malagash Mine and Golden Brook faults to Cape John, with lidar map location outlined in black. Geology is from Ryan and Boehner (1994). B. Lidar Digital Surface Model (DSM) of the area enclosed by the black rectangle in A. C. Lidar DSM with interpreted fault extensions (black dashed lines) following the onshore lineaments.

extrapolated faults also line up with lineaments identified offshore on the east side of Cape John (Fig. 9), separating north-northeast-striking beds on the west side of Megs Cove to the northwest (Fig. 9).

CONCLUSIONS

The topo-bathymetric lidar provides greater detail both on the land and in the submerged nearshore compared to previously available information from geological and hydrographic surveys. Conventional topographic lidar surveys completed between 2006 and 2011 reveal that the land is covered by a blanket of glacial till, and that landforms appear to be dominated by the late movement of ice (Fig. 7). However, because the topographic NIR laser does not penetrate the water column, no information of the submerged terrain is available from these older surveys. The topo-bathymetric lidar data also provide far greater detail to a depth of 6 m compared to a hydrographic chart of the area that was compiled in 1945 (Canadian Hydrographic Service 1945) (Fig. 8). Bedrock geology can only be mapped along the coast, and is only accessible during low tide or by boat, therefore the interpretation of the structural geology is limited by what is seen at the coastal sections. Conversely, the topo-bathymetric lidar study identified nearshore lineaments representing bedding planes and possible faults, which we have correlated with known onshore faults and lineaments. This interpretation has resulted in extending several faults, such as the Malagash Mines and Golden Brook faults, farther east to Cape John, where they explain some of the nearshore deformation in that area. In Brittany, Le Gall et al. (2014) similarly used lidar and multibeam to enhance their structural mapping of the offshore Variscan basement, allowing them to trace lineaments, correlate them with geophysics, and interpret the deformation. Unfortunately, the regional geophysics, including magnetics, in the Cape John area is of low resolution and does not reveal any structural details.

This paper provides an example showing how ALB data can be used to examine and interpret structural geology and to extend onshore mapping into the nearshore. The study has revealed a significant amount of exposed outcrop in the nearshore. The glacial till, which obscures outcrop on land, has been eroded in the nearshore, clearly revealing bedding planes in the high-resolution elevation model derived from ALB. The structural details that can be interpreted from the nearshore bathymetry far exceed the details that can be seen on land, which is covered by a thick blanket of glacial till from the Laurentian ice sheet. Because of the till blanket, the only available outcrop on land is along the coast, which does not provide sufficient lateral extent to allow the full complexity of the geological structures within the study area to be identified. The results of previous mapping, combined with the newly interpreted nearshore bathymetry, have been used to extrapolate several faults and link onshore wetlands and marshes with offshore breaks in the attitude of bedding planes. These techniques can be applied elsewhere and may, for example, allow the extension of known mineral deposits to be traced into the nearshore or, as demonstrated in this study, improve our geological maps and understanding of local tectonics.

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ARTICLE

Elkanah Billings: The Lawyer Who Revealed the Ancient Life of the Past

Jeffrey M. Minicucci

Barrister-at-Law, Solicitor, and Notary Public
229 Glen Park Avenue
Toronto, Ontario, M6B 2E2, Canada
E-mail: priority1mail@rogers.com

SUMMARY

Elkanah Billings is an important, historical example of a 19th century Ontario lawyer who made a contribution to Canadian life by engaging in a pursuit outside the practice of law. An accomplished autodidact (i.e. a self-taught expert) and renowned as the father of Canadian paleontology, Billings has the distinction of being claimed by the global paleontological and geological professional communities, and by the Ontario legal profession. Although some researchers have alleged that Billings had abused alcohol during his life, he nonetheless managed to establish a remarkable career as a paleontologist. He applied the researching, analytical, and argumentative skills that he had acquired during his years of training and practice as a lawyer to the science of paleontology enabling him to peel back the layers of time to reveal the ancient life of the past. In view of his strengths, weaknesses, and professional accomplishments, the example of Billings' history potentially becomes increasingly relevant in the effort to reinforce the importance of ethics and professional responsibility among earth science and evolutionary biology professionals and to promote a shared sense of professional community and heritage. The example of Billings' history also presents a golden opportunity for the synthesist to nurture a closer connection between the law and science in the form of interdisciplinary or multidisciplinary dialogue and collaboration.

RÉSUMÉ

Elkanah Billings est un important exemple historique d'un avocat Ontarienne du XIXe siècle qui a apporté une contribution à la vie Canadienne en se livrant à une poursuite en dehors de la pratique du droit. Autodidacte accompli et reconnu comme le père de la paléontologie canadienne, Billings a la particularité d'être revendiqué par les communautés professionnelles paléontologiques et géologiques mondiales, et par la profession juridique de l'Ontario. Bien que certains chercheurs ont affirmé que Billings avait abusé de l'alcool au cours de sa vie, il a réussi néanmoins à établir une carrière remarquable en tant que paléontologue. Il a appliqué la recherche, d'analyse, et les compétences argumentatives qu'il avait acquises au cours de ses années de formation et de pratique comme avocat à la science de la paléontologie qui lui permet de décoller les couches de temps pour révéler l'ancienne vie du passé. Compte tenu de ses points forts, les faiblesses et les réalisations professionnelles, l'exemple de l'histoire Billings devient potentiellement plus pertinent dans les efforts visant à renforcer l'importance de l'éthique et de la responsabilité professionnelle des sciences de la terre et les professionnels de la biologie de l'évolution et de promouvoir un sens partagé de la communauté professionnelle et le patrimoine. L'exemple de l'histoire Billings présente également une occasion en or pour le synthésiste d'entretenir un lien plus étroit entre la loi et la science sous la forme de dialogue et de collaboration interdisciplinaire ou multidisciplinaire.

NOT A TYPICAL LAWYER…

Some Ontario lawyers have made a special contribution to Canadian life by engaging in activities or careers outside the practice of law (Sedgwick 1972). Elkanah Billings was one such lawyer, who stands in history as the 19th century father of Canadian paleontology (Fig. 1). He used his exceptional knowledge and researching abilities to peel back the layers of time to reveal the ancient life of the past. Long revered by paleobiologists, paleontologists, geologists, and fossil enthusiasts in Canada and throughout the world for the scope of his pioneering scientific work, Billings has arguably been an

Geoscience Canada, v. 43, http://www.dx.doi.org/10.12789/geocanj.2016.43.101 pages 211–222

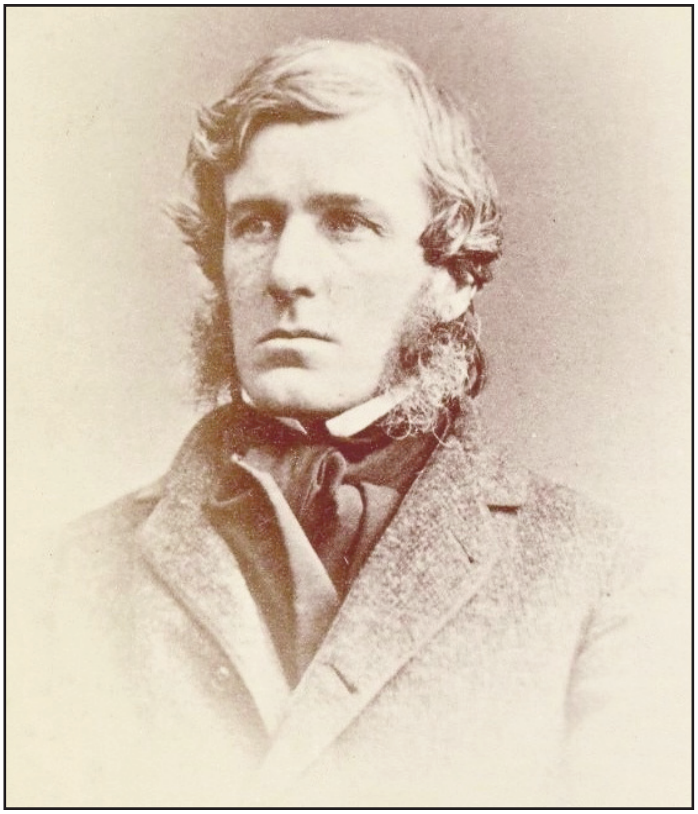

Figure 1. A formal bust portrait of Elkanah Billings by William Notman, dated 1862. From City of Ottawa Archives. Item Number MG002-22-037/CA000423.

unknown in the history of the Ontario legal profession where he began his professional life as a barrister. The Law Society of Upper Canada, the self-governing licensing body and independent regulator of Ontario lawyers since July 17, 1797 and also of Ontario paralegals since May 1, 2007 recognized Billings' work as a paleontologist, perhaps for the first time in the Society's history, in a 2008 online article following an enquiry made by the present author (Lewthwaite 2008). The Ontario legal profession traditionally has paid close attention to recording its collective history, especially significant contributions made by its members to the legal, political, social, and cultural evolution of Ontario and Canada. Although summaries of Billings' life and work have been published since his death, none have been written by a member of the Ontario legal profession. Thus an examination of Billings' professional conduct and career within the context of his duties and responsibilities as a lawyer is arguably overdue. The examination may prove to be informative for lawyers, paleontologists, and interested members of professions and vocations whose careers fall outside the scope of the practice of law or scientific study.

EARLY YEARS

The beginnings of Billings' history predate the existence of the province of Ontario and the country of Canada. Billings was born on May 5, 1820 in the township of Gloucester on the east bank of the Rideau River in the British North American province of Upper Canada (Whiteaves 1878). Billings' parents came to the province from the United States in 1792 following the American Revolutionary War (Edmond and Uren 2010). Britain's enactment of the *Constitutional Act, 1791* created the province to accommodate some of the many thousands of refugees who had fled persecution in the United States because of their loyalty to Britain (United Kingdom 1791). It has been argued that the evidence suggests that the Billings family may have decided to move to Upper Canada primarily for economic reasons (Edmond and Uren 2010). The Billings family holds the distinction of being one of Ottawa's founding pioneer families (Brunton 2004). Their home, constructed during the early decades of the 1800s, still exists as an Ottawa heritage tourist attraction (Billings Estate National Historic Site 2015).

Billings was initially educated in Gloucester and in Bytown (later Ottawa). He briefly interrupted his education during his early teenage years to try farming, and it has been argued that his apparent unhappiness as a farmer may have been one reason why he decided to run away from home when he was around 16 years old. A relative of Billings recounted that Billings had been hired to cut some wood during the time that he had run away from home. The task involved felling a tree, and Billings injured himself while performing the work. Frustrated, he eventually found himself being persuaded to return home. It was at that time that Billings' parents realized that he "was not cut out to be a farmer" (Edmond and Uren 2010). He subsequently resumed his education by attending the St. Lawrence Academy in Potsdam, New York (Edmond and Uren 2010).

The researchers Martha Edmond and Janet Uren co-authored a significant 2010 *Primary Exhibit Research Project, Billings Estate National Historic Site, Final Report* on the Billings family for the Billings Estate National Historic Site. Edmond and Uren (2010) argued that the circumstances of various incidents, events, and correspondence concerning Elkanah Billings suggest the possibility that he and his older brother, the botanist Braddish Billings II (Fig. 2), had abused alcohol during their lives. It could be argued that at least some of the allegations concerning alcohol abuse may have been based on circumstantial evidence or speculation. There do not appear to be any records indicating that the issue had ever been brought to the attention of the Law Society of Upper Canada (see Brunton 2004 for information on Braddish Billings II). Although a review of the pervasive consumption of alcohol in 19th century Upper Canada is beyond the scope of this article, studies on the subject have been published by various authors, including the Honourable Morris J. Fish, a retired justice of the Supreme Court of Canada (Fish 2011). Other relevant sources include Bonnycastle (1846), MacFarlane Lizars (1913), Pearson (1914), Wamsley and Kossuth (2000), and Hopper (2015).

Edmond and Uren (2010) also alleged that in 1847 Billings suffered a betrayal by his older brother, who reportedly blackmailed him for attempting to bring 42 law books into Canada from the United States without paying customs duties. It was argued that while Billings admitted his transgression and paid the amount owing for customs duties, it was unclear as to whether the money went to customs authorities or to his older brother for blackmail (Library and Archives Canada 1847 in

Figure 2. A formal full length portrait of Braddish Billings II by C.W. Parker, ca. 1860, of New York Studio, 140 Sparks Street, Ottawa. From City of Ottawa Archives. Item Number MG002-22-143.

Edmond and Uren 2010). The incident is neither reported nor corroborated in the majority of published accounts of Billings' life.

THE PRACTICE OF LAW

Billings' career path in the legal profession began in 1839 when he entered into legal training as a student member of the Law Society of Upper Canada. The Society, established by a statute enacted by the Upper Canadian legislature, formed the first statutorily empowered, self-governing bar in the British Empire (Province of Upper Canada 1797). Billings articled with several lawyers in Bytown and in Toronto, including the firm of Adam Wilson and Robert Baldwin, the legendary innovator of Canadian responsible government who forever changed the course of Canadian history (Hamilton 1904; see Cross 2012 for information on Robert Baldwin). Billings was called to the bar in 1844 (Whiteaves 1878). While practising law in Bytown, he formed a brief partnership with the county court judge Christopher Armstrong, but the partnership ended when a law was passed that forbade judges from pleading cases at the bar (Whiteaves 1878). Billings married Helen Walker Wilson, the sister of Adam Wilson, in 1845. They had no children. Edmond and Uren (2010) reported that Helen suffered from weak health, including a possible mental illness. In a November 30, 1865 letter addressed to his mother, Billings stated that "Helen has got quite over her sickness of last spring and summer but she is not strong. The mental derangement of which I wrote you has disappeared altogether" (City of Ottawa Archives 1865 in Edmond and Uren 2010).

Billings practised law in Bytown until 1849, sometimes alone, and sometimes in partnership with another lawyer, Robert Hervey (Whiteaves 1878), who acted as a mentor to Billings' younger brother Charles, while Charles was a law student articling in Bytown from 1848–1852 (Edmond and Uren 2010). Bytown would become the city of Ottawa in 1855, but before that time, the town was a simple outpost that has been described as "a rude little lumber town characterized more by sawdust, beer and brawls than by intellectual achievement" (Brunton 2004).

Billings decided to practise law in Renfrew in 1849. In an August 25, 1849 letter written to his mother, Billings made what Edmond and Uren alleged to be a veiled reference to a struggle with alcohol. Billings stated "I have seen enough now to convince me that I shall succeed here and do better than at Bytown provided I keep in my present state of good health" (City of Ottawa Archives 1849 in Edmond and Uren 2010). Billings soon complained that he felt ostracized in Renfrew because lawyers from Perth had apparently claimed the town as their "territory" for the practice of law (Edmond and Uren 2010). Perth lawyers may have felt justified in establishing their territorial claim because of the location of the courts relative to the surrounding towns. It has been reported that "That part of the country had not yet been set off as a District and all the Courts were held at Perth." Perth lawyers even extended their reach to Bytown, as some of them "had branch offices in Bytown and occasionally sent their older clerks to attend to them" (Riddell 1915). Billings expressed his frustrations to his mother in 1852, commenting that he was "as well qualified to enter as any lawyer in Bytown" (City of Ottawa Archives 2015). He returned to Bytown in 1852 to open a new law office, but it was at this time that he began to change the direction of his career by becoming a journalist (Whiteaves 1878). Notably, Billings began an activity in Renfrew that would have a profound effect on his future: he began collecting fossils (Edmond and Uren 2010).

JOURNALIST AND NATURAL HISTORIAN

Billings became the editor of the *Bytown Citizen* (later renamed the *Ottawa Citizen*) newspaper from 1852–1856 (Brunton 2004). He was known to have engaged in a spirited rivalry with the editor of another local newspaper, the *Bytown Gazette* (Whiteaves 1878). He was also a member of the Gloucester Township Agricultural Society. Billings helped establish the Bytown Mechanics' Institute on January 20, 1847 as a continuing education facility and library for working men in the absence of a public library or any other "publicly accessible research organizations in Bytown." Billings acted as curator (Klotz 1898; Brunton 2004; Edmond and Uren 2010). The Institute was subsequently reorganized as the Bytown Mechanics' Institute and Athenaeum on January 29, 1853 following a meeting chaired by Judge Armstrong where Billings acted as secretary (Klotz 1898).

Billings developed a great interest in natural science, but there were hardly any venues in Bytown where Billings could research his interest or share it with others. An informal, local group known as the Silurian Society convened meetings to discuss topics in geology, but the evidence is inconclusive as to the extent to which Billings may have participated in their activities (Brunton 2004). Billings wrote articles on natural science topics as editor of the *Bytown Citizen* and he also reprinted articles from American and European publications (Brunton 2004). It has been argued that the newspaper articles that Billings wrote showed "the enthusiasm of a student just entering upon a new world of inquiry, who has first begun to catch glimpses of his true vocation. They are marked, also, by the absence of that extreme caution which characterized some of his later efforts" (Whiteaves 1878). Billings became a member of the Canadian Institute (Royal Canadian Institute) in 1854, publishing his first group of paleontological papers in the Institute's journal. Some of the province's most distinguished citizens, including several lawyers, were members of the Institute. Lawyer members included representatives from the respected Baldwin, Robinson, and Ridout families in Toronto. The council president for 1853–1855 was Chief Justice Sir John Beverley Robinson, one of the most eminent and politically conservative figures in the province. Billings' peers reported that "The papers communicated by Mr. Elkanah Billings, 'On Some New Genera and Species of Cystidea From the Trenton Limestone' would do credit to the transactions of the most distinguished Societies in Europe and America" (Billings 1854; Anonymous 1855). Billings became a member of the Natural History Society of Montreal in 1854. The organization, which existed from 1827–1928, was to become very important in his life (Whiteaves 1878). He also won a cash prize for writing an essay on Canada for the universal exposition in Paris in 1855 (Whiteaves 1878).

Billings' work on the *Bytown Citizen*, and the concomitant success that he had experienced in publishing articles on natural science, prompted him in 1856 to begin publishing his own journal, which became the first natural science journal in the history of Ontario. The journal, known as the *Canadian Naturalist and Quarterly Journal of Science* and the *Canadian Naturalist and Geologist,* covered a range of "delightful and insightful" geological, paleontological, and zoological topics that "demonstrated both excellent powers of observation and a keen appreciation of the importance of documenting the appearance and constitution of original landscape conditions" (Wallace 1948; Brunton 2004). By publishing articles in the journal, Billings could qualify himself as a field geologist (Miller 2007). He also wanted to educate Canadians on the natural history of their land (Whiteaves 1878; Miller 2007). The first year sales of the journal were not sufficient to defray its publishing costs, but Billings' commitment to the cause of education enabled the journal to prevail (Whiteaves 1878). His parents also contributed some financial assistance (Edmond and Uren 2010). In an effort to promote the journal, he provided copies of the first issue to members of the Canadian legislature and to Sir William Logan, the preeminent Canadian geologist with whom Billings had been corresponding since 1852 (Whiteaves 1878; Clark 2004).

VICTORIAN AUTODIDACTS, LEARNED PROFESSIONS, AND MULTIPLE CAREERS

Because of his intense fascination with natural science and his profound learning skills, Billings became an autodidact (i.e. a self-taught expert) in aspects of biology, zoology, entomology, paleontology, geology, optics, and trigonometry (Whiteaves 1878). By pursuing an interest in natural science, Billings followed the pattern of some Victorian naturalists who had also been trained in the gentlemanly professions of either the law, or medicine, or both. Multiple professions could consequently complement one another, and the juxtaposition of lawyer and natural scientist was not necessarily contradictory or otherwise incompatible (compare with Berger 1983). Dr. William Warren Baldwin, one of the greatest fathers of the Upper Canadian legal profession in the early 19th century, was a lawyer, physician, architect, politician, and judge. His outstanding architectural knowledge was entirely self-taught (Baldwin and Baldwin 1969). Dr. John Rolph, another legendary figure in Upper Canadian history, was a lawyer, physician, and politician. In early 20th century Ontario history, the Honourable Mr. Justice Francis Robert Latchford, chief justice in appeal from 1931–1938 of what was then known as the Supreme Court of Ontario, was renowned as a published conchologist (Minicucci 2015). Latchford was no stranger to paleontology, having accompanied the legendary Canadian geologist Joseph Burr Tyrrell on field trips for the Geological Survey of Canada in 1881–1882 (Loudon 1930).

Billings' membership in the Law Society of Upper Canada was not terminated as he began turning to journalism and natural science as career choices. He continued to identify himself as "E. Billings, Barrister at Law" as the covers of issues of the *Canadian Naturalist and Geologist* indicated during the period that Billings was solely responsible for editing and publishing the journal (Brunton 2004). Although Billings never abandoned being a lawyer, he readily acknowledged by 1856 that he had "abandoned" the practice of law for natural science, which "ultimately became the ruling passion of his life" (Whiteaves 1878). Billings understood and accepted that publishing a journal was a difficult enterprise. In a February 29, 1856 letter to Sir William Logan, he admitted "*I am well aware that I shall have great difficulties to encounter, but I can overcome them as I have done others*" (City of Ottawa Archives 1856 in Whiteaves 1878). The Reverend John Lowry Gourlay, who wrote a comprehensive history of the Ottawa Valley in 1896, fondly recollected Billings as a lawyer and as the publisher of a geological journal:

> *'Mr. Elkana*[h] *Billings, the lawyer, we remember in our school days, as a gentleman of talent, energy, and fond of the young science of geology, then coming into notoriety. He left Bytown, and went to Montreal, where he published a geological monthly magazine very highly spoken of among scholars"* (Gourlay 1896).

CREDENTIALISM AND CREDENTIAL MONGERING

Billings' accomplishments as a paleontologist potentially speak strongly to the issues of credentialism and credential mongering, although the contexts within which one may consider such issues arguably were quite different in the 19th century as compared with the 21st century. The issue of credentialism exists when an excessive reliance is placed upon degrees, diplomas, certificates or professional designations as proof of the attainment of knowledge and competence in a subject. The value of certain credentials may deflate to the point of worthlessness when a sufficient number of people perceive a consequent need to earn the credentials. The issue of credential mongering exists when people attempt to inflate their own importance by using their existing credentials to mislead others into believing that they hold expertise in areas where they have no actual, relevant training.

Billings attained the degree of barrister-at-law as a consequence of being called to the bar. This credential is not a university or law school degree in present-day Ontario, but a license to practise law. The license remains designated as a degree because the province of Ontario conferred law degree granting powers on the Law Society of Upper Canada (Province of Ontario 1990). The Society historically maintained a monopoly on the education and licensing of Ontario lawyers until 1957, at which time the responsibility for academically educating Ontario lawyers was delegated to university law schools. The Society, as the regulator of the Ontario legal profession, remains responsible for licensing examinations and an apprenticeship or practical training component. The Society's ability to grant law degrees was a vestige from a time when the Society operated a law school, which subsequently moved to the campus of York University in suburban Toronto in 1968 and became a part of the university (Kyer and Bickenbach 1987). Present-day lawyers in Canada typically possess the tripartite combination of an undergraduate degree conferred by a university, a law degree conferred by an accredited university law school, and a license to practise law granted by the regulator in a Canadian province or territory. Billings and his contemporaries had experienced a significantly different process of lawyer education and licensing.

On deciding to become a professional paleontologist, Billings did not perceive a need to attain university degrees or other related credentials as a means to convince others of the legitimacy of the scientific knowledge and skills that he acquired through self-study and competent practical experience. His prospects of professional advancement as a paleontologist were not predicated on his obtaining a terminal or doctoral degree from a university. A terminal degree was not a necessary corollary to his achieving full professional recognition as a paleontologist. It could be argued that Billings' membership in the legal profession may have afforded him a professional advantage that obviated any need for him to attain additional credentials. Concerning the issue of credential mongering, Billings did not misuse the respected title of barrister-at-law to convince others of his authoritativeness as a paleontologist. He arguably may have benefitted from the public respect associated with identifying himself as a lawyer, but relevant and substantive knowledge underpinned his paleontological research. See Loxton and Prothero (2013) for an example of discussions on the issues of credentialism and credential mongering.

CHARACTER, COMPETENCE, AND ACTIVISM

It is frustratingly difficult to ascertain or evaluate Billings' character and competence as a lawyer based solely on the quality of his work product in the practice of law because nothing of any substantially informative value appears to exist. His work as a paleontologist demonstrates the observational skills, researching skills, and argumentative skills characteristic of a well-trained practitioner of the law. His social views on the law are potentially revealing. It has been argued that Billings' "keen sense of justice was often wounded by what seemed to him unjust juridical decisions, and it is said that he once barely escaped being indicted before the Grand Jury by his former partner Judge Armstrong for remarks published in the *Citizen* reflecting on one of his judgments" (Whiteaves, 1878). If he was truly an activist lawyer, Billings arguably may have been comparable to some of the more liberal members of the early 19th century legal profession in Upper Canada who sought political, governmental, and social reform. The profession at that time tended to be a bastion of British conservative traditions imported into the province. Billings' overall character has been described as "marked by great firmness and decision, by an unwavering love of truth and justice, and by an unaffected and winning modesty of demeanour" (Whiteaves 1878).

Although it would be acceptable for a lawyer to publicly present legal and public policy arguments to critique a judgment of a court, a personal attack against a judge would be irresponsible according to both 19th century and 21st century standards of professional conduct for Ontario lawyers. Whether acting as plaintiff's counsel, defendant's counsel, Crown prosecutor, or criminal defence, a lawyer must always treat any tribunal, including a court, with utmost respect. The duty applies in court and in public (Law Society of Upper Canada 2014). In the 19th century, the Law Society of Upper Canada and the provincial Court of Queen's Bench could have each taken action against Billings if it had been determined that he had behaved inappropriately towards Judge Armstrong. The court could have struck Billings off its rolls as a solicitor or attorney and the Society could have disbarred Billings by striking him off its rolls as a barrister. See Riddell (1928) for 19th century examples of lawyers being struck off the rolls of the Court of Queen's Bench as solicitors or attorneys and subsequently being struck off the rolls of the Law Society of Upper Canada as barristers. The provincial legislature empowered the Society to assume full jurisdiction over solicitors in addition to barristers in 1857 (Riddell 1916, 1928). Thenceforth, all solicitors became subject to certification and licensing by the Society before being admitted by the courts. All lawyers in the province are consequently barristers and solicitors to the present day.

CANADA'S FIRST PROFESSIONAL PALEONTOLOGIST

A series of political changes in British North America ultimately precipitated an unexpected opportunity that would change Billings' life forever and enable him to consolidate his reputation as "Canada's first professional paleontologist" (Brunton 2004). A British statute, the *Act of Union, 1841*, joined together the provinces of Upper Canada and Lower Canada to form the United Province of Canada in 1841 (United Kingdom 1841). The amalgamated province would ultimately be reconstituted as the provinces of Ontario and Quebec when the British North American provinces began uniting as one dominion on July 1, 1867 to form the country of Canada as defined by the *Constitution Act, 1867* (United Kingdom 1867). The legislature of the United Province of Canada resolved to perform a geological survey in an effort to assess the province's natural resources, and the Geological Survey of Canada was accordingly inaugurated in 1842, with Sir William Logan being appointed as director of the survey (Harrington 1883).

William Lyon Mackenzie and Charles Fothergill

During the 1830s, people who had not typically been known for having had any connection to earth sciences, like the radical journalist, politician, and Upper Canadian Rebellion of 1837 leader William Lyon Mackenzie, had recognized the need for a geological survey, but nothing had come to fruition during those difficult years (Harrington 1883; Zeller 2009). Against the backdrop of the monumental struggle for responsible government, the province of Upper Canada had endured a tumultuous general election and the beginnings of an economic depression in 1836; a rebellion in 1837; and the Patriot War of 1838–1842. See Guillet (1963) for an overview of these momentous events in the early history of the province of Ontario.

The short-lived York Literary and Philosophical Society, which had formed in 1831, had petitioned the Upper Canadian government in December, 1832 for funds "to provide for an investigation of the geology, mineralogy, and natural history of the Province" but nothing had resulted. Charles Fothergill, the first competent researcher in the natural sciences to have lived in Upper Canada, was one of the individuals who had formed the scientific organization. He had been a journalist, editor, and a member of the Upper Canadian Legislative Assembly from 1824–1830. He had been hobbled by the consequences of his political disagreements with the oligarchical Upper Canadian government during the years that he had served in the virtually powerless Legislative Assembly. He died penniless in 1840 (Harrington 1883; Bailey 1944).

In a surprising and admittedly foolish move, Mackenzie turned against the government agency that he had sought to establish. He publicly castigated Logan and the Geological Survey of Canada in 1858 because Logan had relied upon his profound geological knowledge to deduce that a supposed coal deposit on a farm near Bowmanville, Ontario was a fraud without making a personal visit to the site. Rather than encourage the public to trust Logan's judgment, Mackenzie painted a rather unflattering portrait of the Geological Survey of Canada as a group of lofty scholars wasting public funds. Logan's deductions were proven correct: not only did coal not naturally occur in the region at issue, but the perpetrators of the fraud had left evidence of their activities by inadvertently mixing some bread and cheese with the coal that they had placed at the site. When one of Logan's friends eventually brought him a sample of the coal, Logan immediately recognized it as "A good bit of Newcastle coal" (Harrington 1883; Mackenzie 1858 in Gates 1988). So much for criticisms that the Survey did not sufficiently apply itself to practical purposes. The friend with whom Logan had discussed the matter was William Bostford Jarvis (1799–1864), sheriff of the Upper Canadian Home District from 1827–1856; member of the politically conservative Toronto establishment during the early 19th century; and founder of Toronto's Yorkville neighbourhood. Toronto's Rosedale neighbourhood was named after Jarvis' house.

A Career for Life

When Logan was presented with the opportunity and the government funding to hire a paleontologist to work at the Geological Survey of Canada, he searched for candidates to fill the position. He knew of Billings' published articles on paleontology, recognized his talents, and secured Billings in 1856 as the Survey's first paleontologist (Whiteaves 1878; Edmond and Uren 2010). Billings relocated to the Survey's base of operations in Montreal, and for the rest of his life he worked at the herculean task of arranging, describing, and classifying the substantial number of fossils that the Survey collected (Whiteaves 1878). He also collected fossils himself, but only from local areas in the United Province of Canada (the provinces of Ontario and Quebec as of July 1, 1867), and in the nearby American states of Vermont and New York (Whiteaves 1878; Clark 2004). In addition, he sought to arrange the fossils in the Survey's geological museum for public exhibition (Whiteaves 1878). The Natural History Society of Montreal took over the duties of editing and publishing the *Canadian Naturalist and Geologist* after Billings accepted his post at the Geological Survey of Canada (Whiteaves 1878). The name of the journal was amended in 1884 to the *Canadian Record of Science*, with the first number titled the *Canadian Record of Natural History and Geology*. Publication was reportedly suspended in 1898 and from 1905–1913, but ultimately ceased in 1916 (Wallace 1948).

Billings briefly visited England and France in 1858. He exchanged ideas with luminaries in the field of paleontology and geology, including Thomas Henry Huxley, Sir Andrew Ramsay, Sir Roderick Murchison, and Joachim Barrande. Huxley may be fairly characterized as one of the greatest 19th century British autodidacts in the natural sciences. As a consequence, he was almost certainly in a position to have fully appreciated the depth and scope of Billings' self-taught knowledge and skills. Billings was similarly in a position to have recognized in Huxley the spirit of a fellow advocate, although Huxley's skills as an advocate would arguably not be definitively exhibited to the public at large until his legendary 1860 Oxford debate on evolution against Samuel Wilberforce. Perhaps it would not be unreasonable to postulate that Huxley's skills in oral advocacy would have made him an ornament to the legal profession in almost any part of the British Empire! See Huxley (1903) for a review of the 1860 Oxford debate. Huxley applied for a professorship in natural history at the University of Toronto in 1851, but when the matter was finally decided in 1853, he was rather astonishingly rejected. The professorship went to William Hincks, the brother of Sir Francis Hincks, who, at the time, served as premier of Canada West for the United Province of Canada (Huxley 1903).

It was at the time of his visit to England and France that Billings was made a fellow of the Geological Society of London (Whiteaves 1878). In a letter written to his father on May 28, 1860 Billings expressed hope that the geological museum of the Geological Survey of Canada would become a permanent institution, affording him with a career in paleontology "for life." Delighted with his paleontological work, he informed his father that "the occupation is exactly what I like and if I can live by it to the last I shall always think myself fortunate" (City of Ottawa Archives 1860). Billings and Logan were acknowledged for developing the geological museum into "one of the principal objects of attraction in the city." The museum was recognized as being "remarkable for the extent and variety of rock specimens, and the great number and beauty of the fossils; no geological survey on this or any other continent has been carried forward with greater energy or skill" (Harrington 1883).

WORK PRODUCTIVITY

Billings published numerous papers in Canadian, American, and English journals during his life. In particular, it has been estimated that he published around 93 articles in the *Canadian Naturalist and Geologist* (Whiteaves 1878). Billings also contributed to Logan's monumental work *Geological Survey of Canada: Report of Progress from its Commencement to 1863* (Logan et al. 1863; Ludvigsen 1979). Some of Billings' greatest published works include *Figures and Descriptions of Canadian Organic Remains* (Billings et al. 1858, 1859), *Palaeozoic Fossils* (Billings 1865, 1874), and *Catalogues of the Silurian Fossils of the Island of Anticosti, with Descriptions of Some New Genera and Species* (Billings 1866). Billings' work should be understood in the context of the times in which he lived. He was one of the world's pioneers in the fledgling science of paleontology. The articles that he published during the period from 1855–1857 predate the revolution in natural science that began in 1859, when Charles Darwin published *On The Origin of Species* (Darwin 1859; Desilets and Pageau 2003). The beginnings of Billings' work had even predated the significant popularization of paleontology afforded by the 1864 novel *Journey to the Centre of the Earth* (*Voyage au centre de la Terre*) by the legendary French author Jules Verne (Butcher 1998). It has been argued that Billings and Logan "were among the vanguard of Victorian scientists gathering clues – deemed crucial for Canada's intellectual and economic development – about the Earth's structure, mineral resources and biological history" (Boswell 2009). Billings wanted to understand fossil organisms in a broader paleobiological and paleoecological context instead of limiting his work to only describing and classifying them.

It has been suggested that Billings had a preference for field work over administrative work, which brought him into disagreement with Logan, who commented to Billings in an April 27, 1869 memorandum that "Your constant absence from the office is a worrying annoyance, particularly as I have reason to suspect that it does not arrive from rheumatism" (Boswell 2009). The matter may have evidenced nothing more than an unremarkable workplace disagreement that almost any earth sciences professional undertaking field work might arguably experience. Edmond and Uren (2010) alleged that alcohol abuse was the reason for Billings' absenteeism, and that Billings should have taken Logan's 1869 memorandum as a warning to cease abusing alcohol (Winder 2004; Edmond and Uren 2010). In a May 26, 1869 letter that Billings' mother wrote to his sister, his mother expressed hope that he and his older brother would "overcome" a "bad habit". She stated: –

> "*I had a very kind letter from Elkanah in which he writes that he has reformed from a bad habit he thinks that he has overcome the apetite* [sic] *and that I may rest assured that he will not fall again – and Braddish still continuing in the office all right. I write this to you for I know you will rejoice with me…*" (City of Ottawa Archives 1869 in Edmond and Uren 2010).

Billings reportedly sought help through periodic membership in a temperance league (Billings Estate National Historic Site 1978 in Edmond and Uren 2010). Edmond and Uren (2010) alleged that Braddish II and his son Walter ultimately died because of alcohol abuse.

Billings' work productivity was voluminous. It has been reported that he identified around 61 new genera and 1,065 new species of fossil organisms (Ami 1901a). Some of these identifications have withstood the test of time, but others have understandably been subject to revision as methods of paleontological investigation changed or improved over the years and new discoveries were made. The thoroughness of Billings' research ultimately facilitated future interpretations of his discoveries. Billings' work also anticipated the problems associated with researchers unjustifiably splitting one species into several different species, or unjustifiably consolidating several different species into one (Desilets and Pageau 2003). In a subsequent attempt to re-describe some of Billings' fossils, Charles E. Resser (1937) argued that "Billings evidently did little preparatory work on his fossils, preferring to describe them by inference of what was hidden by the matrix." It has been argued that Billings' efforts were limited by the tools and methods available at the time that he performed his research, and by his lack of extensive travel experience and his limited, local field experience (Whiteaves 1878). Although it has been purported that Billings was not the quintessential "field man par excellence" (Copeland 1993) he has nonetheless been credited with describing new genera and species "in a concise and exact manner" (Desilets and Pageau 2003).

DISAGREEMENTS WITH OTHER PALEONTOLOGISTS

True to his training as a lawyer, Billings was knowledgeable in the literature and he could cite the appropriate sources to support his arguments. He knew how to properly contrast and compare new fossil species with existing descriptions of known fossil species. His legal skills also afforded him the ability to vigorously defend his position, if challenged (Desilets and Pageau 2003).

Dispute with Addison Emery Verrill and William Harmon Niles

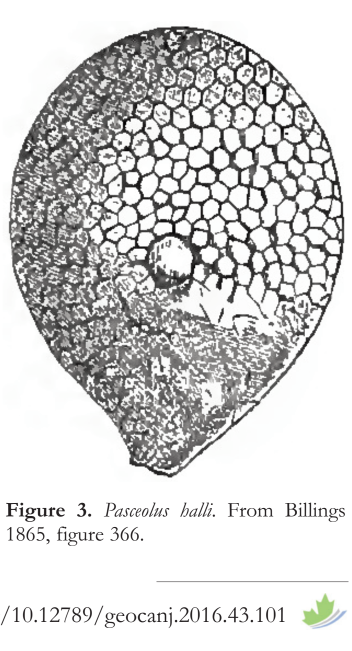
Figure 3. *Pasceolus halli*. From Billings 1865, figure 366.

In one incident concerning the fossil organism *Pasceolus halli* (Fig. 3), two renowned American researchers, Addison Emery Verrill and William Harmon Niles, apparently misinterpreted Billings' analysis of *P. halli* and alleged that Billings had believed that a certain family of fossil organisms (sphaeronitid echinoderms) was related to another group (ascidian chordates) to which the family had no close affinities (Anonymous 1866). The matter was not unusual, controversial or outside the scope of proper scientific investigation, analysis, and debate. But Billings' response is important because it arguably provides further insight into how his legal training had shaped his critical and argumentative skills as a paleontologist. Billings countered Verrill and Niles by reviewing his own work and satisfactorily concluding that "In all that I have written on the subject I cannot find a single remark from which it could be supposed that I ever entertained such an idea." Billings considered *P. halli* to be a valid, but enigmatic fossil taxon. He demonstrated that Verrill and Niles had based their conclusions in the *P. halli* matter on unwarranted assumptions and on attempts to connect unrelated facts: the respected researcher, Karl Eduard von Eichwald, had apparently described the genus *Pasceolus* under the name of the sphaeronitid echinoderm, *Cyclocrinites* (Billings 1865). Billings subsequently explored the possibility that the affinities of *P. halli* might be with ascidian chordates. Verrill and Niles suggested that it might be a cystidean echinoderm. Verrill and Niles appeared to have drawn the improper conclusion that Billings must have meant to imply that sphaeronitids were closely related to ascidians because von Eichwald's work had connected *Pasceolus* with sphaeronitid echinoderms and Billings had subsequently connected *P. halli* with ascidian chordates (Billings 1866). Billings applied his skills to unravel what may have appeared to have been a veritable Gordian knot of tangled or misinterpreted facts. Although the affinities of *P. halli* were not definitively resolved, 20th century research found that although chordates and echinoderms are not closely related, they are broadly related as members of the Deuterostomia within the Bilateria.

Disputes with James Hall

Billings wrote articles that have been characterized as "scathing" concerning the "supposed manipulation of specimens and publication dates" by the renowned American paleontologist and geologist James Hall. It has been argued that Hall's allegedly "opportunistic tactics" in response to Billings' articles "were no match for Billings' legal treatment of the dispute," which rendered Billings' position in the matter "unassailable" by modern scientific standards (Clark 2004). Billings had read that Hall had apparently published a paper purporting to rename a fossil that Billings had previously named. Problems associated with the naming of fossil species have not been rare occurrences in the history of paleontological research. Billings requested a colleague to provide him with a copy of Hall's published paper. In response, Billings unexpectedly received from the colleague some pages that turned out to be Hall's proof sheets, instead of a published paper. The sheets evidenced information and dates of descriptions and names of fossils that suggested to Billings that the subject matter of the proof sheets had previously been published. Hall appeared to have twisted the matter into an opportunity to defame Billings, accusing Billings of improperly obtaining and viewing proof sheets containing data that Hall had not yet published. Billings published an explanation, exposing Hall's accusation as unsupported, vindictive, and sensationalized:

> *"By blending a mere particle of truth with a great deal that is not true, he has magnified 25 pages obtained unintentionally after publication, into whole volumes of proof sheets procured designedly before. This is only a continuation of the unfair treatment I have received from him during the last four years…I would recommend all persons who may have occasion to read Prof. Hall's papers to examine them closely, as it is not unusual for him – especially in questions of priority to arrive at decidedly erroneous conclusions"* (Billings 1862).

Billings' disciplined analysis contrasted sharply with Hall's apparent strategy of exaggeration, intimidation, and defamation, and potentially revealed a troubling aspect of Hall's alleged approach to publishing research. Why did material that Hall argued was unpublished apparently contain information and dates suggesting that the subject matter of the material had previously been published? The possible implication is that Hall allegedly attempted to backdate or otherwise manipulate the dates of his descriptions of fossils ostensibly to enable him to gain priority over other researchers, including Billings, in first describing and naming the fossils. If Hall's proof sheets comprised evidence of unethical publication practices, it is doubly ironic that the person who had unexpectedly come into possession of the evidence was on one hand a scientist whom Hall had sought to disadvantage, and who understood the technical implications of the evidence, and on the other hand a lawyer who understood the legal implications of such evidence against Hall, and who could formulate the appropriate legal arguments, accordingly.

Billings alleged that Hall had purposely attempted to frustrate Billings' work by publishing descriptions of Canadian fossils that Hall knew or ought to have known Billings was in the process of describing. Hall allegedly attempted to facilitate his goal by borrowing fossils from Billings' collections without disclosing his true reason for doing so and by procuring fossils from a collector whom he knew was collecting for the Geological Survey of Canada. In contrast, Billings argued that he avoided interfering with Hall's work on New York State fossils by collecting fossils from that state only for the limited purpose of comparing them with Canadian specimens, and not for the purpose of describing and naming them. Billings argued that when he described and named fossils, he did so in an open and transparent manner in the public interest. He appealed to legal concepts of natural justice and procedural fairness, arguing that Hall had acted improperly by violating customary laws of scientific publication: –

> "*With regard to publication, I hold it to be the duty of an author who describes new fossils to make his work accessible to the public. If he fail* [sic] *to do this, he cannot claim priority over one who has published in the regular way. His work may be adopted as a matter of courtesy, but not to take precedence over fair publication…*
>
> *…I hold that there are laws which result spontaneously from the very nature of the circumstances to which they relate. These laws exist perpetually, although not instituted by legislative enactment, and although they may be habitually transgressed by any number of unscrupulous persons. The law of publication is one of these. Every true naturalist instinctively feels and knows that such a law*

does exist, and that it is his duty to observe it" (Billings 1872a). Various codes existed to address issues concerning the naming and classification of animal life, but the issues would not be definitively addressed until the International Commission on Zoological Nomenclature, founded on September 18, 1895, eventually published its first edition of the *International Code of Zoological Nomenclature* (Melville 1995; International Commission on Zoological Nomenclature 1999). Billings demonstrated that he had no desire to forsake his commitment to ethical professional conduct when he proved that he could respond to personal attacks in a reasoned and civil manner. John M. Clarke, the biographer of James Hall, recounted that Hall and Billings had been amicable and respectful towards one another as "brothers-in-arms" prior to around 1860. Clarke agreed that Billings' work "has not been surpassed in refinement in the field of palaeozoic palaeontology. He was gentle, generous, just, and loyal" (Clark 2004).

SCOPE OF RESEARCH

Billings sought to correlate strata of the same age in different parts of the world to enable him to gain a better understanding of fossil organisms in a global context (Desilets and Pageau 2003). It has been argued that "his recognition of fossil assemblages was instrumental in the determination of the precise limits and distribution of geologic formations" (Miller 2007). Billings' work enabled Logan to identify the nature of a North American geological feature that Logan termed the Quebec Group, which has since been used to describe a structural feature known as Logan's Line (Clark 2004; Miller 2007). It has been argued that the accomplishment was "first due to a right apprehension of the fossils, for which Mr. Billings deserves much of the credit" (Harrington 1883). Billings' contribution has been described as a "most important and sagacious discovery" (Harrington 1883).

The fossil organisms that Billings researched ranged across geological time. The Paleozoic Era marine organisms that he studied, which lived during various periods from 541–252 million years before the present, included trilobites, brachiopods, molluscs, echinoderms, annelids, bryozoans, cnidarians, poriferans, archaeocyathids, and many other kinds of invertebrate fossils. He also described various Ontario fossil mammals from the Quaternary Period, which is dated from around 2.6 million years ago to the present, including a beluga whale, now classified as *Delphinapterus leucas*, from Cornwall (Billings 1870; Wagner 1984); a mastodon, now classified as *Mammut americanum*, from Dunnville (Billings 1869); and a mammoth, now classified as *Mammuthus primigenius*, from Burlington Heights (Billings 1856, 1863). His paper on the mammoth demonstrated his skills in comparative osteology (Whiteaves 1878). Billings evidently did not limit his research to only one particular group of fossil organisms. His mind and spirit seemed to have been profoundly attuned to the range of past and present life on Earth.

PROOF OF THE EXISTENCE OF PRECAMBRIAN FOSSILS

The magnitude of one of Billings' accomplishments went almost unrecognized during his lifetime. He described and named the fossil *Aspidella terranovica* in 1872 based on small, disc-like structures that a geologist had found preserved on rocks from St. John's, Newfoundland (Billings 1872b). Billings made the "bold" decision to identify *A. terranovica* as the preserved evidence of a Precambrian organic structure (Fedonkin et al. 2007). The Precambrian is the part of geological time dated before 541 million years ago. Fossils from this time were virtually unknown in Billings' day, but he was able to correctly interpret the stratigraphic clues to ascertain that *A. terranovica* was from the Precambrian. The apparent absence of preserved Precambrian organisms in the fossil record was a problem that frustrated Darwin in his desire to bolster the theory of evolution by identifying the Precambrian ancestors of fossil organisms already known from the Cambrian Period. Although Darwin was aware of Billings' paleontological publications, he apparently did not realize that Canada's first paleontologist had solved the problem concerning proof of the existence of Precambrian fossils (Ramsay 1859 in Burkhardt and Smith 1985). But many researchers either paid no attention to Billings' classification of *A. terranovica*, or simply doubted that *A. terranovica* represented an organic structure and assumed that Billings' identification was a mistake (Boswell 2009). Some researchers did accept that *A. terranovica* represented "problematical forms…which may be Crustaceans or Mollusks allied to the limpets" from strata "underlying the Lower Cambrian" (Dawson 1897) and perhaps more specifically "apparently referable to the Huronian" (Nicholson 1897). Billings' conclusions on the nature of *A. terranovica* would not be completely vindicated until 2000, when *A. terranovica* was not only demonstrated to be a fossil consisting of the preserved evidence of a circular holdfast of a sessile, frond-like organism, but was also demonstrated to be the first fossil to have been named from the geological period of the Precambrian known as the Ediacaran Period dated from around 635–541 million years before present (Gehling et al. 2000). It has been argued that Billings saw Precambrian fossils "with a clarity that no one did for more than half a century." He recognized that the fossils represented soft-bodied organisms, and that the rocks in which they were found were from a geological age older than the Cambrian Period (Boswell 2009). Billings also wisely declined an opportunity to accept a lead role in supporting the argument made by other researchers that a Precambrian, non-organic geological structure that had been named *"Eozoon canadense"* was a fossil (Dawson 1897; Clark 2004). Researchers in the 21st century have described many assorted Ediacaran soft-bodied organisms from extraordinary fossil deposits (known as Konservat–Lagerstätten deposits) around the world. Ediacaran fossil deposits from Newfoundland, including the famous Mistaken Point Lagerstätten, are among the richest in the world (Fedonkin et al. 2007; Boswell 2009).

RECOGNITION AND AWARDS

Billings was recognized for his exceptional work during his lifetime as his scientific reputation spread to various nations. In addition to being made a fellow of the Geological Society of London, he was the vice-president of the Natural History Society of Montreal. It has been reported that he was often asked to be president, but he always declined the honour (Whiteaves 1878). He was awarded medals by the International Exhibition of London in 1862; by the Natural History Society of Montreal in 1867; and by the Paris Exposition of 1867 (Whiteaves 1878; Miller 2007). The Paleontology Division of the Geological Association of Canada began awarding the prestigious Elkanah Billings Medal in 1978 (Fig. 4) to "an individual in recognition of an outstanding long-term contribution to any aspect of Canadian paleontology or by a Canadian to paleontology" (Geological Association of Canada 2011). As "a fitting link from past to present" the 1997 recipient of the medal, Thomas E. Bolton, was a curator of the fossil collections that Billings had started (Nowlan and Smith 1998).

THE END OF BILLINGS' LIFE

Although Edmond and Uren (2010) alleged that Billings struggled with alcohol abuse, he nonetheless evidenced an undisputed dedication to his paleontological work: "Until his health failed him, he was to be found at his desk as early as half-past seven in the morning, and he often took his work home with him at night. He possessed a capacity for brain labour such as falls to the lot of few." He was also reputed to possess "analytical powers of a high order." It has been further suggested that his success as a paleontologist was attributable to his ability to "concentrate his mind on one object." Billings was also known to be an impressive polyglot, being able to read and write in German, Norwegian, Swedish, and Danish (Whiteaves 1878). In addition, several fossil organisms were named in his honour (Ami 1901a). Billings posed for a photograph taken by the renowned Scottish-Canadian photographer William Notman in 1862 (Fig. 1). A painting of Billings by William Raphael was commissioned in 1876 and placed in the hall of the Natural History Society of Montreal. The Ottawa Field-Naturalists' Club commissioned a painting of Billings by Charles E. Moss and presented it to the Geological Survey of Canada in 1900 (Whiteaves 1878; Ami 1901b; Anonymous 1901).

Billings' life ended in Montreal on June 14, 1876 after he suffered for three years from a type of kidney disease historically known as Bright's Disease (Whiteaves 1878). Edmond and Uren (2010) alleged that the illness may have been precipitated by or exacerbated by alcohol abuse (Billings Estate National Historic Site 1978 in Edmond and Uren 2010). As may often be the case when scientists undertake multiple or complex extended projects and perform ongoing research, Billings left "a large amount of unfinished work" at the time of his death (Ami 1901a). The amount of unfinished work may have been inevitable in view of the tremendous amount of fossil material that Billings had been responsible for sorting and classifying during his lifetime. It has been argued that he could have achieved greater accomplishments and he could have continued to revise and refine his work, had he lived longer (Whiteaves 1878). History demonstrated that the long term viability and advancement of paleontological research at the Geological Survey of Canada had not been irrevocably prejudiced by the death of Billings as the incumbent staff paleontologist. The volume, scope, and thoroughness of the work done by Billings and Sir William Logan had laid the appropriate foundations for Billings' successor, Joseph F. Whiteaves. Whiteaves earned a place of distinction in the history of Canadian paleontological research. Of all of the publications on the life and work of Billings, the 1878 obituary authored by Whiteaves arguably remains one of the best.

Figure 4. Elkanah Billings Medal awarded by the Geological Association of Canada Paleontology Division since 1978. From Geological Survey of Canada. 1992-054A&B. Undated.

A Mystery Concerning Billings' Final Resting Place

Published accounts of Billings' life and work differ on the location of the place of his burial. Records indicate that Billings was buried at Saint Andrew's Presbyterian Church in Montreal (Quebec Vital and Church Records 1876; Bibliothèque et Archives nationales du Québec 1876 in Edmond and Uren 2010; City of Ottawa Archives, undated). It has also been written that he "was buried in the Wilson family plot in Toronto" located at the Toronto Necropolis (Ludvigsen 1979; Clark 2004; Miller 2007) where Billings' wife Helen was subsequently buried when she died on May 4, 1882 (Ontario Registrar General 1882; City of Ottawa Archives, undated). Necropolis records state that Billings died in Montreal on June 14, 1876 from "Dis of Heart" (heart disease?) and that he was buried at the Toronto Necropolis on June 17, 1876 in a plot owned by "G.N. Wilson" (Ontario, Toronto Trust Cemeteries 1876). Assuming that the Necropolis records are correct, if Billings' remains had ever rested at Montreal, a decision must have been made to promptly transfer them to Toronto to inter them at the Necropolis.

LEGACY

Elkanah Billings is a Canadian historical figure, who has the distinction of being claimed by the global paleontological and geological professional communities, and by the Ontario legal profession (Lewthwaite 2008). It is potentially important for new and emerging Canadian talent in the various branches of the earth sciences and evolutionary biology to be aware of the lives of historical, pioneering researchers, like Billings, in an effort to reinforce the importance of ethics and professional responsibility and to promote a shared sense of professional community and heritage. The example of Billings' history also presents a golden opportunity for the synthesist to nurture a closer connection between the law and science in the form of interdisciplinary or multidisciplinary dialogue and collaboration. The professions and ultimately the public serve to benefit as information, issues, systems, and methodologies are shared, discussed, and integrated. With a knowledge of the history of his strengths and weaknesses, and with an understanding of his record of professional accomplishments, members of the Ontario legal profession recognize the status that Elkanah Billings holds in Canadian history by remembering that he was, and always will be, one of their own.

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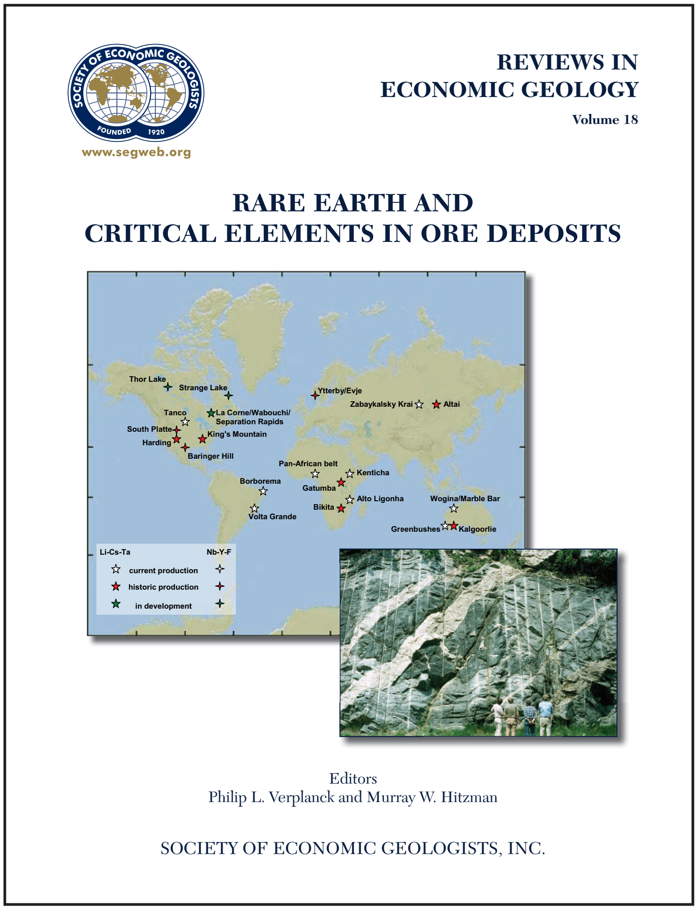
REVIEW



Rare Earth and Critical Elements in Ore Deposits

Philip L. Verplanck and Murray W. Hitzman *(editors)*

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Reviewed by Andrew Kerr
Department of Earth Sciences
Memorial University
St. John's, Newfoundland and Labrador, A1B 3X5, Canada
E-mail: akerr@mun.ca

It has often been said that the only thing that remains constant in the world of natural resource commodities is *change* – and this was especially true in the first decades of our new century, which saw sudden and often unpredicted interest in a range of unfamiliar minor commodities. This new Reviews Series volume, *Rare Earth and Critical Elements in Ore Deposits,* from the Society of Economic Geologists provides a timely review of the geology and mineralogy of a diverse group of minor elements that are now commonly termed the *critical minerals* or *critical elements*. In this context, criticality means at least two things – first, many of these commodities are vital in modern technology, particularly in clean and efficient energy generation, but also in computers and communications. The omnipresent iPhone, and all other such devices, depend on at least 20 of these little-known and rare elements. Secondly, many of these elements are equally critical in another sense, as major reserves and most production are geographically focused in countries not noted for their stability, or for political agendas closely aligned with those of western industrial consumer nations. For some elements, for example tantalum (Ta), ethical concerns have been expressed about the use of resource revenues to fuel long-lived conflicts involving human rights violations. Despite the wide perception of some of these elements as 'green' commodities, many comments have also been made concerning the environmental impacts and carbon footprints associated with their extraction and processing. In short, nothing is simple when it comes to critical minerals, and their geology is no exception. This excellent volume is a response to the need for better technical information, prompted by increased exploration to identify new sources. Much of this effort has been corporate, tempted by the prospect of strong returns on investment, but many governments also have a strong interest in reducing reliance on outside sources and their associated political-economic risks. Given this framework, it is not surprising that the United States Geological Survey (USGS) is an important supporter of this publication, which is in part a valuable outgrowth of their own work to document domestic REE resources. The fourteen chapters, each framed as an independent paper with an abstract summary and full bibliography, review known deposits and metallogenic environments largely

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The photos above show examples of REE-enriched minerals and exploration methods in northern Canada. From the top left corner, in a clockwise order: a) The distinctive mineral eudialyte (red) from the Red Wine Mountains, Labrador. This mineral, which contains significant REE but very little U or Th, is of great interest as a potential source, but it has proved difficult to process. b) Magmatic-hydrothermal breccia with purple fluorite matrix from the Strange Lake REE deposit, on the Labrador-Quebec border. c) The interest in the REE led to massive exploration efforts in northern Canada, exemplified by the Quest Minerals Exploration Camp at Lac Brisson, Quebec, adjacent to the Strange Lake deposit. d) Diamond drilling in remote mountainous tundra along the Quebec-Labrador border. Photo credits: A. Kerr.

on the basis of existing data, but also incorporate information and ideas gained from recent exploration. Many papers implicitly or explicitly highlight the frustrating lack of critical facts and data – or at least the availability of such information. For example, assessment of the rhenium (Re) resources associated with copper–molybdenum deposits depends on limited and possibly unrepresentative data – in some cases only a single analysis per deposit. As Earth Scientists, we can work only with what we have, but I suspect that much more information may exist behind corporate and bureaucratic walls. The individual papers cover a wide range of topics, and they have diverse authorship, with many contributors coming from the USGS. It goes without saying that examples from Canada figure prominently in some of these papers, as we are fortunate to be endowed with significant, undeveloped resources for many of these critical minerals.

The most prominent of the so-called critical minerals are the rare-earth elements (REE), which are regular features in the popular press and no longer familiar only to chemists. These are important in many applications, from the mundane (e.g. fridge magnets) to sophisticated devices such as smart phones, flat-screen displays, wind turbines and hybrid cars. The REE were once produced in small quantities from diverse sources as primary and by-product commodities, but for almost 20 years, China has produced almost all of the global supply. Taxation policies that restricted REE exports predictably caused their prices to surge, which led to a worldwide frenzy of exploration. Like many critical minerals, the REE are actually very widely distributed across the globe, but this does not diminish the challenges in bringing new deposits into production, as several Canadian Junior Mining Companies have discovered. The closely similar chemical behaviour of this group of elements is well-known to geochemists – this is why we use them in research studies – and the selective production of the much rarer ‘heavy’ REE (gadolinium (Gd) to lutetium (Lu) in the periodic table) is nigh impossible. About half of this volume (six full chapters and important parts of others) are related to the REE, for they truly are the poster child of critical minerals. Other elements typically associated with the REE, such as zirconium (Zr), niobium (Nb), tantalum (Ta), hafnium (Hf), beryllium (Be) and thorium (Th) also receive attention as part of this comprehensive treatment, although their sources are more diverse. Several other chapters have a different structure in that they discuss the abundance and occurrence of selected critical elements as minor components of several more familiar mineral deposit types, and the potential for by-product extraction. Some of these associations are well-known, e.g. rhenium (Re) in some porphyry-type deposits, but others are less well-documented, e.g. the enrichment of a range of minor elements in modern sea-floor massive sulphide deposits. As one would expect, granitic pegmatites – which are the very sources from which many of these unusual elements were first isolated – are given a discrete chapter of their own, and lithium brines merit similar treatment. The papers vary considerably in length and detail, but most are on the long side, with extensive tables listing known examples and features, and thorough reviews of geological and geochemical controls. Some papers extend this treatment to discussions of exploration and mineral processing methodology, but the emphasis is mostly towards geological attributes – even though the greatest obstacles to developing many deposits lie in beneficiation and refining.

I doubt that interested readers will complain about a volume that has a page for every day of the year, because these are reference pieces that will have lasting value. We would not expect them to be light reading, but many are really quite readable given their bulk. The relevance of many papers extends beyond the critical elements that might occur in a given setting, because authors also provide full descriptive and interpretive reviews of host metallogenic environments. Although the information for specific critical elements in epithermal gold deposits might in the end be fragmentary, the value of the review paper on this setting is undiminished by the inevitable questions it raises. As a neophyte editor, I was impressed with the clarity of writing and presentation and the general absence of errors. I now know only too well how hard such things are to eliminate, especially in any work that involves wide compilation of numerical data and multiple figures and maps. The consistency of presentation and figure quality is also impressive.

Most economic geologists and students of the subject will find the six chapters devoted to Rare Earth Elements (REE) the most useful and widely applicable portion of the volume. One of these papers, by Yuling Xie and others, provides a review of REE deposits in China, finally presenting descriptive material that has always been hard for geologists outside China to obtain. Two long chapters discuss the most familiar settings for REE deposits, i.e. carbonatites (by Philip Verplanck and others) and alkaline-peralkaline igneous suites (by Jarda Dostal). Both provide comprehensive information on the major deposits associated with such rocks, and do a good job of tackling the sometimes bewildering variety amongst these small-volume, aberrant igneous suites and their variably endemic mineralogy. I would not go so far as to say that my own long-standing confusion about carbonatites was eliminated through reading, but it was certainly greatly diminished! Other chapters present material that is less familiar, including an excellent descriptive and process-oriented review of so-called *ion-adsorption-type* REE deposits (by Kenzo Sanematsu and Yasushi Watanabe). These surficial deposits still remain the dominant source for many of the valuable heavy REE elements and, unlike other types of REE deposits, economic examples do appear to be restricted to Chinese territory. There are few easily understandable papers about the features and origins of these deposits, and this paper fills a prominent knowledge gap. Might such deposits occur elsewhere in subtropical regions underlain by granites of appropriate composition, and if they do, should Society sanction their exploitation? Interesting questions, indeed, but beyond the aims of this book. Other papers tackle placer REE deposits (by Debashish Sengupta and Bradley Van Gosen) and the important question of sedimentary phosphorite REE deposits (by Paul Emsbo and others). Amazingly, over 50,000 tonnes of REE (of which almost half represent valuable heavy REE) are mined, beneficiated and put into solution every year, but are not recovered. Evidently, phosphorite deposits could potentially meet a large portion of the world’s growing demand for these elements. Interestingly, there appears to be secular variation in the abundance of REE-enriched phosphorites in the geological record, implying wider controls by oceanic chemistry, oxidation states, and perhaps global tectonic cycles. Again, this broad treatment and assessment of REE resources in this environment fills important scientific and economic needs.

Tackling the subject of pegmatites and critical elements is a very tall order, as these rocks vary enormously in composition and texture, and virtually every critical element is found in some kind of pegmatite somewhere on the Earth. The treatment by David London focuses to significant extent on the physical and chemical processes involved in this transitional magmatic- hydrothermal environment, and emphasizes some of the more valuable minerals (e.g. columbite-tantalite, spodumene, beryl, petalite and pollucite – sources of Ta, Li and Cs) that are preferentially restricted to this environment. The remaining chapters in this volume are focused on the abundance of and potential for critical elements as by-product commodities from the processing of other types of ore deposits. These include epithermal gold deposits associated with alkaline igneous rocks (by Karen Kelley and Paul Spry – emphasis on Te, PGEs, REE, F and V) and also other types of gold deposits (by Richard Goldfarb and others – emphasis on Bi, Hg, In, Sb, Se and W). Base-metal deposits receive a similar assessment, both in the modern seafloor setting (by Thomas

Monecke and others) and in ancient sedimentary-hosted examples (by Erin Marsh and others). Associated critical elements in submarine hydrothermal systems are very diverse, including Bi, Cd, Ga, Ge, Hg, In and others, with differences in the signatures of Cu-rich and Zn–Pb-rich systems, and also interesting contrasts with ancient examples preserved as VMS deposits. Some of these same elements are also present in sediment-hosted sulphide deposits of various types, although available data are limited. The final two papers of this type assess critical-element abundances in sandstone-hosted uranium deposits (by George Breit – emphasis on Mo, Re, Sc, REE, V and Se) and the well-known association between Re enrichment and porphyry copper-molybdenum deposits (by David John and Ryan Taylor). Although both deposit types constitute important economic resources in the western United States, it seems that data on minor element geochemistry for such settings remains scattered and of variable quality. The final contribution on lithium-rich brines (by Lee Ann Munk and others) is another example of a much-needed global review of a topic for which previous syntheses are nonexistent or hard to obtain. These represent one of the lowest-cost options for meeting growing demand for this commodity, linked to its widespread use in the power sources that fuel our mobile technology. This subject is also one of major relevance in the western United States, where known and potential resources exist.

This volume is definitely not a mainstream text book with a wide potential audience, but for those with a specific interest in these diverse commodities, or in educating students about the sheer breadth and scope of economic geology, I believe that it will prove invaluable. It provides not only an up-to-date summary of these important deposit types, but also highlights the gaps in knowledge that need to be filled in the interests of greater understanding and more successful exploration. It also makes a good case for systematic geoscience of the kind completed by the USGS and its sister organizations – without this public input, much of the data here would probably never have been acquired, or collated in such seamless form. The Society of Economic Geologists is to be congratulated for its efforts in bringing this project to fruition, and the editors are to be congratulated for what must at times have seemed a hard and endless task. The authors also deserve congratulations, for some of these papers represent enormous compilation and interpretation efforts. It is hard to predict exactly which of the critical elements will remain critical in the light of increased exploration and other political or economic developments, but one thing is for sure – this compilation will remain a critical source of knowledge, and should disseminate that knowledge well. For anyone with a broad interest in economic geology, it is a rare and valuable commodity in its own right.

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