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Is There an Open-Access Future for Geoscience Canada?

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The Shifting Sands of Shoreline Signatures

Ontario's Water Future: Plumbing the Depths of Stratigraphy

2021 Volume 48

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Cover Image: Waterside Beach, New Brunswick, Canada in September 2015. Waterside Beach was the beach-shoreface system from which the Tidally Modulated Shoreface was developed (see Dashtgard et al. in this issue). Image source: Google Earth.

EDITORIAL

Is There an Open-Access Future for GEOSCIENCE CANADA?

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Almost exactly a year ago, I was trying to return home to Newfoundland with little understanding of what would unfold from the Global Pandemic that has since influenced - or more accurately, controlled - most aspects of our lives. I have read various opinion pieces about the 'positive side-effects of the pandemic' or similar constructs but, like many, I find it difficult to identify or enumerate these. But I can think of at least one development that relates to *Geoscience Canada* - for the last twelve months, we have functioned as an open access journal, with content freely available to all. This proved to be a help in producing the journal through 2020 - which certainly had its challenges - but we feel also that it helped to raise our profile in the Global Geoscience Community. As an editor soliciting contributions, it was wonderful to be able to refer potential authors directly to current or recent issues on our websites. To promise that any published article would be immediately available and could be freely distributed was also an asset. We hope that the impact of this increased visibility will assist us as we proceed through 2021, which likely will still pose many challenges. However, even before the pandemic, we were almost there - we had already taken an important step along the road to Open Access when the subscription window for *Geoscience Canada* articles went from two years to one, in conjunction with other journals of the Érudit consortium. This first issue of Geoscience Canada for 2021 is also fully Open Access, but this reflects specific arrangements for the papers that it contains; the previous policy will return for the remaining issues in volume 48. I view that reprise with some regret, so perhaps this is a good chance to revisit issues connected to a possible Open Access future and think about ways to achieve that goal. If, indeed, this is something that we really want to pursue. Nobody will be surprised to learn that this is a complex matter, or that issues of funding and sustainability lie at its core.

In 2016, soon after becoming editor, I wrote a commentary about Open Access (Kerr 2016) and much of what it contains remains true. At that time, a complete transition did not seem viable for us, but we had to consider ways to accommodate this growing trend. In the end, we opted for what is termed the "hybrid model", in which immediate Open Access is 'sold' to authors who desire it. Initially we had two options - immediate transfer, and transfer one year from publication, with a 50% discount for the latter. Following Érudit's decision that all affiliated content should be Open Access after one year, the higher rates were eliminated. Today, if you publish a paper with us that occupies 10 journal pages, the price tag for immediate Open Access is CAD$ 1000 - a CAD$ 500 flat-rate fee, and CAD$ 50 per page. Even without accounting for currency exchange rates, this is much less than for most commercial journals, if indeed they offer such options. If you wonder how successful this approach proved, I might as well provide an honest answer: it largely failed. To my knowledge, we never received *any* purchases at the higher rate but when the policy was adjusted and rates were cut in half, we *did* gain revenue - largely from Government science agencies who had funded the research in question. There was less interest in this option from the academic research community because we already met the one-year standard required by funding agencies, or from our many authors who do not enjoy financial support for research and writing. The response in the last two years is encouraging but it does not yet provide us with a route towards what we really need, i.e. a system that will allow us to make all content fully available, but at the same time survive and fund the hard work that has to go into every issue. How might we make that transition without digging our own financial grave? What advantages would full Open Access bring to *Geoscience Canada* and are they worth this potentially risky step? These are just some of the questions that we would need to consider.

As usual, the core issues relate to money. As an online journal, *Geoscience Canada* does not confront the high costs associated with hardcopy print runs. We are easily able to publish longer papers, and we can use colour imagery as widely as we or the authors choose. There is a general perception that online publishing costs next-to-nothing, but this view is wildly incorrect. The overall cost of producing the journal in 2020 was some $25,000 and was down from previous years because Issues 1 and 2 were combined and our page count reduced. Like many smaller journals, our operations depend on efforts from largely unpaid volunteers, but those alone could not possibly sustain us. From submission to final appearance, there is a constant back-and-forth dialogue with authors, and also with reviewers of the paper; some papers go through review a sec-

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ond time, which adds to the time commitment and workload. The acceptance of a paper is just the start of another process, involving copy-editing and pre-layout. Illustrations often need additional work to make them legible or adjustment for page layout, and not all of this is done by the authors; a lot of it ends up on my desk, in addition to the role of Editor. The final steps produce the polished document with its integrated figures and tables, and then assemble the complete issue. The complexity of layout varies, but it is rare that the first edition is the final edition, and even rarer that last-minute corrections and fixes are not needed somewhere. The papers that eventually emerge by then have become familiar characters in our daily lives, and I mean that quite literally. Some of that effort comes from volunteer power, but this could never do all of it. The work of our Managing Editor, Cindy Murphy, and external services such as document layout and French translation are important components of our annual costs, and they are essential.

Clearly, the costs of production must at least be balanced by revenues. On paper, *Geoscience Canada* makes a small financial contribution to GAC, with annual revenues of some $40,000 in 2020. In the past, we have received some additional support via the Canadian Geoscience Foundation, and from other sources, which were provided to help us become self-sufficient. Income from Open Access charges is a small component of our overall revenue, and subscription income contributes most to this equilibrium. We still benefit from this, as the recent Open Access interlude was a temporary measure in response to the global impacts of the pandemic. This issue is at the core of any movement towards full open access – how do we replace that revenue on a long-term basis if it were to be discontinued?

Many Open Access journals have adopted a model that is essentially "author-pay" to cover the costs associated with publication. The authors of accepted papers - or agencies that support their research - pay an article processing fee, structured to reflect the length and/or complexity of the article, and eventual publication of the article is contingent on payment of the fee. It clearly works - at least on a multi-year basis - but there are many questions about such a model. The most obvious are editorial objectivity and the maintenance of standards for articles. If the revenue is directly tied to the number of paid contributions, it is only natural that some will question the quality of all the science or the integrity of peer review. The unsolicited emails that I frequently receive seeking submissions for such journals attest to a mass marketing effort on the part of some of them. Such a system would also favour those with greater research funding or personal resources, and disadvantages students, retired professionals, or other independent contributors. In a wider perspective, it also disadvantages many scientists from countries outside the wealthy, developed world. In many lower-income countries, funding for research is very difficult to obtain, and some of these fees would represent a major portion of the annual income for academic staff. Realistically, this author-pay model is not one that *Geoscience Canada* could seriously consider. We may not publish large numbers of papers, but we strive for high-quality, readable articles, and are proud of what we publish. We also publish many solicited or invited articles and these are often written by individuals who may not have financial support. We cannot solicit papers with one hand and then later issue invoices with the other.

A second option is for *Geoscience Canada* to seek funding sources that can ultimately remove our dependence on subscription revenue. But what might such sources be? There are examples of larger organizations that receive voluntary financial contributions from those that they serve. Wikipedia and Mozilla are great examples in the world of online technology - like many, I make extensive use of both, and have been willing to contribute a little at times. In this case, we would be looking more for a reader-pay concept that is not a formal subscription. Other potential contributors for an independent Canadian geoscience journal like us could include academic and government institutions (for example Geological Surveys) or private enterprise involved in the technical side of resource exploration and development. The payment of Open Access options over the last few years may in part have been recognition that our efforts do in the end save costs involved in internal publication of science by such agencies. It is not likely that single large donors could be found, and this might not even be desirable, but smaller contributions distributed widely might go some way to bridging the gap. I am not aware of any journals that raise money independently through methods such as *gofundme.com*, but neither am I aware of anything that would prevent us from trying such an approach. I have long pointed out that the cost of an individual subscription to *Geoscience Canada* is an order of magnitude less than the annual cost of one cup of coffee per work day from your preferred franchise. We would be more than happy to see some of those personal caffeine funds redirected to dissemination of geoscience research, I can assure you. There is only one way to find out if such a strategy might actually work and from what I understand of how such crowd-sourcing processes work, this is in the "next to nothing to lose" category.

A more conventional approach might be to look again at the current Open Access structure and present it in a different light. Many journals have not ventured along the road towards Open Access, but they continue to request page charges in order to support their operations. However, such charges are voluntary and are not required in order for a paper to be published, so this is not strictly an author-pay approach. The page charges requested by many journals are considerably higher than those in our current Open Access fee system, and in many cases bring fewer tangible benefits to the authors. In some cases, they do nothing to actually breach the subscription wall for readers, or they may impose restrictions on distribution and website posting. During my time working professionally for a Government Agency, few objections were ever raised about the payment of such page charges. Is it possible that we could reframe our current Open-Access surcharges in a manner akin to those of page charges, perhaps at a reduced rate? This would not have to be a stand-alone strategy, for it could be combined with other efforts to seek funding more widely from external sources. It is also something that we could try on an experimental basis over the next year or two, without any need to actually change existing policies. Any decision to alter or remove subscriptions would need to be considered very carefully because it is not readily reversible, but at least we would then have some basis on which to contemplate it.

Are there real advantages to becoming an open-access journal? What should we expect if we are ultimately able to make such a transition? Above all, do we really want to take such a step? The first and most obvious advantage is wider circulation and readership, which benefits authors and GAC as our parent organization. As editor, one of my main tasks is to solicit papers and contributions, but I freely admit that it is difficult to find the time to do as much of this as is really required. When I do so, I am commonly asked about the 'visibility' of *Geoscience Canada* and how widely a paper that we publish will actually be read and (most importantly) cited. This is understandable, especially for younger scientists who need to build and develop careers. Being able to say 'we are open to all' is a powerful statement to make in this context. The more readers who become aware of the high-quality articles that we strive to produce, the greater the chance of increasing unsolicited submissions to the journal, which will help to build our profile higher, and raise that all-important "impact factor". If there is one thing we would all love to see, it would be more articles in every single issue. But we must remember that the costs involved in producing the journal would grow with its article and page count, and there would be increased pressure on those who presently contribute their time and effort without payment. We need to think of ways to link an increased profile with potential for increased revenue, but such considerations are issues we would love to confront – If they emerge, it is a sign of accomplishment. In summary, any move towards full Open Access is a delicate balancing act, and one that needs to be approached very carefully. It is also an issue on which we would clearly benefit in receiving opinions from those who ultimately make the journal function - our authors and our readers. So, we would like to hear from you. And, of course, we would be delighted to receive manuscripts!

In closing, I wish to sincerely thank those who assist with the effort that goes into Geoscience Canada every year. In particular, I thank Cindy Murphy (Managing Editor), Bev Strickland (layout and design) Evelise Bourlon (French Translation), Peter Russell (graphic icons), Karen Dawe (GAC HQ Liaison) and also tireless volunteer copy editors Robert Raeside, Lawson Dickson, Stephen Amor and Janice Allen. We are always in need of volunteer support and are currently seeking section editors interested in continuing or developing thematic series papers. If you have ideas or interests in specific areas and have good persuasion skills to try out on your professional colleagues, we would be very interested to hear more from you.

Deanne van Rooyen is thanked for thoughts and suggestions that improved the hastily-written text of this contribution.

REFERENCE

Kerr, A., 2016, Open Access – Panacea or Pandora's Box?: Geoscience Canada, v. 43, p. 93–95, https://doi.org/10.12789/geocanj.2016.43.092.

GEOLOGICAL ASSOCIATION OF CANADA
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Please join the Geological Association of Canada in a virtual Celebration of Canadian Geoscience! This event will take place over several days in May 10–22, 2021, and will showcase present and past medallists, our Sections, Divisions, and partner organizations. We will celebrate the Canadian Geoscience community at a time when we cannot gather together in our traditional events. All members are invited to attend as many of the talks as they wish, hear about new publications and upcoming conferences, and participate in the GAC Annual Business Meeting.

A detailed schedule will be announced in early April on our website and by email for members. All events will be scheduled between 2:30 to 4:30 pm Eastern time and will be approximately an hour long, hosted on zoom. As an example, join us for the presentation of this year's National medallists (Logan, Ambrose, Hutchison, and Neale medals) on May 14th, the Logan medallist talk on May 17th and the GAC Annual Meeting on May 19th. Other events will include talks and medallists from Sections and Divisions, and events related to publications and something for students.

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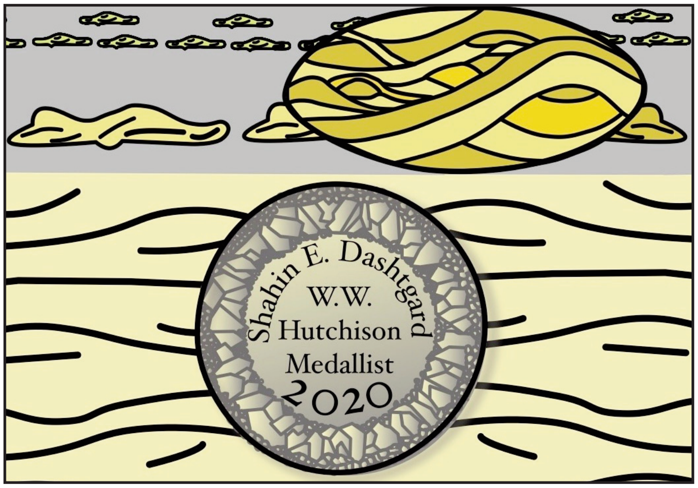

Hutchison Medallist 1. Wave-Dominated to Tide-Dominated Coastal Systems: A Unifying Model for Tidal Shorefaces and Refinement of the Coastal-Environments Classification Scheme

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SUMMARY
Coastal depositional systems are normally classified based on the relative input of wave, tide, and river processes. While wave- through to river-dominated environments are well characterized, environments along the wave-to-tide continuum are relatively poorly understood and this limits the reliability and utility of coastal classification schemes. Two tidal shoreface models, open-coast tidal flats (OCTF) and tidally modulated shorefaces (TMS), have been introduced for mixed wave-tide coastal settings. Following nearly two decades of research on tidal shorefaces, a number of significant insights have been derived, and these data are used here to develop a unified model for such systems. First, OCTFs are components of larger depositional environments, and in multiple published examples, OCTFs overlie offshore to lower shoreface successions that are similar to TMS. Consequently, we combine OCTFs and TMSs into a single tidal shoreface model where TMS (as originally described) and TMS-OCTF successions are considered as variants along the wave-tide continuum. Second, tidal shoreface successions are preferentially preserved in low- to moderate- wave energy environments and in progradational to aggradational systems. It is probably difficult to distinguish tidal shorefaces from their storm-dominated counterparts. Third, tidal shorefaces, including both TMSs and OCTFs, should exhibit tidally modulated storm deposits, reflecting variation in storm-wave energy at the sea floor resulting from the rising and falling tide. They may also exhibit interbedding of tidally generated structures (e.g. double mud drapes or bidirectional current ripples), deposited under fairweather conditions, and storm deposits (e.g. hummocky cross-stratification) through the lower shoreface and possibly into the upper shoreface.

The development of the tidal shoreface model sheds light on the limitations of the presently accepted wave-tide-river classification scheme of coastal environments and a revised scheme is presented. In particular, tidal flats are components of larger depositional systems and can be identified in the rock record only in settings where intertidal and supratidal deposits are preserved; consequently, they should not represent the tide-dominated end-member of coastal systems. Instead, we suggest that tide-dominated embayments should occupy this apex. Tide-dominated embayments exhibit limited wave and river influence and include a wide range of geomorphological features typically associated with tidal processes, including tidal channels, bars and flats.

RÉSUMÉ
Les systèmes de dépôts côtiers sont normalement classés en fonction de l'apport relatif des processus liés à la houle, aux marées et aux rivières. Si les environnements dominés par la houle et les rivières sont bien caractérisés, les environnements le long du continuum houle-marée sont relativement mal compris, ce qui limite la fiabilité et l'utilité des systèmes de classifi-

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cation des côtes. Deux modèles d'avant-plages tidales, les estrans ouverts (*open-coast tidal flats*; OCTF) et les avant-plages modulées par la marée (*tidally modulated shoreface*; TMS), ont été introduits pour les milieux côtiers mixtes, houle-marée. Suite à près de deux décennies de recherche sur les avant-plages tidales, un certain nombre d'informations importantes ont été obtenues et ces données sont utilisées ici pour développer un modèle unifié pour ces systèmes. Tout d'abord, les OCTF sont les composants de systèmes de dépôt plus vastes et, dans de nombreux exemples publiés, les OCTF recouvrent des successions sédimentaires allant du large à l'avant-plage inférieure, similaires à celle des TMS. Par conséquent, nous combinons les OCTF et les TMS en un seul modèle d'avant-plage tidale où les TMS (tel que décrit à l'origine) et les successions TMS-OCTF sont considérés comme des variantes le long du continuum houle-marée. Deuxièmement, les successions d'avant-plages tidales sont préférentiellement préservées dans des environnements ayant une houle faible à modérée et dans des systèmes progradant et aggradant. Il est probablement difficile de distinguer les avant-plages tidales de leurs homologues dominés par les tempêtes. Troisièmement, les avant-plages tidales, incluant à la fois les TMS et les OCTF devraient présenter des dépôts de tempête modulés par la marée, reflétant ainsi la variation de l'énergie des vagues de tempête sur le fond marin liée à la marée montante et descendante. Les avant-plages tidales peuvent également présenter une interstratification de structures générées par la marée (par exemple, des doubles drapages argileux ou des rides de courants bidirectionnelles) déposées pendant des conditions de beau temps, et des dépôts de tempête (par exemple, des stratifications en mamelons) au niveau de l'avant-plage inférieure et éventuellement de l'avant-plage supérieure.

Le développement du modèle d'avant-plage tidale met en lumière les limites de la classification tripartite (houle-marée-rivière) des environnements côtiers actuellement acceptée et une classification révisée est présentée. En particulier, les OCTF et les estrans sont des composantes de systèmes de dépôt plus importants et ne peuvent être identifiés que dans le registre sédimentaire dans les milieux où les dépôts intertidaux et supratidaux sont préservés; par conséquent, ils ne devraient pas représenter le membre extrême des systèmes côtiers dominé par la marée. Nous suggérons plutôt que les baies dominées par la marée occupent cette place. Les baies dominées par les marées présentent une influence limitée des vagues et des rivières et comprennent un large éventail de caractéristiques géomorphologiques généralement associées aux processus de marée, notamment des chenaux, des barres et des platiers tidaux.

1. INTRODUCTION

Coastal systems and their associated deposits are extremely diverse, yet sedimentological models promote the notion that coastal deposits can be identified as wave-, tide-, or river-dominated (or any combination of the three) on the basis of their sedimentary features. The tripartite process-based subdivision of coastal systems was first introduced by Galloway (1975) for deltas and later expanded to include all coastal to shallow marine systems (Fig. 1A; Boyd et al. 1992; Ainsworth et al. 2011). These classification schemes proved useful for distinguishing and classifying large scale variations in the geomorphology of coastal environments as a function of relative energy input, but significant issues remained within classification schemes, especially along the wave- to tide- continuum. Wave- and tide-dominated settings are distinctive in terms of their physical processes and geomorphology, and this results in the two end-member environments, beach-shorefaces (wave-dominated) and tidal flats (tide-dominated), exhibiting distinctive facies and grain-size distributions (e.g. Weimer et al. 1982; Dalrymple 2010; Plint 2010; Dashtgard et al. 2012; Pemberton et al. 2012). A range of mixed wave-tide settings (i.e. tidal shorefaces) occur between the wave-dominated and tide-dominated end members, and sedimentological signatures of both tide- and wave-processes are manifested in these mixed influence systems (Fig. 1B; Yang et al. 2005; Dashtgard et al. 2009).

Herein, we consider depositional models that have been proposed for coastal to shallow marine systems along the wave-tide continuum. We compare and contrast two closely related tidal-shoreface variants, open-coast tidal flats (OCTF) and tidally modulated shorefaces (TMS), both of which have been proposed for mixed wave-tide coastlines. Over the past 10 years, deposits interpreted as either OCTF or TMS have been described from the sedimentary record and this literature is summarized and compared to the original models (Table 1; Basilici et al. 2012; Smosna and Bruner 2016; Wei et al. 2016; Vaucher et al. 2017, 2020; Bádenas et al. 2018; MacNaughton et al. 2019; Angus et al. 2020; Kalifi et al. 2020; Sleveland et al. 2020). We then propose a unified model for tidal shorefaces taking into account the multiple variants described so far. Second, we propose a revision to the classification scheme for coastal environments that incorporates our findings and other insights on wave-, tide-, and mixed wave-tide coastal systems. The revised classification scheme better encapsulates the range of coastal settings that occur along the wave-tide continuum and how they relate to other environments with changes in relative energy input from waves, tides and rivers.

1.1 End Member Systems – Beaches and Shorefaces

One of the earliest beach-shoreface models was developed for gravel beaches and showed the distribution of clasts across the beach as a function on grain shape and size (Bluck 1967). Sand-dominated beach-shoreface systems received significantly more attention, and it has been demonstrated repeatedly that the distribution of sedimentary structures in these wave-dominated settings is controlled by a predictable distribution of oscillatory processes and wave-induced currents in increasingly shallow water up through the shoreface and onto the beach face (Fig. 2; e.g. Psuty 1967; Galvin 1968; Clifton 1969; Clifton et al. 1971; Davies et al. 1971; Kumar and Sanders 1976). Storm influence on shorefaces was also noted very early in the study of beach-shoreface systems (Bluck 1967; Hayes 1967; Clifton et al. 1971) indicating that storm influence is a ubiquitous contribution to shoreface development. Based on the relative impact of storm-wave versus fairweather wave processes on deposition, three end-member shoreface successions were

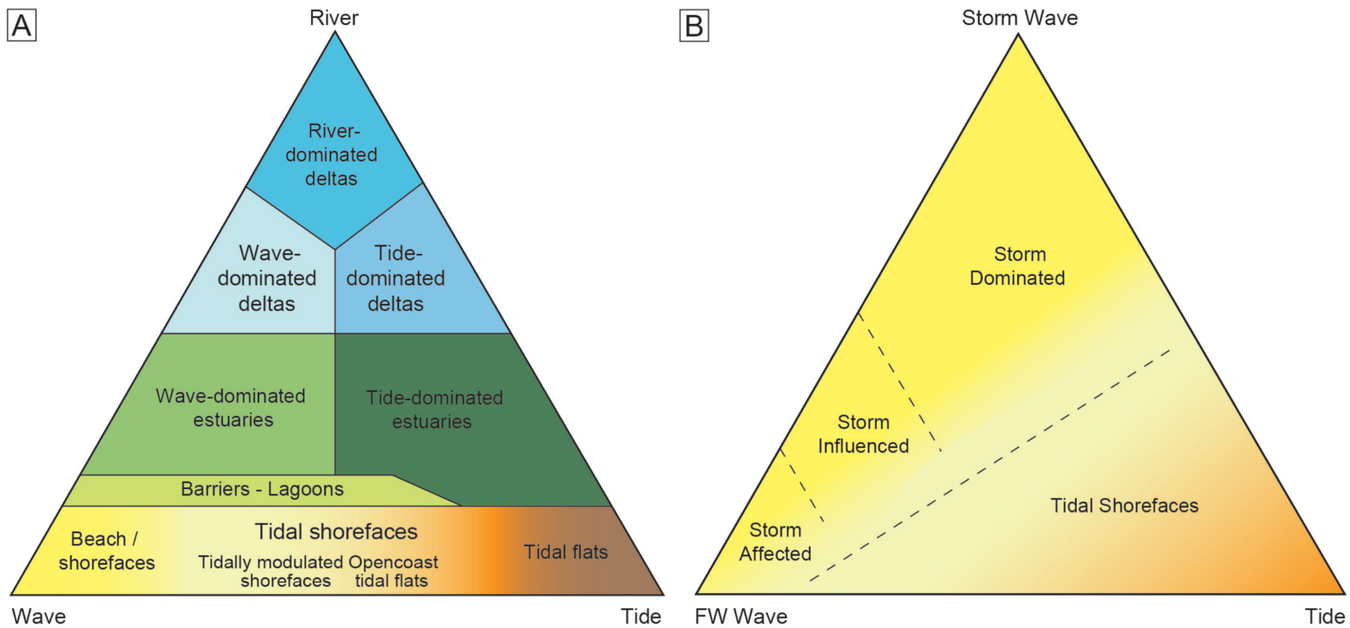

Figure 1. A) Ternary diagram showing the relative distribution of coastal to shallow-marine systems relative to the degree of wave-, tide-, and river input/energy (modified after Boyd et al. 1992; Yang et al. 2005). B) Ternary diagram for mixed wave-tide systems wherein waves are divided between fairweather (FW) and storm waves. Note the dominance of storm-wave processes in determining the character of the preserved deposit (modified after Dashtgard et al. 2012).

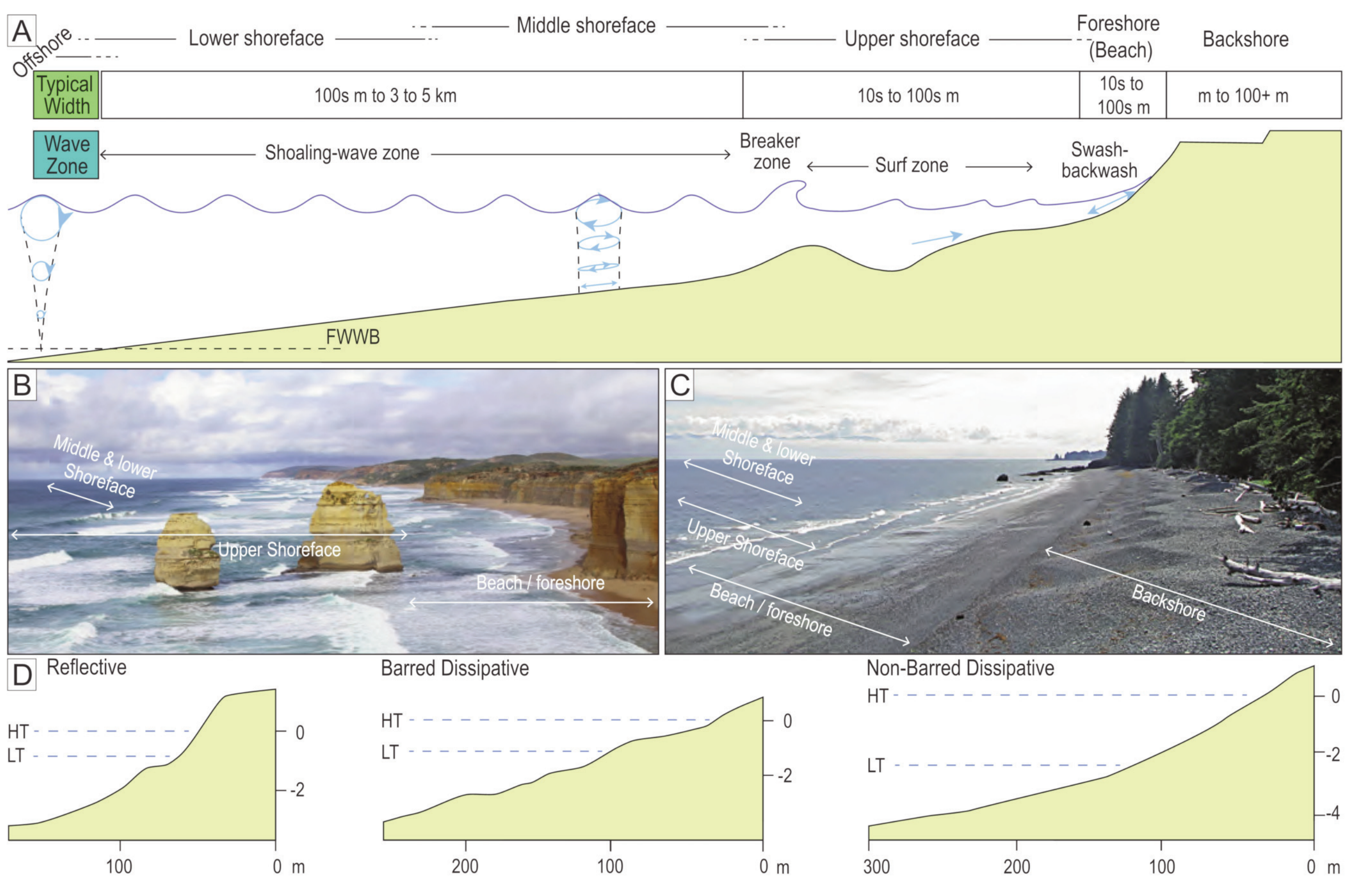

Figure 2. Conceptual models for wave-dominated beach-shorefaces. A) An idealized profile of a beach-shoreface system showing the distribution of wave processes and shoreface subenvironments from offshore to the backshore, and the general range for the shore-normal width of those zones. B) Photo of the shoreface and beach at the Twelve Apostles (Victoria, Australia) with wave zones indicated. C) Photo of Sandcut Beach (south coast of Vancouver Island, Canada) with wave zones indicated. D) Three morphological profiles proposed by Masselink and Short (1993) for shorefaces with limited tide-influence relative to wave influence. Acronyms: low tide (LT), high tide (HT), fairweather wave base (FWWB).

Table 1 – Summary of geological units interpreted as tidal shorefaces. General context and recognition criteria used by the original authors are listed.

Interpretation	Geological Unit	Age	Location	Context of Deposition	Recognition Criteria	References
Wave-dominated open-coast tidal flat	Lagarto and Palmares formations	Cambrian–Ordovician	Brazil	Foreland basin	(i) Wave processes are indicated by wave ripples and HCS. (ii) Tidal processes are interpreted from cross-stratification (tidal bundles); climbing ripples that alternate repeatedly with mud drape lenses; stacked ripples; wavy lamination and wave ripples in anisotropic HCS beds; flaser, wavy and lenticular bedding; bidirectional ripples alternating with mudstone beds; and, herringbone cross-bedding.	Basilici et al. 2012
Tide-dominated beach	Cabos Formation	Middle Cambrian – Early Ordovician	Spain	Post-rift	(i) Interpreted beach deposits comprise small 2-D dunes composed of fine-grained sand (ridge-and-runnel system). Dunes form via wave processes and are interpreted to have both accreted upward and migrated landward during rising tide, and then subsequently reworked by ebb currents and surface runoff during periods of emergence. (ii) Tidal reworking was interpreted from herringbone cross-bedding, discontinuity surfaces, and superimposed bed forms. Associated structures formed near low tide include interference ripples, double-crested ripples, flat-topped ripples, current ripples with muddy troughs, and mudstone partings. (iii) Rhythmically interbedded mud and sand with sparse bioturbation is interpreted to record accumulation in the subtidal nearshore. Tides and waves formed uni- and bidirectional current ripples, oscillatory wave ripples, combined-flow ripples, erosional sand mounds, rhythmic bedding, and heterolithic bedding.	Smosna and Bruner 2016
Storm-dominated, tide-influenced delta front	Rannoch Formation	Middle Jurassic Aalenian	Northern North Sea	Pre-rift	Two facies are frequently interbedded and form "storm-tide couplets". The two facies include (i) thin mud drapes and double mud drapes that comprise up to 15% of the entire thickness and are interpreted as tidal deposits formed during fairweather conditions. These beds are preserved between (ii) unburrowed, well-sorted sandy beds reflecting storm events that lack a capping bioturbated mudstone interval.	Wei et al. 2016
Tidally modulated ridge-and-runnel upper shoreface	Fezouata Shale and Zini Formation	Early Ordovician Tremadocian - Floian	Morocco	Post-rift, passive margin	(i) Symmetrical and slightly asymmetrical oscillatory related sedimentary structures of various wavelengths interbedded with dominantly low-angle or plane-parallel stratification suggest tide modulation of wave processes in the upper shoreface-foreshore. (ii) Combined-flow ripples that show evidence of both aggradation and migration alternate with purely aggrading wave ripples/HCS. This is interpreted as recording tide-modulated storm deposits. (iii) Ubiquitous stacking of oscillatory-induced structures of shorter-to-longer wavelengths reflects continuous tide modulation of the wave action on the seafloor.	Vaucher et al. 2017, 2018a

*Acronyms: hummocky cross-stratification (HCS); swaley cross-stratification (SCS)

Table 1 – *(Cont.)* Summary of geological units interpreted as tidal shorefaces. General context and recognition criteria used by the original authors are listed.

Interpretation	Geological Unit	Age	Location	Context of Deposition	Recognition Criteria	References
Mixed (clastic and carbonate), wave (storm)-dominated open coast tidal flat	Aguilar del Alfambra Formation	Late Jurassic Tithonian - Berriasian	Spain	Syn-rift	(i) Thinning and finning upward, poorly bioturbated heterolithic interval displaying HCS, and current, wave and combined-flow ripples reflect together open-coast tidal flat deposits. (ii) Several beds showing a vertical evolution form current to combined-flow ripples to HCS are observed within (i) and possibly point a tide-modulation of storm waves across the intertidal zone.	Bádenas et al. 2018
Wave-dominated tidal-flat	Elk Mound Group	Late Cambrian Miaolingian - Furongian	U.S.A.	Epeiric sea	Sedimentary structures reflecting storm wave deposition (parallel-lamination, cross-bedding, but no hummocky cross-stratification) and fairweather deposition (oscillation ripples) occur concomitantly. Indicators of fluctuations in water depth (washouts, flat-topped ripples and stranded medusoids) and subaerial exposure (desiccation cracks, raindrop imprints and adhesion marks) are present.	MacNaughton et al. 2019
Tidally modulated, barred shoreface	Weald Basin	Late Jurassic Kimmeridgian - Tithonian	England / France	Extensional basin	(i) Pervasive interstratification of wave-formed sedimentary structures that are interpreted as forming at different depths occur throughout and reflect repeated variations in water depth induced by tides. This is interpreted as tide modulation of wave processes (ii) Upper shoreface and foreshore deposits are abnormally thick. (iii) Trace fossils typically attributed to either the *Skolithos* or *Cruziana* Ichnofacies co-occur within lower shoreface deposits.	Angus et al. 2020
Open-coast intertidal	Upper Marine Molasse	Miocene Upper Aquitanian - Langhian	France	Foreland basin	(i) Plane-parallel lamination vertical evolving into SCS/HCS within the same sandstone bed suggest tide modulation of wave processes. (ii) Combined-flow ripples frequently display oblique foresets with downcutting in their bottomsets pointing out an increase of the tidal flow while the structures developed (see text for explanation).	Kalifi et al. 2020
Storm-Influenced subtidal flat	Upper Mulichinco Formation	Early Cretaceous Valanginian	Argentina	Post-rift / back-arc	Interbedding of (i) weakly bioturbated, well-sorted sandstones displaying HCS, SCS, low-angle and trough cross-stratification with isolated *Thalassinoides*, *Gyrochorte*, and *Ophiomorpha*. and either (ii) trough cross-stratified muddy sandstone with reactivation surfaces, herringbone, current and combined-flow ripples, bundled symmetric ripples, climbing ripples, lenticular, wavy, and flaser bedding, or (iii) extensively bioturbated sandstone beds reflects storm events (i) in subtidal environments (ii and iii).	Sleveland et al. 2020
Wave-dominated tide-modulated foreshore	Angosto del Moreno Formation	Late Cambrian Furongian	Argentina	Extensional basin	Interbedding of (i) low-angle planar-laminated, unbioturbated fine- to medium-grained sandstone (i.e. swash cross-stratification) and (ii) sandstone having symmetrical and asymmetrical ripples and rare trace fossils is interpreted as reflecting deposition in a wave-dominated, tidally modulated foreshore, where planar bedding (i) is formed by swash processes (at low tide) and alternates with combined-flow to oscillatory processes stemming from wave and tide processes (at high tide; (ii)).	Vaucher et al. 2020

*Acronyms: hummocky cross-stratification (HCS); swaley cross-stratification (SCS)

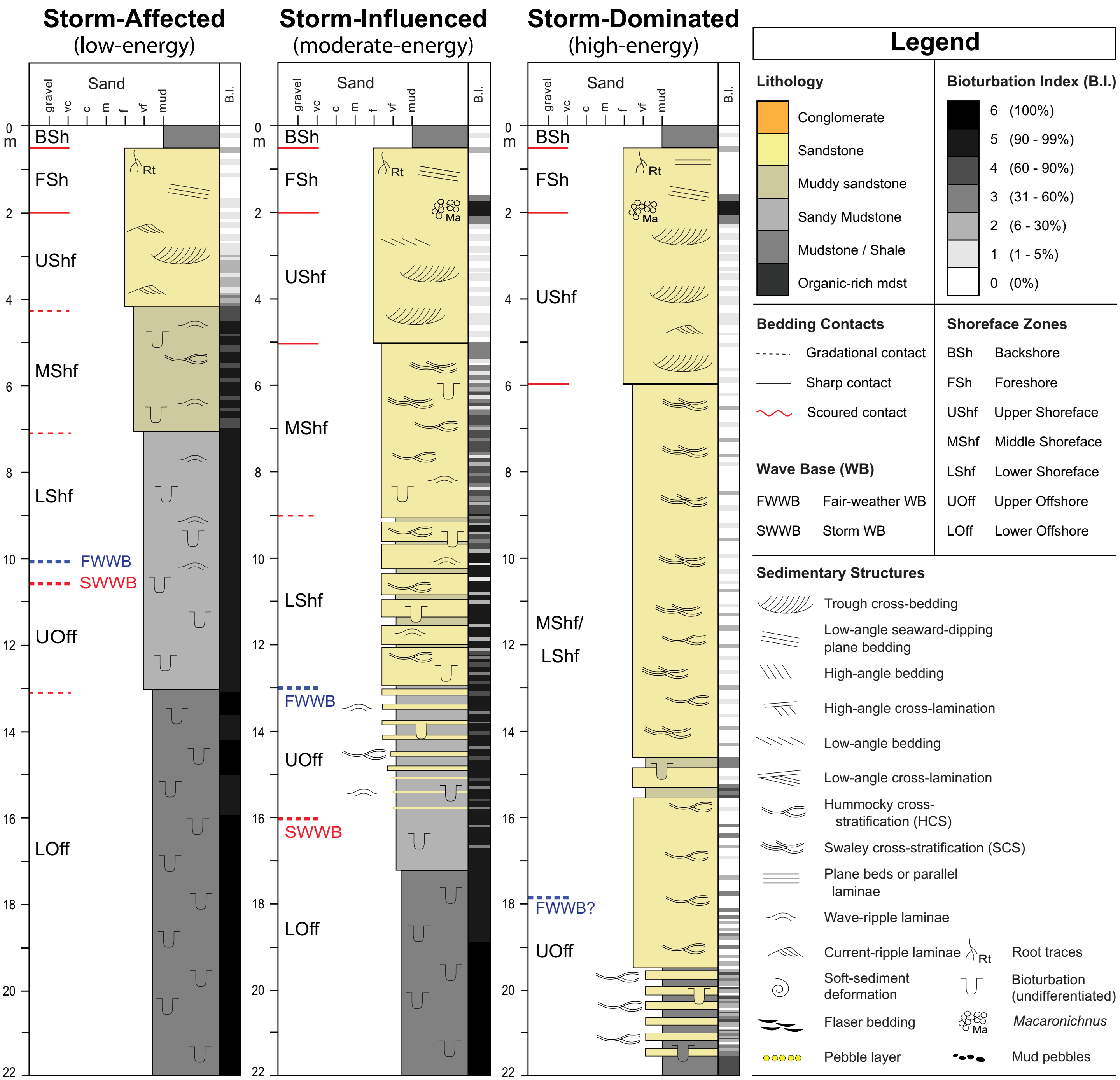

Figure 3. Conceptual models for three archetypes of wave-dominated shorefaces that show increasing storm influence from storm-affected to storm-dominated. The revised names of each shoreface archetype proposed herein is shown in brackets below the names for each succession. Note the increase in thickness of the upper shoreface and foreshore, and the amalgamation of HCS/SCS with increasing storm influence in high-energy settings (modified after Dashtgard et al. 2012).

proposed, including (in order of increasing storm-wave influence): storm-affected, storm-influenced, and storm-dominated (Figs. 1B and 3; Clifton 2006; Dashtgard et al. 2012). This nomenclature is discussed further in Section 5. In all progradational, wave-dominated shoreface variants, grain size coarsens upward from offshore to the surf zone (Fig. 3), and this reflects the increase in effective wave energy in increasingly shallow water up the shoreface (Fig. 2).

1.2 End Member Systems – Tidal Flats

At the other end of the spectrum of wave-tide systems are tidal flats (Fig. 1A), which have been described extensively in the literature. Models for tidal flats are largely derived from modern settings due to the ease of accessing these environments during low tide (e.g. Häntzschel 1939; Van Straaten 1961; Kellerhals and Murray 1969; Reineck 1975; Swinbanks and Murray 1981; Weimer et al. 1982; Dalrymple 1992, 2010).

Tidal flats commonly occur in protected settings with very low depositional slopes (Van Straaten and Kuenen 1957; Van Straaten 1961; Reineck 1975; Ainsworth et al. 2015) and/or in restricted waterways and embayments, including estuarine and back-barrier systems (i.e. areas that are sometimes referred to as "inshore" settings; Dashtgard 2011b; Flemming 2012). They develop as a result of low levels of wave action, due either to sheltering or attenuation by frictional retardation of wave-orbital motion and wave-forced currents across the flats, accompanied by tidal-current amplification and tidally induced water-level fluctuations. Deposition is controlled mainly by the settling and scour lags, processes that control the landward movement of fine-grained sediment in a tidal environment (Van Straaten and Kuenen 1958; Dalrymple and Choi 2003; Pritchard and Hogg 2003), and grain size varies as a function of both sediment input and river-, wave-, and tide-influence. Progradational tidal flats typically become finer toward the high-tide shoreline and are manifested in the rock record as fining-upwards successions. This reflects the onshore decrease in depositional energy which results in both an onshore decrease in grain size and a landward increase then decrease in the intensity of bioturbation from the low to high intertidal zone (Fig. 4). In inshore settings, tidal flats typically overlie channelized facies; however, tidal flats also commonly overlie other depositional systems (e.g. shorefaces and delta fronts; Weimer et al. 1982; Dalrymple 2010; Dashtgard 2011a, b). This association of tidal flats with other shallow-marine subenvironments reflects the fact that tidal flats are developed in the shallowest water positions (equivalent to the upper shoreface and beach) of coastal depositional environments.

2. MIXED WAVE-TIDE SYSTEMS

The expression of tidal processes in beach-shoreface systems was largely overlooked in early models with the exception of recognizing the intertidal zone (the beach/foreshore zone; Fig. 2). Tidal influence on the geomorphology of beach-shoreface systems was explored in the 1980s and 1990s (Fig. 5; Short 1984, 1991, 1999; Masselink and Short 1993; Masselink and Hegge 1995), but sedimentological models that incorporated expressions of tidal processes in the preserved character and architecture of shorefaces did not occur until the mid- to late-2000s with competing and, in some cases, complementary models for open-coast tidal flats (OCTF; Yang et al. 2005, 2006, 2008b), tidally modulated shorefaces (TMS; Dashtgard et al. 2009; Dashtgard et al. 2012; Pemberton et al. 2012; Vaucher et al. 2018a), micro-meso tidal shorefaces (Vakarelov et al. 2012), and tide-influenced shorefaces (Frey and Dashtgard 2011; Dashtgard et al. 2012). With the exception of the micro-meso tidal shoreface model (Vakarelov et al. 2012), all models were developed in modern depositional settings.

Herein, "tidal shorefaces" encompass depositional environments along the wave-tide spectrum wherein both wave- and tidal-processes operate and are recognizable in the sedimentary record (Figs. 5–7). The earliest model for one element of tidal shorefaces, the OCTF, was developed from a very fine- to fine-grained sandy tidal flat (the Baeksu tidal flat) along the west coast of Korea (Fig. 5). This system experiences meso- to macro-tidal conditions (mean tidal range: 3.9 m; maximum range: 6.8 m), with small waves during the summer monsoon season, and large waves during the winter and infrequent tropical cyclones during the summer and fall. The stark contrast in wave energy between the summer and winter is manifested in the sediment. Indeed, the flats exhibit all of the characteristics of tidal flats during the summer months, being covered by mud nearly to the low-tide level, but in the winter the sediment in the outer to middle regions of the tidal flat comprises mainly hummocky cross-stratification (HCS) reflecting the dominant storm influence on sedimentation (Yang et al. 2005, 2006, 2008a, b). The Korean tidal flats from which the OCTF model was derived, also preserve mud at the landward end of the flats, at least locally, and in the troughs of landward translating swash bars (Yang et al. 2009). The character of preserved deposits across the Baeksu tidal flat indicates a strong storm-influence, and the evolution of storm-waves landward across the flat is manifested in an increase and then decrease in grain size (Fig. 6C). As well, there is a landward increase in the amount of bioturbation. The prevalence of HCS in the outer and middle flats (Fig. 6C) is similar to sedimentary structures seen in beach-shoreface systems (Fig. 3). However, the increase in bioturbation from the outer to the inner flats, and the decrease in grain size from the middle to the inner flats are characteristics shared with other tidal flats (Fig. 4). As such, OCTF are considered to represent a more tide-dominated expression of mixed wave-tide systems than TMS (Fig. 1A). We note that OCTFs can also be mud-dominated when downdrift of river mouths (Fan 2012; Cummings et al. 2015; Zhang et al. 2018), but we focus here on the sandy variant because of its close association with TMSs.

Despite the fact that the OCTF model was established solely on the basis of modern environments (Yang et al. 2005, 2006, 2008b), its idealized vertical, progradational succession can be reasonably derived from mapped grain-size trends, vibracore descriptions, and high-resolution seismic data (Fig. 6C). As with tidal flats, OCTFs comprise sediment exposed mainly intertidally, and hence the model includes the upper subtidal, intertidal, and supratidal zones only. Progradational expressions of OCTFs coarsen upwards in their subtidal to lower intertidal portion in a fashion similar to the upper part of progradational shorefaces and TMS. The lower and middle intertidal extent of these systems is dominated by storm-wave generated sedimentary structures. In the upper intertidal zone, OCTF exhibit a fining-upward profile reflecting the attenuation of wave energy landward across the inner flat. Subtidally, OCTFs can, theoretically, overlie deposits that are sedimentologically akin to shorefaces, TMS or delta fronts, and the middle to outer part of the flats is considered to be equivalent to the upper shoreface (Fig. 6; Dalrymple 2010). Consequently, an OCTF will probably be manifested in the rock record at the top of a storm-influenced shallow-marine succession, and be expressed as a coarsening-upward succession with interlayered bioturbated mud and sand in an overall fining-upward succession in the upper 1–3 m. It will probably be topped by rooted, muddy tidal marsh deposits if complete preservation occurs (Fig. 6C).

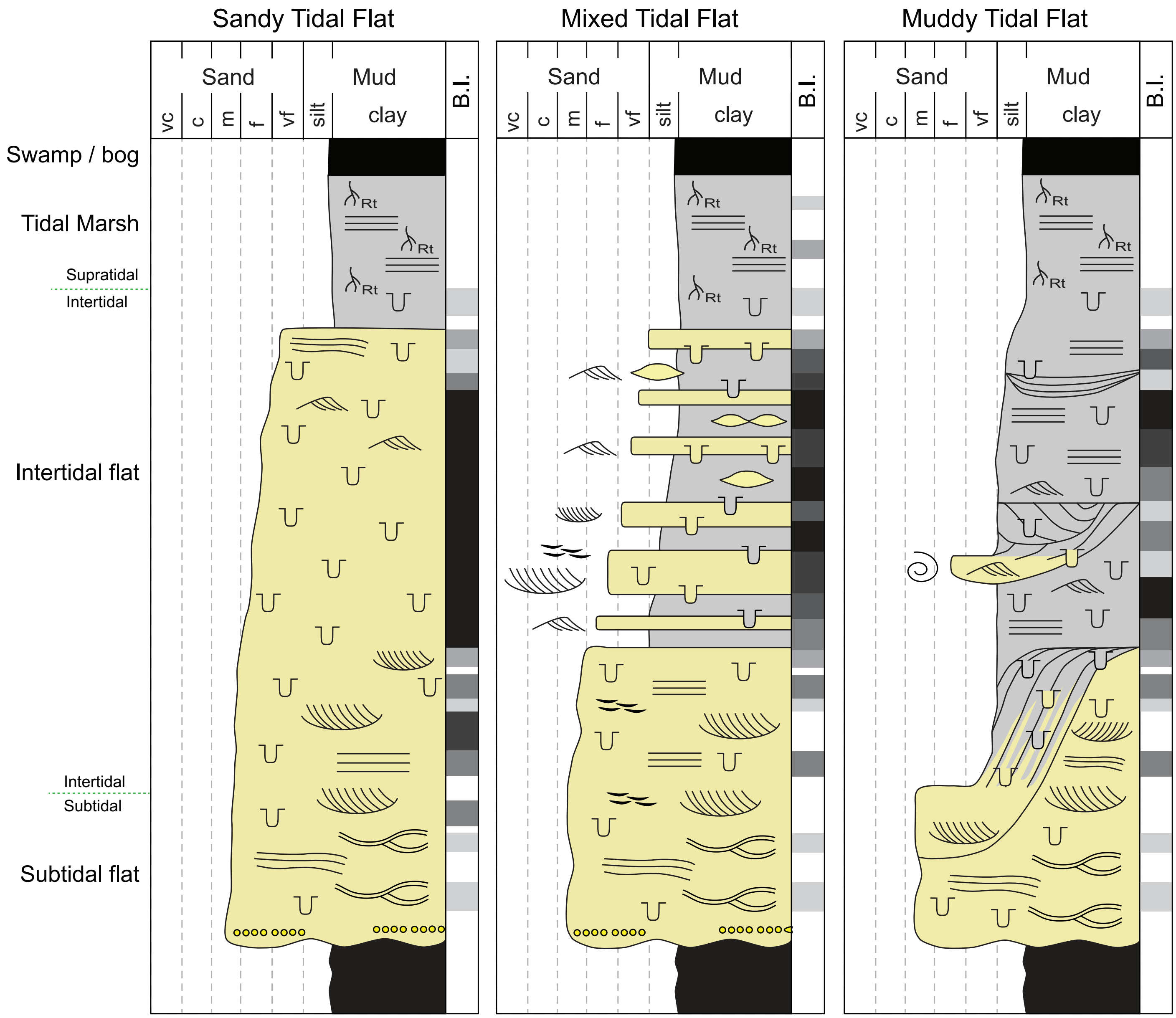

Figure 4. Conceptual models for the vertical expression of preserved, progradational tidal flats based on Boundary Bay (sand-dominated tidal flat) and Mud Bay (mud-dominated tidal flat), British Columbia, Canada. The strip logs also assume the base of the tidal-flat succession is a channel-base scour surface, although it is equally plausible that these deposits overlie and grade up from delta front or other shallow-marine strata (strip logs are adapted from Dalrymple 1992, 2010; Siddiqui et al. 2017). The vertical scale is dependent on the tidal range (in this case ~4 m for the intertidal zone). Refer to the legend in Figure 3 for definitions of acronyms, colours and symbols used in this figure.

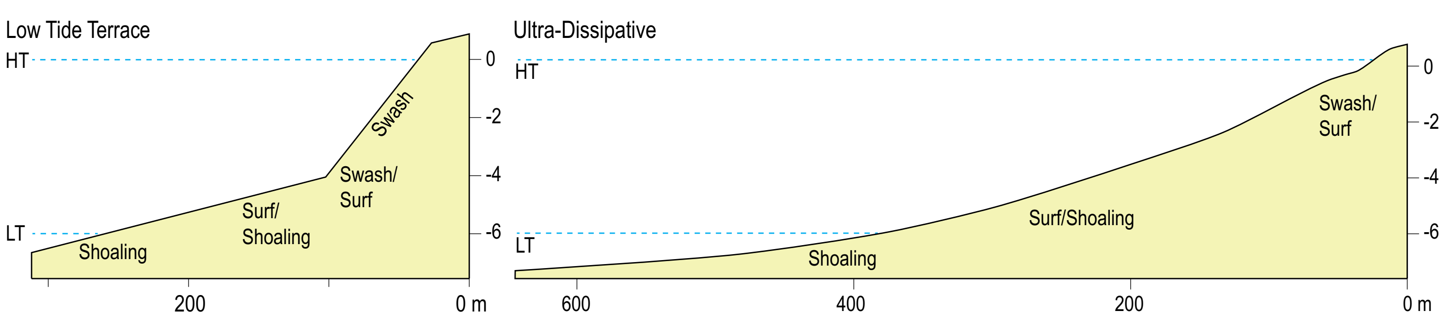

Figure 5. Two morphological profiles proposed by Masselink and Short (1993) for beach-shorefaces with strong tide influence relative to wave influence. Masselink and Short (1993) predict shorelines transition to tidal flats as tide influence increases. Acronyms: low tide (LT), high tide (HT).

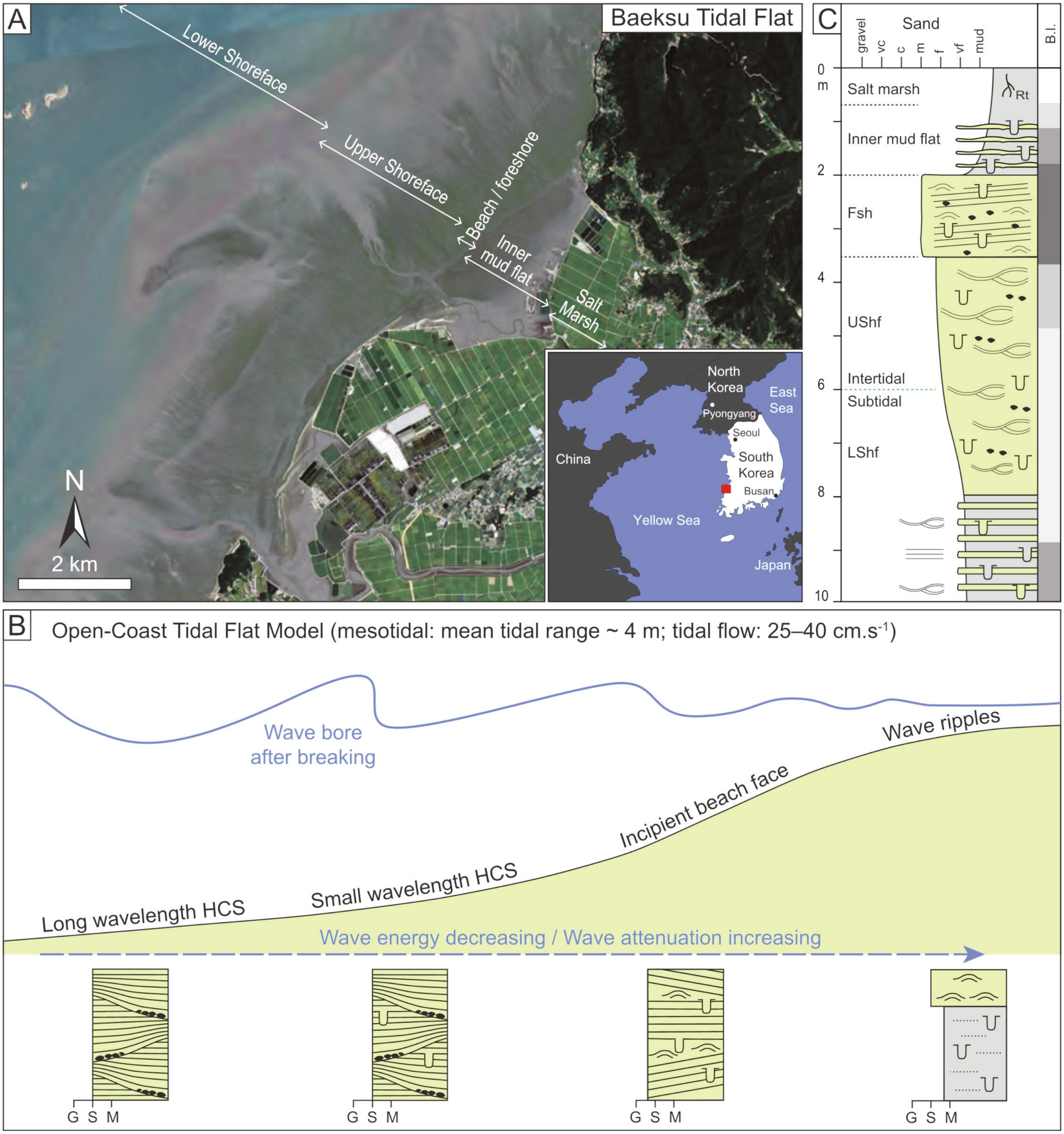

Figure 6. A) Airphoto of Baeksu tidal flat, South Korea, from which the open-coast tidal-flat model was originally derived. The approximate position of shoreface-equivalent (or tidal flat) subenvironments are demarcated by the white lines (Google Earth airphoto). B) Distribution of preserved sedimentary structures across the tidal flat (modified after Yang et al. 2005). C) Hypothetical reconstruction of a preserved vertical profile for an OCTF assuming the system is progradational. Refer to the legend in Figure 3 for definitions of acronyms, colours and symbols used in this figure.

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The TMS model was developed from a beach-shoreface in the Bay of Fundy, Canada using mapped grain-size trends, boxcore and vibracore x-radiographs and descriptions, and shallow-seismic profiles (Waterside Beach, Fig. 7; Dashtgard and Gingras 2007; Dashtgard et al. 2009, 2012), and the model builds on wave-process characterization of geomorphologically similar beach-shoreface systems globally (Figs. 2D and 5; Masselink and Short 1993; Masselink and Hegge 1995). Waterside Beach experiences maximum tidal amplitudes of > 11 m and with a mean tidal range of 9 m. Wave processes dominate the system year-round with wave zones translating across the beach-shoreface with the rising and falling tide. The translation of wave zones is preserved across the beach-shoreface with different parts of the TMS being dominated by different sedimentary structures (i.e. seaward-dipping plane beds, multidirectional trough cross-stratification, HCS, etc.; Fig. 7B), but with interbedding of sedimentary structures reflecting different water depths occurring across the whole shore-normal transect (Fig. 7C). Bioturbation is reduced relative to equivalent deposits in wave-dominated beach-shorefaces, and the degree of bioturbation decreases landward, which is typical of wave-dominated beach-shorefaces. Grain size also increases in the landward direction. The onshore-offshore trends in grain size, distribution of wave-formed sedimentary structures, and degree of bioturbation in TMS is more akin to wave-dominated beach-shorefaces, and hence, TMS are considered to be a more wave-dominated expression of the spectrum of mixed wave-tide systems (Fig. 1A).

2.1 Similarities and Differences Between OCTFs and TMS

Both OCTFs and TMS as currently defined are mixed wave–tide systems where both tides and waves influence the preserved sediment character. Here we highlight the differences and similarities between the two models (Figs. 6 and 7).

1) Grain size

The small tidal prism and strong attenuation of wave energy across the gently sloping surface of OCTFs produces low-energy tidal currents and waves, which result in mud deposition across the flats, particularly during non-storm periods and in more proximal (i.e. uppermost) positions close to the high-tide level (see Fig. 8 in Yang et al. 2005). Consequently, grain size increases and then decreases in a landward direction (Fig. 6C). In contrast, TMS are persistently wave-dominated throughout their entire vertical extent, and wave processes (e.g. shoaling, breaking, swash-backwash) are partially segregated (shore-normally) under fairweather conditions (Masselink and Hegge 1995; Dashtgard et al. 2009). The dominance of wave processes across TMS is manifested in a continuous landward increase in grain size from the offshore to the surf zone, and onto the beach if the system contains gravel-sized material (Fig. 7).

2) Bedforms / sedimentary structures

The systems used to develop both the OCTF and TMS models experience numerous storms, and storm-influence is evident in preserved deposits in the form of HCS and the preservation of unbioturbated sediment. In TMS, tides are expressed in the interbedding of wave-formed sedimentary structures that result from the across-shore translation of wave zones (shoaling, surf, swash-backwash), and the accompanying tidal modulation of wave energy at any given location, with the rising and falling tide (Dashtgard et al. 2009; Vaucher et al. 2018a). For example, during high tide, swash-backwash will occur at the landward side of the beach while the lower intertidal zone will be subjected to shoaling waves and the offshore will be dominated by offshore currents (probably tidal currents). At low tide, most of the TMS is subaerially exposed: the lower intertidal zone experiences swash-backwash, and the offshore experiences shoaling waves. The preserved character of the TMS beach-shoreface is strongly influenced by storm-wave activity and the translation of wave zones during storms. In consequence, storm-derived bedforms (e.g. plane bed, hummocks and swales, 3D wave ripples, dunes) and their preserved sedimentary structures (e.g. planar lamination, HCS/SCS, trough cross stratification) in TMS are distributed across the entire offshore-to-onshore profile as a result of the rising and falling tide.

Wave-zone translation also occurs across OCTFs (as with all intertidal zones), although the distribution of sedimentary structures differs. First, the low depositional slope and attenuation of wave energy across the flats results in a landward decrease in the scale of HCS and an increase in the preservation potential of parallel-laminated and bioturbated mud in the inner to middle flats (Yang et al. 2005, 2006, 2008a,b). Second, OCTFs like Baeksu do not exhibit trough cross-stratification, and this reflects 1) the dominant sand grain size (very fine- to fine-grained sand), 2) the dominance of shoaling wave-processes during major storms and at high tide, and 3) a general absence of breaking waves and strong wave-forced currents across the flats. Third, due to the fact that wave size above shallowly submerged tidal flats is mainly a function of water depth, wave energy at any point on the tidal flat will change rapidly over each tidal cycle (namely tidal modulation of wave energy). Such depositional processes are attributed with forming two unique sedimentary deposits: wave bundles (Yang et al. 2008a) and tidally modulated storm deposits (Vaucher et al. 2017; Yang and Chang 2018; Sleveland et al. 2020) as a result of the interaction of waves and reversing tidal currents over a single tidal cycle. Tidally modulated storm deposits (Vaucher et al. 2017) and wave bundles also form in TMS. Note that descriptions of OCTFs are restricted to the intertidal zone, which is mainly equivalent to the upper shoreface and foreshore/beach. The offshore- to lower-shoreface expression of OCTFs remains largely undocumented.

3) Ichnology

In OCTFs, tidal currents operate throughout the year and supply food and oxygen to support large communities of infauna resulting in significant bioturbation in the flats (e.g. Yang et al. 2009). Yet wave reworking of the flats during storms results in high substrate mobility such that preservation of traces is low relative to most classic and sheltered tidal flats (e.g. Reineck

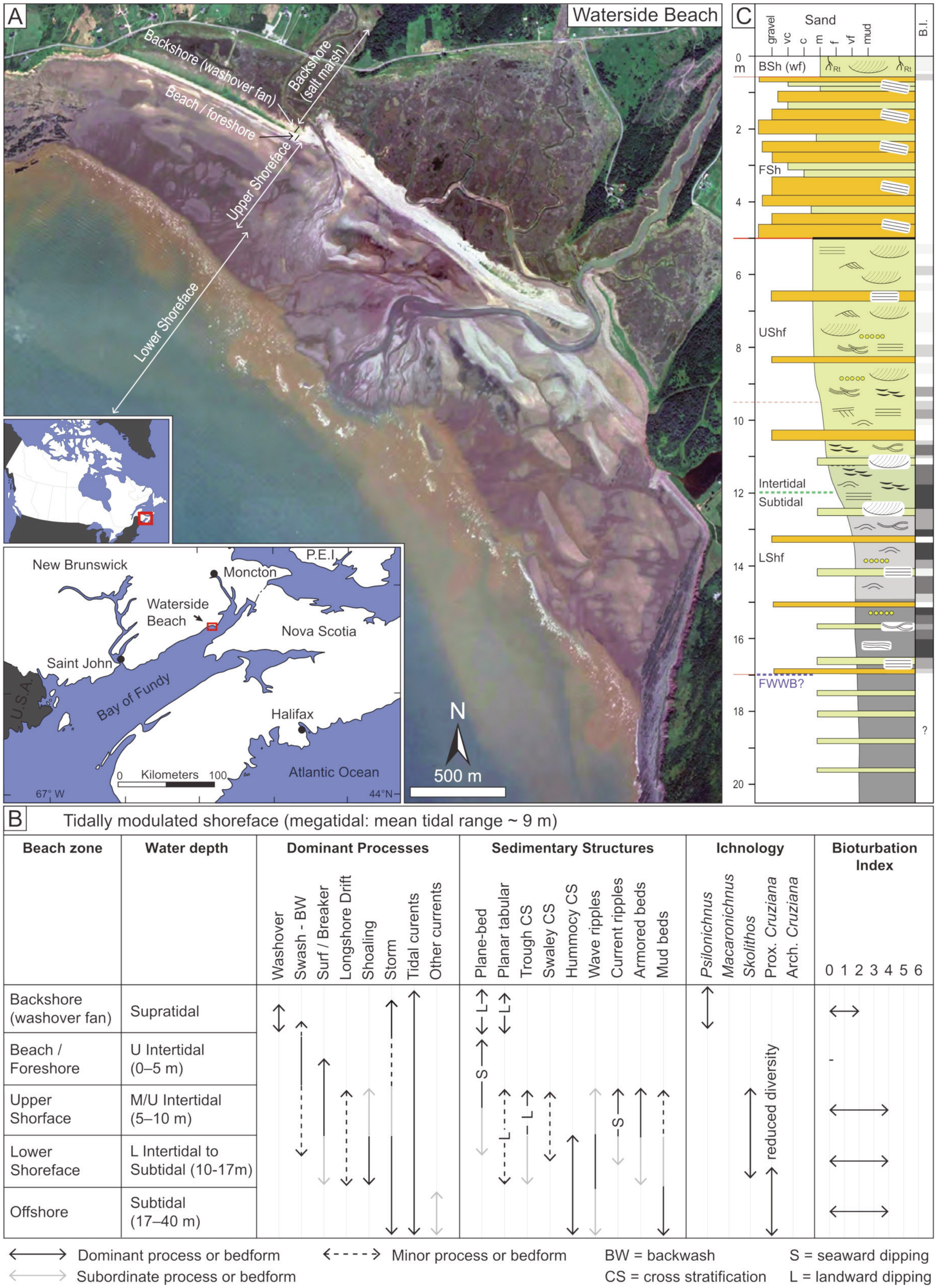

Figure 7. A) Airphoto of Waterside Beach, Bay of Fundy coast, New Brunswick, Canada, from which the tidally modulated shoreface model was derived. The approximate position of shoreface subenvironments are demarcated by the white and black lines (Google Earth airphoto). B) Distribution of preserved sedimentary structures and ichnology across the beach (modified after Dashtgard et al. 2009). C) Hypothetical reconstruction of a preserved vertical profile for a TMS assuming the system is progradational (modified after Dashtgard et al. 2012). Refer to the legend in Figure 3 for definitions of acronyms, colours and symbols used in this figure. Additional acronym: washover fan (wf).

1967; Gingras et al. 1999; Dashtgard 2011b; Dashtgard and Gingras 2012; Wang et al. 2019). TMS also show reduced bioturbation relative to microtidal beach-shorefaces due to regular subaerial exposure, high substrate mobility (arising from both the translation of wave zones during tidal cycles and tidal currents), and precipitation during exposure of the intertidal portion. The decrease in bioturbation is most pronounced in the lower shoreface (permanently subtidal to lower intertidal zone; Fig. 7; Dashtgard et al. 2009, 2012).

Both the OCTF and TMS models have existed for more than 10 years, and equivalent strata have been described from the rock record. In the next section we summarize rock record examples as they offer insights into the preserved character of tidal shorefaces that enable us to refine the tidal shoreface models described above.

3. ROCK RECORD EXPRESSIONS OF TIDAL SHOREFACES

Table 1 summarizes the published literature dealing with geological units interpreted as tidal shorefaces, either OCTF or TMS. Below we present the main recognition criteria (Table 1) used to interpret sedimentary successions as OCTF or TMS, and we provide a summary of the most frequently used sedimentary signatures.

Tidal shorefaces interpreted from the rock record (Table 1) have been identified either by recognizing the interbedding of clear tidal and wave/storm signatures in the deposits (Basilici et al. 2012; Wei et al. 2016; Bádenas et al. 2018; Kalifi et al. 2020; Sleveland et al. 2020) and/or by documenting tidal modulation of wave processes (Smosna and Bruner 2016; Vaucher et al. 2017, 2018a, 2020; MacNaughton et al. 2019; Angus et al. 2020). Tidal signatures used in these studies include tidal bundles, herringbone structures, lenticular, wavy, and flaser bedding, and mud drapes (Fig. 8A). Wave/storm processes were interpreted from low-angle to planar lamination, wave and combined-flow ripples, and HCS/SCS (Fig. 8A). Tidal modulation of wave processes was interpreted from the interbedding of oscillatory-generated structures (i.e. HCS/SCS, wave- and combined-flow ripples) of different wavelengths and within the same event bed, and in some cases, with low-angle to planar stratification (Yang et al. 2008b). This interbedding is interpreted as reflecting depth-dependent variation in storm-wave processes that resulted from the across-shore shift of wave zones as water depths vary through tidal cycles (Fig. 8B).

The sedimentary structures mentioned in the previous paragraph reflect direct wave or tide processes acting on the sediment at a given water depth; however, other criteria for combined wave-tide processes acting at the same time have been proposed. For example, Vaucher et al. (2018b) described the internal architecture of bedforms (3D dunes; see their Fig. 4) induced by supercritical backwash under fairweather conditions in the intertidal zone of a modern TMS. They hypothesized that the downcutting of the bottomsets of these bedforms reflects water-level changes during a tidal cycle (also suggested by Dalrymple and Rhodes 1995), which increased the impact of supercritical backwash at a given water depth in a relatively high-energy, wave-dominated intertidal zone. Similar sedimentary features were described from ancient nearshore strata in France and England (Vaucher et al. 2018b; Kalifi et al. 2020).

Determining the character of tidal shorefaces subtidally and into the offshore has not yet been done effectively from modern environments, but a few studies of tidal shoreface deposits from the rock record provide clues as to the character of the deeper-water part of these systems (Fig. 9; Vaucher et al. 2017). First, the distinction between a storm-dominated shoreface lacking a significant tidal overprint (Fig. 3) and a wave / storm-dominated tide-modulated system (Fig. 9) is not straightforward as the tidal signature is typically obliterated by storm processes in storm-dominated tidal shorefaces, such that the preserved offshore-to-shoreface succession is dominated by HCS and SCS (Fig. 9). The identification of a storm-dominated tidal shoreface relies on recognizing tidal modulation of storm-generated sedimentary structures or the preservation of tidal deposits formed during inter-storm periods (Table 1; Fig. 8B; Wei et al. 2016). Sedimentological evidence of tidal modulation of wave processes (e.g. Vaucher et al. 2017; Bádenas et al. 2018) includes: (i) sandstone beds displaying HCS passing gradationally upwards into combined-flow ripples and then back to HCS without evidence of multiple depositional events (i.e. deposition during one (or more) tidal cycles rather than stacked discrete storm beds); and, (ii) the pervasive stacking of oscillatory structures of shorter-to-longer wavelengths, and *vice versa*, reflecting the continuously changing water depth through tide cycles during a single storm; this acts to vary the size of the wave orbitals acting on the seafloor. Both of these stratal architectures can be interpreted as either stacked storm beds or tidal modulation of storm deposits, and so neither is diagnostic, especially if the high-energy parts of cycles are erosionally based. However, the repeated occurrences of one or both bed architectures through a conformable shoreface succession is more suggestive of tidal modulation than stacked storm beds since most storm-dominated (high energy) shoreface successions do not show significant bed-to-bed variability in the scale of HCS (e.g. Walker 1984; Plint and Walker 1987; Clifton 2006; Jelby et al. 2020).

4. A REFINED MODEL FOR TIDAL SHOREFACES

The TMS model extends from the offshore to the backshore (Fig. 7), while the OCTF occurs at elevations that are equivalent to the lower shoreface through to the backshore (Fig. 6); thus, the two models overlap spatially. Conceptually, the TMS model can be divided into lower (offshore to lower shoreface) and upper (upper shoreface to backshore) intervals. The middle shoreface is not a distinct zone in TMS or OCTF (Figs. 6 and 7) because the tidally induced lateral translation of wave zones across the intertidal zone blurs the boundaries between wave zones. In the upper interval, and under certain conditions, OCTFs and potentially other intertidal sedimentary environments can develop. Based on multiple published examples of OCTFs, both along modern coastlines and from the rock record, they typically overlie offshore to lower shoreface successions that are similar to the lower part of TMS successions. In consequence, we combine the two mixed wave-tide

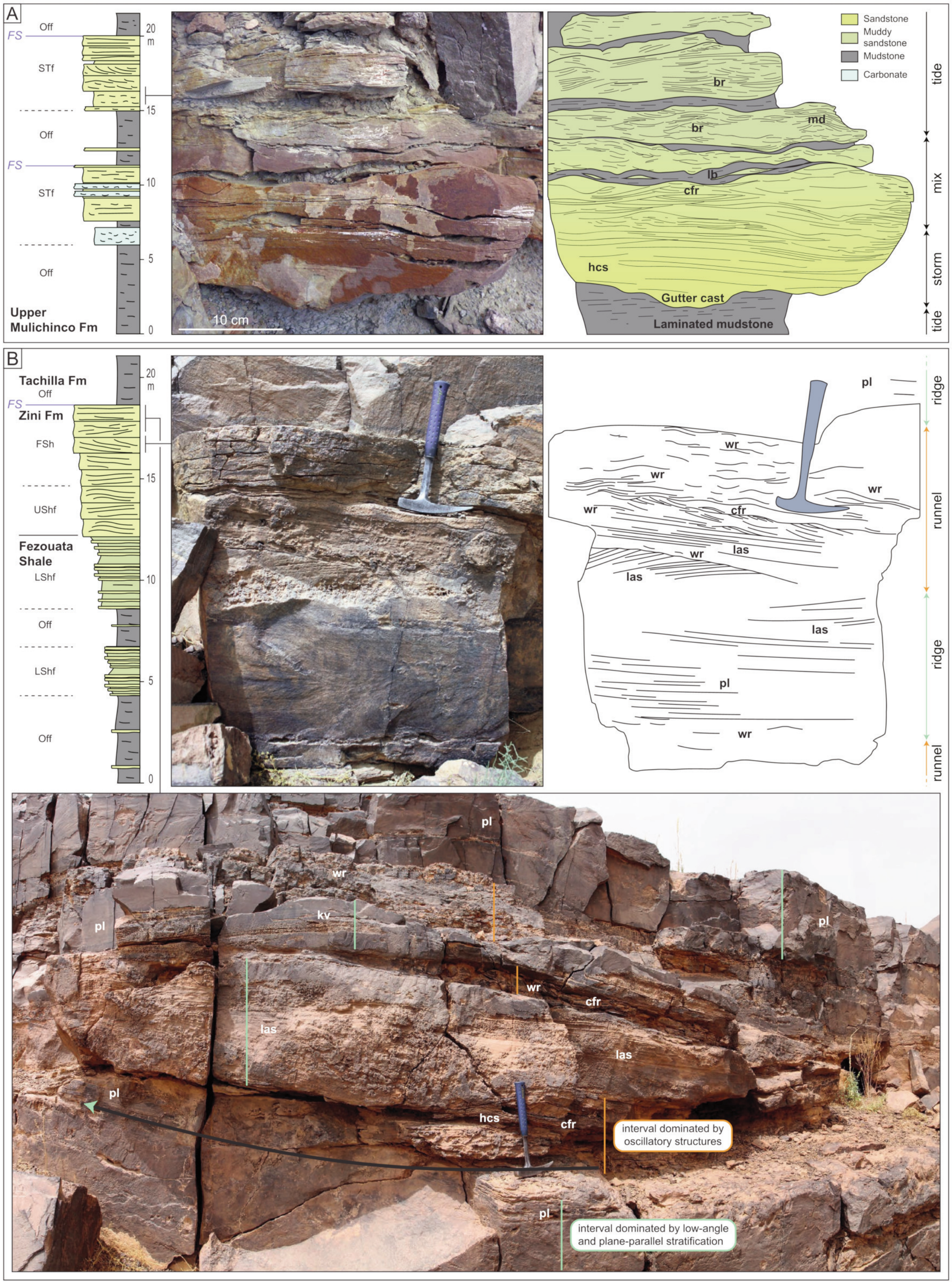

Figure 8. Examples of tidal-shoreface deposits from the rock record. A) Two parasequences that both show a shallowing-upward profile from offshore to subtidal-flat environments. The subtidal flat (STf) showcases a gradual transition from storm (sandstone) to tidal (muddy sandstone) deposits preserved in the storm-influenced (medium-energy) subtidal flat of the Upper Mulichinco Formation (Barranca Los Loros, Early Cretaceous, Argentina; modified after Sleveland et al. 2020). B) Regressive sequence that defines the Fezouata Shale and Zini Formation (Early Ordovician), which is overlain by the transgressive Tachilla Formation (Middle Ordovician), Morocco. The fine- to medium-grained sandstones from the Zini Formation are interpreted as a tidally modulated ridge-and-runnel foreshore-shoreface showcasing the repeated vertical and lateral transition from ridge to runnel in the intertidal zone (adapted from Vaucher et al. 2017, 2018a). Scale: hammer is 32 cm long. Orange and green lines refer to the colour code on Figure 9. Refer to the legend in Figure 3 for definitions of acronyms, colours and symbols used in this figure. Additional acronyms: Flooding surface (FS); bidirectional ripples (br), mud-draped ripples (md), lenticular bedding (lb), combined-flow ripples (cfr), planar lamination (pl), low-angle stratification (las), wave ripples (wr), and keystone vugs (kv).

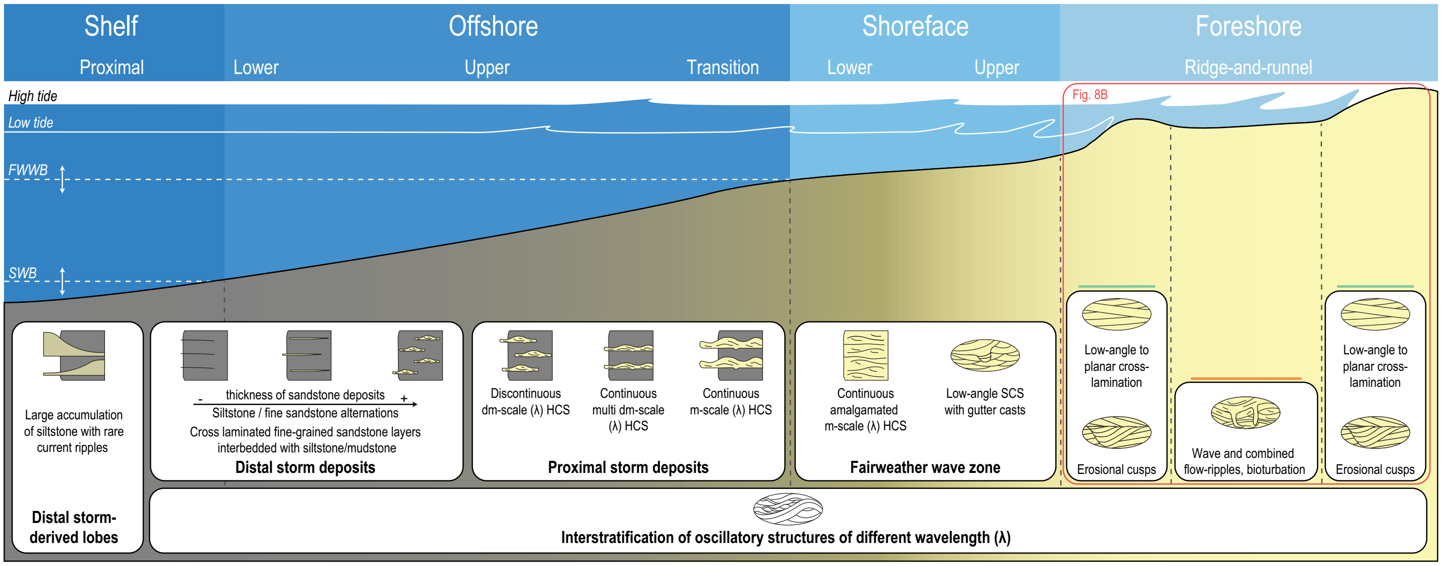

Figure 9. Facies model developed for the deposits of a wave-dominated, tide-modulated system ranging from proximal shelf to foreshore environments that occur in Fezouata Shale and the Zini Formation (Early Ordovician, Morocco; modified after Vaucher et al. 2017). Note that the overall system closely resembles a pure storm-influenced/dominated system as the succession is dominated by hummocky cross-stratification (see Figure 3). Refer to the legend in Figure 3 for definitions of acronyms, colours and symbols used in this figure.

systems into a single tidal shoreface model where TMS (as originally described) and TMS-OCTF are considered as tidal-shoreface variants along the wave-tidal continuum. We also note that TMS and OCTF are distinctive elements of mixed wave–tide systems, and so it is possible to form various combinations of OCTF and TMS with other coastal subenvironments (e.g. TMS overlain by wave-dominated upper shoreface and foreshore deposits (Fig. 7) or OCTF overlying delta-front deposits (Fan 2012; Zhang et al. 2018).

A key limitation of recognizing tidal shorefaces in the rock record is the obliteration of the tidal signature by strong storm- (high-energy) wave action. In these cases, tidal shorefaces will appear similar to storm-dominated shorefaces or storm-dominated delta fronts (compare Figs. 3 and 9). Both storm-dominated shorefaces and storm-dominated delta fronts, regardless of tidal range, are expressed as vertical successions of stacked HCS and SCS that increase in scale (thickness and wavelength) from the offshore to the lower/middle shoreface or distal delta front (Fig. 3; MacEachern et al. 2005; Hansen and MacEachern 2007; Dashtgard et al. 2012; Jelby et al. 2020). Interbedded mudstone through to muddy sandstone from the offshore to the lower/middle shoreface or distal delta front tends to be bioturbated with a decrease in the degree of bioturbation into shallower water (MacEachern and Pemberton 1992). The energy of breaking waves and turbulent wave-forced currents in the upper shoreface of storm-dominated shorefaces and proximal delta fronts of wave-dominated deltas results in preservation of trough cross-stratified sandstone (reflecting onshore and alongshore-migrating dunes and bars), and trough cross-stratified sandstones are overlain by seaward-dipping plane beds in the foreshore / lower delta plain (reflecting the vertical translation of swash-backwash; compare Figs. 3 and 7C). The cumulative vertical thickness of sedimentary strata that preserve the various wave zones in storm-dominated shorefaces and delta fronts should be greater in tidal shorefaces (or their deltaic equivalent) as a result of vertical expansion of the depth range over which the various processes operate because of the tidal range (Masselink and Hegge 1995; Dashtgard et al. 2009; Angus et al. 2020), although the facies would appear very similar. While tidal modulation of storm waves can be inferred from sedimentological evidence recorded in stacked HCS successions (see Section 3), the most reliable means to confidently distinguish a storm-dominated tidal shoreface from a storm-dominated shoreface or storm-dominated delta front is to acquire quantitative geometric data of coastal to shallow marine systems in a single parasequence. Without these data, we urge caution when interpreting a geological unit as a storm-dominated tidal shoreface.

Recognition of tidal shorefaces is easier in systems that experience low- to moderate- storm influence (Dashtgard et al. 2009, 2012). It is in such limited-energy systems that the defining characteristics of tidal shorefaces (see Sections 2.1 and 3) are most likely to be preserved, enabling their identification.

Tidal shorefaces have been described from the rock record in foreland (Basilici et al. 2012; Kalifi et al. 2020), pre-rift (Wei et al. 2016), syn-rift (Bádenas et al. 2018), post-rift (Smosna and Bruner 2016; Vaucher et al. 2017; Sleveland et al. 2020), and extensional (Angus et al. 2020; Vaucher et al. 2020) basins, as well as the margins of an epeiric sea (Table 1; MacNaughton et al. 2019). Although no general consensus exists for the type of basins in which tidal shorefaces are preserved, there is the potential for tidal shorefaces to develop more regularly on the margins of semi-enclosed basins with a tapered basin morphology that can amplify tidal currents (Dalrymple and Padman 2019). The preservation potential of tidal shorefaces is also controlled by other factors that influence preservation of shallow-marine environments including accommodation creation and sediment supply (e.g. Reading 1996). Tidal shoreface

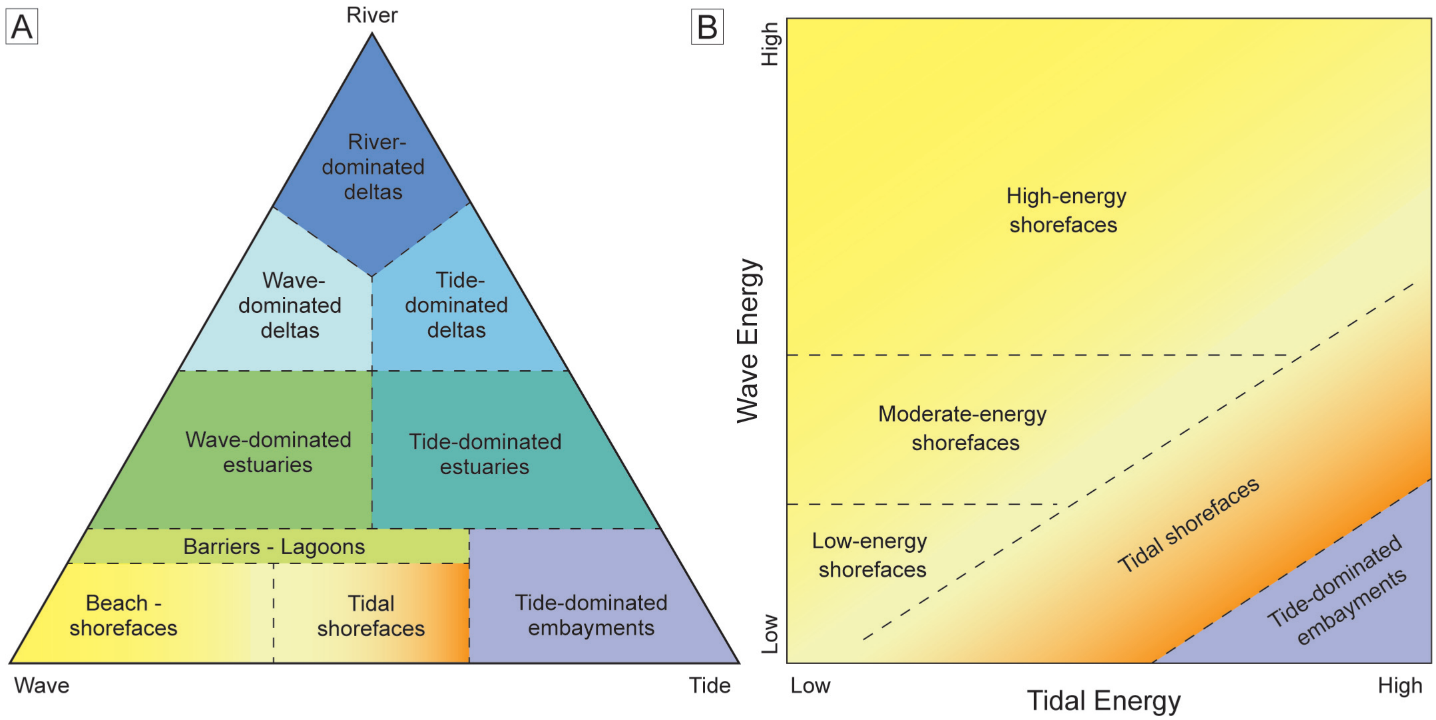

Figure 10. A) Revised classification scheme for shallow-marine and coastal depositional environments based on the relative input of energy by Rivers, Waves, and Tides. Note the merger of OCTF and TMS into a single model for tidal shorefaces, and the replacement of tidal flats at the tide-dominated apex with tidal embayments. Dashed lines indicate that all coastal environments grade into each other with changing relative energy inputs and, thus, multiple variants of these systems are possible. B) Bivariate classification of mixed wave-tide shallow-marine to coastal environments that distinguishes between low-energy waves (formerly fairweather waves), high-energy waves (formerly storm waves), and tidal processes with a range of energy levels. Note the dominance of high-energy wave processes in determining the preserved character of mixed wave-tide environments.

successions should occur more commonly in basins that experience high sedimentation and have high rates of accommodation creation (Yang et al. 2008b; Wei et al. 2016; Bádenas et al. 2018; Vaucher et al. 2018a), which suggests that tectonically active basins and river-mouth-proximal (i.e. deltaic) settings *should* favour the preservation of these systems. This hypothesis requires further investigation.

5. A REVISED TERNARY CLASSIFICATION SCHEME

In reconciling the complementary models and published examples of tidal shorefaces several issues are recognized in the widely used river-wave-tide classification scheme of coastal depositional environments and particularly along the wave-tide continuum. These issues relate to, but are not limited to, the vertical extent and position of tidal flats in coastal systems, the difference between storms and high-energy waves, and the lateral transition between various coastal systems. To address these issues, we have modified the most commonly employed coastal classification schemes (Fig. 1) with revised versions (Fig. 10), and below we explain the changes made and the reasons for them.

First, OCTFs (as with all tidal flats) occur in the intertidal zone, and hence, form only part of vertical successions representative of coastal to shallow-marine depositional environments regardless of the width of the tidal flat. Consequently, variants of tidal flats can overlie shorefaces, delta fronts, and TMS making these deposits poor candidates as a stand-alone, end-member coastal system at the tide-dominated apex of the classification scheme (Fig. 1). We have addressed this issue in the revised classification scheme of coastal environments (Fig. 10A) by replacing tidal flats with tide-dominated embayments and merging OCTFs with TMS based on the criteria discussed in Section 4. Tide-dominated embayments are commonly (but not necessarily) funnel-shaped, and the mouth of the embayment experiences strong tidal flow, and relatively little or no river input and only small waves. It is difficult to produce tide-dominated embayments with no river input or waves and so pure tide-dominated embayments are probably rare, perhaps occurring primarily in arid climate belts. Tide-dominated embayments are gradational with tide-dominated estuaries as the degree of river influence in the system increases, and tide-dominated estuaries transition to tide-dominated deltas as the volume of sediment input by rivers increases still more, leading to shoreline progradation (Fig. 10A). Two excellent examples of tide-dominated embayments include the Khor Al Adaid embayment (Rivers et al. 2020) and the Al Dakhirah lagoon (Billeaud et al. 2014) both of which are situated in Qatar.

Second, the terms "storm" and "fairweather" (cf. Fig. 1B) refer globally to the origin of waves rather than the energy of them, and consequently, do not adequately describe the wave energies experienced along all of the world's shorelines. For example, fairweather swells experienced along the west coast of Canada greatly exceed the size of storm waves experienced in Lake Erie, Canada. To address this discrepancy, we replace the fairweather wave and storm-wave apices of the fairweather wave–storm wave–tide ternary classification of mixed wave-tide systems (Fig. 1B) with the terms low-energy waves and high-energy waves, respectively (Fig. 10B). These terms are still used in a relative sense. We also emphasize that while low-energy and high-energy are not synonymous with fairweather waves and storm waves, there is a higher probability that fairweather waves will be low-energy waves and storm waves will be high-energy waves, particularly within the same depositional system.

We also convert the fairweather wave–storm wave–tide ternary diagram (Fig. 1B) into a bivariate plot of wave energy versus tidal energy (Fig. 10B). This revised classification scheme of mixed wave-tide coastal systems remains relative where low- and high-wave energy and low- and high-tidal energy are not defined herein. This is consistent with previous publications that use relative energy inputs (e.g. Boyd et al. 1992), and with studies that have attempted to quantify tidal and wave energy, but still rely on the relative difference in energy between the two processes (Davis and Hayes 1984; Harris et al. 2002). The replacement of fairweather and storm with low-energy and high-energy, respectively, is useful because: 1) it decouples wave-energy from weather events (i.e. wave amplitudes are not dictated solely by storm intensity); 2) it accounts for the fact that wave-energy is highly variable between depositional settings; and 3) it recognizes that storm- and fairweather-waves and their products cannot be universally distinguished (c.f. Clifton 2006). The use of a bivariate plot versus a ternary diagram is also useful as it accounts for variation in tidal energy as well as wave energy (Fig. 10B). Based on this, we propose that storm-affected, storm-influenced, and storm-dominated shorefaces be renamed as low-energy, moderate-energy, and high-energy shorefaces, respectively (Figs. 3 and 10B).

The final revision of the coastal-environments classification scheme is the merger of OCTFs and TMSs into a single *tidal shoreface* model (Section 4; Fig. 10). This revision recognizes that tidal shorefaces represent mixed wave-tide systems with limited river influence (Fig. 1A) and occur in settings with low- to moderate-storm (low- to moderate-energy) wave influence. We do not expect tidal shorefaces to be recognizable if wave energy is high (Fig. 10B).

6. CONCLUSIONS

Both tidally modulated shorefaces and open-coast tidal flats demonstrate the variability in the character and architecture of mixed wave-tide coastal systems, and the models for both were developed from modern examples. Following over ten years of testing these models in modern settings and the rock record, the available evidence suggests that while OCTF and TMS are distinctive in the intertidal zone of modern shorelines, the two deposit types are likely to share comparable features in the subtidal zone. Based on this we merge the models into a single *tidal shoreface* model. The TMS model, as originally defined (Fig. 7; Dashtgard et al. 2009; Dashtgard and Gingras 2012), is considered a more wave-dominated variant of tidal shorefaces, whereas a TMS that transitions upward into a OCTF in the intertidal zone (a combined TMS-OCTF) is proposed as a more tide-dominated variant.

Tidal shorefaces are most easily identified in settings with low- to moderate-energy waves and strong tidal influence, and in settings with high rates of sediment accumulation. Recognizing tidal shorefaces in the rock record can be used as evidence of a mesotidal or greater tidal range along a paleo-coastline. Preservation of tidal shoreface deposits can also be interpreted as evidence of low to moderate storm-wave influence. In storm- (high-energy wave) dominated systems, distinguishing tidal shorefaces from microtidal (non-tidal) shorefaces is tenuous unless there is exceptional preservation of tidally generated fairweather strata and/or robust, quantified data on the geometry and character of shallow-marine geobodies. For example, a tidal shoreface in a moderate- to high-energy wave-setting should generate a succession containing thicker-than-normal intervals of trough cross-stratified beds overlain by seaward dipping plane beds at the top of the succession because of the vertical expansion of the various wave zones by tidal modulation of water levels. However, confidently identifying a storm-dominated tidal shoreface would require extensive data on the thickness of all wave-dominated beach-shorefaces along a paleo-coastline to enable identification of overthickened successions.

Tidal flats are components of a wide range of shallow-marine depositional systems including tide- and river-dominated deltas, lagoons, and tide- and wave-dominated estuaries. Many of these larger depositional environments are not tide-dominated (Fig. 1A), and therefore, tidal flats should not be situated at the tide-dominated apex of coastal classification schemes. Instead, we recommend that tide-dominated embayments occupy this position. These environments grade into tide-dominated estuaries and then tide-dominated deltas as the degree of river influence increases (Fig. 10A).

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ARTICLE

A Hydrostratigraphic Framework for the Paleozoic Bedrock of Southern Ontario

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SUMMARY
Groundwater systems in the intermediate to deep subsurface of southern Ontario are poorly understood, despite their value for a number of societal uses. A regional hydrostratigraphic framework is a necessary precursor for improving our understanding of groundwater systems and enabling development of a 3-D hydrostratigraphic model to visualize these groundwater systems. This study is a compilation and integration of published and unpublished geological, hydrogeological, hydrochemical and isotopic data collected over the past 10 years to develop that framework.

Bedrock is covered by a thin veneer of surficial sediments that comprise an aquifer/aquitard system of considerable local variability and complexity. Aquifers in the bedrock are thin and regionally extensive, separated by thick aquitards, within a well-defined lithostratigraphic framework and a well-developed hydrochemical depth zonation comprising a shallow fresh water regime, an intermediate brackish to saline sulphur water regime, and a deep brine regime of ancient, evaporated seawater. Occurrence and movement of groundwater in shallow bedrock is principally controlled by modern (Quaternary) karstic dissolution of subcropping carbonate and evaporite rocks, and in the intermediate to deep subsurface by paleokarst horizons developed during the Paleozoic. Flow directions in the surficial sediments of the shallow groundwater regime are down-gradient from topographic highs and down the regional dip of bedrock formations in the intermediate regime. Shallow karst is the entry point for groundwater penetration into the intermediate regime, with paleo-recharge by glacial meltwater and limited recent recharge by meteoric water at subcrop edges, and down-dip hydraulic gradients in confined aquifers. Hydraulic gradient is up-dip in the deep brine regime, at least for the Guelph Aquifer and the Cambrian Aquifer, with no isotopic or hydrochemical evidence of infiltration of meteoric water and no discharge to the surface.

Fourteen bedrock hydrostratigraphic units are proposed, and one unit comprising all the surficial sediments. Assignment of lithostratigraphic units as hydrostratigraphic units is based principally on hydrogeological characteristics of Paleozoic bedrock formations in the intermediate to deep groundwater regimes, below the influence of modern meteoric water. Carbonate and evaporite rocks which form aquitards in the subsurface may form aquifers at or near the surface, due to karstic dissolution by acidic meteoric water, necessitating compromises in assignment of hydrostratigraphic units.

RÉSUMÉ
Les systèmes d'eaux souterraines du sous-sol intermédiaire à profond du sud de l'Ontario sont mal compris, malgré leur valeur pour de nombreux usages par la société. Un cadre hydrostratigraphique régional est un préalable nécessaire à l'amélioration de notre compréhension des systèmes d'eaux souterraines et au développement d'un modèle hydrostratigra-

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phique 3D pour visualiser ces systèmes d'eaux souterraines. Cette étude est une compilation et une intégration de données géologiques, hydrogéologiques, hydrochimiques et isotopiques publiées et non publiées recueillies au cours des 10 dernières années afin de développer ce cadre.

Le substrat rocheux est recouvert d'un mince placage de sédiments de surface qui comprend un système d'aquifères et d'aquitards d'une variabilité et d'une complexité locales considérables. Les aquifères du substrat rocheux sont minces et étendus au niveau régional, séparés par des aquitards épais, dans un cadre lithostratigraphique bien défini et une zonation hydrochimique verticale bien développée comprenant un régime peu profond d'eau douce, un régime intermédiaire d'eau sulfureuse saumâtre à saline et un régime profond de saumure résultant de l'évaporation d'eau de mer ancienne. La présence et le mouvement des eaux souterraines dans le substrat rocheux peu profond sont principalement contrôlés par la dissolution karstique moderne (quaternaire) des roches carbonatées et évaporitiques sub-affleurantes, et dans le sous-sol intermédiaire à profond par les horizons paléokarstiques développés au Paléozoïque. Les directions d'écoulement des eaux dans les sédiments de surface du régime peu profond sont en aval des sommets topographiques et en aval du pendage régional des formations de substrat rocheux dans le régime intermédiaire. Le karst peu profond est le point d'entrée pour l'infiltration des eaux souterraines dans le régime intermédiaire, avec une paléo-recharge d'eau de fonte glaciaire et une recharge récente limitée d'eau météorique aux bords de sous-affleurement, et un gradient hydraulique en aval-pendage dans les aquifères confinés. Le gradient hydraulique est en amont-pendage dans le régime profond de saumure, au moins pour l'aquifère de Guelph et l'aquifère du Cambrien, sans indication isotopique ou hydrochimique d'infiltration d'eau météorique et sans déversement à la surface.

Quatorze unités hydrostratigraphiques du substrat rocheux sont proposées, et une unité comprenant tous les sédiments de surface. L'attribution des unités lithostratigraphiques en tant qu'unités hydrostratigraphiques repose principalement sur les caractéristiques hydrogéologiques des formations du substrat rocheux du Paléozoïque dans les régimes intermédiaires à profonds des eaux souterraines, sous l'influence des eaux météoriques modernes. Les roches carbonatées et évaporitiques qui forment les aquitards dans le sous-sol peuvent former des aquifères à la surface ou près de la surface, en raison de la dissolution karstique par l'eau météorique acide, ce qui nécessite des compromis dans l'attribution des unités hydrostratigraphiques.

Traduit par la Traductrice

INTRODUCTION

An understanding of geological controls on groundwater occurrence and quality is important as population growth elevates demands for a sustainable supply of water for residential and industrial use, both in Ontario and worldwide. Groundwater studies to date in southern Ontario have focussed on aquifers in the shallow subsurface that are able to meet quality standards for potability (e.g. Sharpe et al. 2014). Groundwater in the intermediate to deep subsurface has quality constraints that has discouraged its investigation. In some parts of North America these deeper waters are increasingly being considered as potential resources, necessitating a better understanding of their hydrogeological and hydrostratigraphic relationships. For example, the states of California, Florida, Texas, Kansas, Virginia and Utah currently treat brackish to saline groundwater to remove dissolved solids to provide public water supply for human consumption (Dieter et al. 2018). In the United States the potential volume of brackish groundwater is conservatively estimated at 35× the total annual volume of fresh groundwater utilized for all uses (Stanton et al. 2017). Comparable data are not available for Canada.

The feasibility of utilizing brackish and saline groundwater is limited by legal and environmental considerations, hydrochemical composition and lack of data on recharge mechanisms and sustainability. Without efficient recharge pathways, large-scale development of these groundwater resources will result in groundwater depletion. In Canada, groundwater sustainability has been identified as a significant knowledge gap (Canadian Council of Ministers of the Environment 2010).

Deep brine aquifers in the northeastern United States and Ontario have been proposed for sequestration of carbon dioxide emissions from fossil fuel power plants and cement plants (e.g. Shafeen et al. 2004; Shafeen and Carter 2009). High-calcium brine from select deep aquifers in southern Ontario is utilized for ice control on Ontario's 400 series expressways. Intermediate to deep aquifers in southern Ontario are presently utilized for disposal of saline oil-field fluids, which are a by-product of oil and natural gas production. In the past, some of these aquifers were also utilized for disposal of industrial wastes (Raven et al. 1990). Deep aquifers and aquitards are also important hydrochemical indicators of the long residence time of deep subsurface groundwaters, thus helping establish a safety case for deep disposal and long-term isolation of nuclear wastes (e.g. Hobbs et al. 2011; Intera Engineering Ltd. 2011; Clark et al. 2013). Brackish and saline groundwater may be utilized for underground injection to support enhanced oil production (e.g. Craig 1993).

To provide a framework for supporting these various subsurface management strategies a 3-D geological model has been constructed of the Paleozoic sedimentary sequence (Carter et al. 2019) and the overlying sediments (Logan et al. 2020). This lithostratigraphic framework requires reclassification and rationalization to support development of a 3-D hydrostratigraphic model which is in progress. Frey et al. (2020) recently developed a proof-of-concept fully integrated groundwater-surface water model for southern Ontario.

The objective of this study is to establish a high-level hydrostratigraphic classification of the aquifer and aquitard systems of southern Ontario within the shallow, intermediate, and deep hydrochemical groundwater regimes identified by Carter and Fortner (2012) and Sharpe et al. (2014). The focus is on groundwater systems in the intermediate to deep bedrock, which are largely non-potable, and evidence for interaction with shallow groundwater systems. Understanding the geological context and the geological processes that created pathways for groundwater movement guides and informs development of conceptual models of groundwater flow.

The classification is based on a wealth of data compiled from both published and unpublished sources, including water intervals records from petroleum wells, stable isotope and hydrochemical analyses, interpreted flow directions, stratigraphic relationships, geological controls on groundwater occurrence and movement, field observations, hydraulic conductivity measurements, DNA microbial profiling, faults and fractures, and karst studies.

Previous Hydrostratigraphic Classifications

Singer et al. (2003) were the first to attempt a regional classification of aquifers for southern Ontario. Their focus was exclusively on shallow potable water aquifers in the unconsolidated sediments and the shallow bedrock relying on water well records of the Water Well Information System (WWIS) of the Ontario Ministry of Environment, Conservation and Parks. The classification preceded recognition of the occurrence of a regionally extensive and laterally connected fresh water aquifer at the contact (contact aquifer) between the Paleozoic bedrock of southern Ontario and the overlying unconsolidated sediments (e.g. Dillon Consulting Ltd. and Golder Associates Ltd. 2004; Husain et al. 2004; Strynatka et al. 2007; Carter and Fortner 2012).

For the northwestern part of the study area, including Bruce and Huron counties, Intera Engineering Ltd. (2011) proposed an assignment that resolved the lithostratigraphy into nine hydrostratigraphic units within three hydrogeological systems. The classification was based largely on very detailed geological, hydrochemical, hydrogeological and isotopic data acquired from 6 deep (450–905 m) and 3 shallow (< 200 m) boreholes drilled at the Bruce Power nuclear generating station (Bruce site) on Lake Huron, in Bruce County. The three hydrogeological systems are analogous to the three hydrochemical regimes identified by Sharpe et al. (2014) and used in the present study: shallow, intermediate, and deep. The 15 hydrostratigraphic units of the present study are similar, with differences due largely to representation of younger stratigraphic units and regional facies variations not present at the Bruce site.

A proof-of-concept 3-D integrated groundwater–surface water numerical model of southern Ontario developed by Aquanty Inc. uses 5 sediment layers and 12 bedrock layers (Frey et al. 2020). Bedrock hydrostratigraphic layers are similar to those considered in the present study.

GEOLOGICAL SETTING

The study area includes all southern Ontario west of the Frontenac Arch, with the exception of Manitoulin Island, and extends to the international boundary with the United States beneath lakes Huron, St. Clair, Erie, and Ontario, for a total area of approximately 110 000 km^2 (Fig. 1).

Southern Ontario is underlain by marine sedimentary rocks deposited in a shallow epeiric sea that periodically covered this part of eastern North America during the Paleozoic Era from approximately 501 to 250 Ma. The Paleozoic strata unconformably overlie Precambrian crystalline metamorphic rocks of the Canadian Shield, over 1 Ga, which are exposed at the surface in northern Ontario and large parts of eastern Ontario. Southern Ontario straddles a broad ridge in these Precambrian rocks known as the Algonquin Arch, and its southwestern extension, the Findlay Arch. A fault-bounded structural depression known as the Chatham Sag separates the two arches (Fig. 1). The Precambrian rocks were eroded to a low relief peneplain during an extended period of subaerial exposure lasting perhaps 450 million years (R.M. Easton personal communication 2021). Paleozoic strata are deposited unconformably on this eroded surface.

The Paleozoic strata dip shallowly at 3 to 6 m/km along the crests of the arches into the Chatham Sag, and at 3.5 to 12 m/km down the flanks of the arches westwards into the Michigan Basin and southwards into the Appalachian Basin (Armstrong and Carter 2010). Regional dip generally increases with depth and with distance away from the crest of the arch. The eroded edges of the shallowly dipping formations form northwest- to southeast-trending subcrop belts and carbonate-capped cuestas with progressively older units exposed at surface or subcropping beneath surficial sediments towards the east and north (Fig. 1) and create opportunities for infiltration of meteoric water into the subsurface along porous and permeable horizons in the bedrock formations.

The Paleozoic strata are formally subdivided into ~70 formations (Fig. 2). Rock types include limestone, dolostone, sandstone, shale, siltstone, anhydrite, and beds of halite (Armstrong and Carter 2010). In general, strata in the Appalachian Basin are dominated by clastic sedimentary rocks (shale, siltstone, sandstone), while those in the Michigan Basin are predominantly carbonate rocks (limestone, dolostone) with some thick beds of halite and anhydrite/gypsum. Maximum preserved thicknesses are 4800 m in the Michigan Basin to the west and 7000 m in the Appalachian Basin to the southeast (Armstrong and Carter 2010), with thickness in southwestern Ontario limited to ~1500 m within the Chatham Sag beneath Lambton County and west-central Lake Erie.

Subsidence in the Michigan Basin had begun by the Late Cambrian with subsequent intermittent periods of subsidence and uplift, continuing into the Late Jurassic (Sloss 1988; Howell and van der Pluijm 1990; Brunton and Brintnell 2020). The cause of subsidence is not well established and has been variously ascribed to a mantle plume or to a far-field response to compressional effects of Appalachian tectonics (see discussion by Brunton and Brintnell 2020). The Appalachian Basin formed in response to major continental collision events that resulted in four major orogenies: the Taconic (mid Ordovician to early Silurian), Salinic (Silurian), Acadian (Devonian), and Alleghanian (Pennsylvanian to Permian) orogenies (Johnson et al. 1992; Ettensohn 2008).

Depositional pattern, thickness, and structure of Paleozoic strata were controlled by episodic basinal subsidence and arch-centred uplift in response to both orogenic and epeirogenic forces generated during the Appalachian orogenies (Johnson et al. 1992). Episodes of regional crustal uplift periodically exposed the strata to erosion, creating regional disconformities

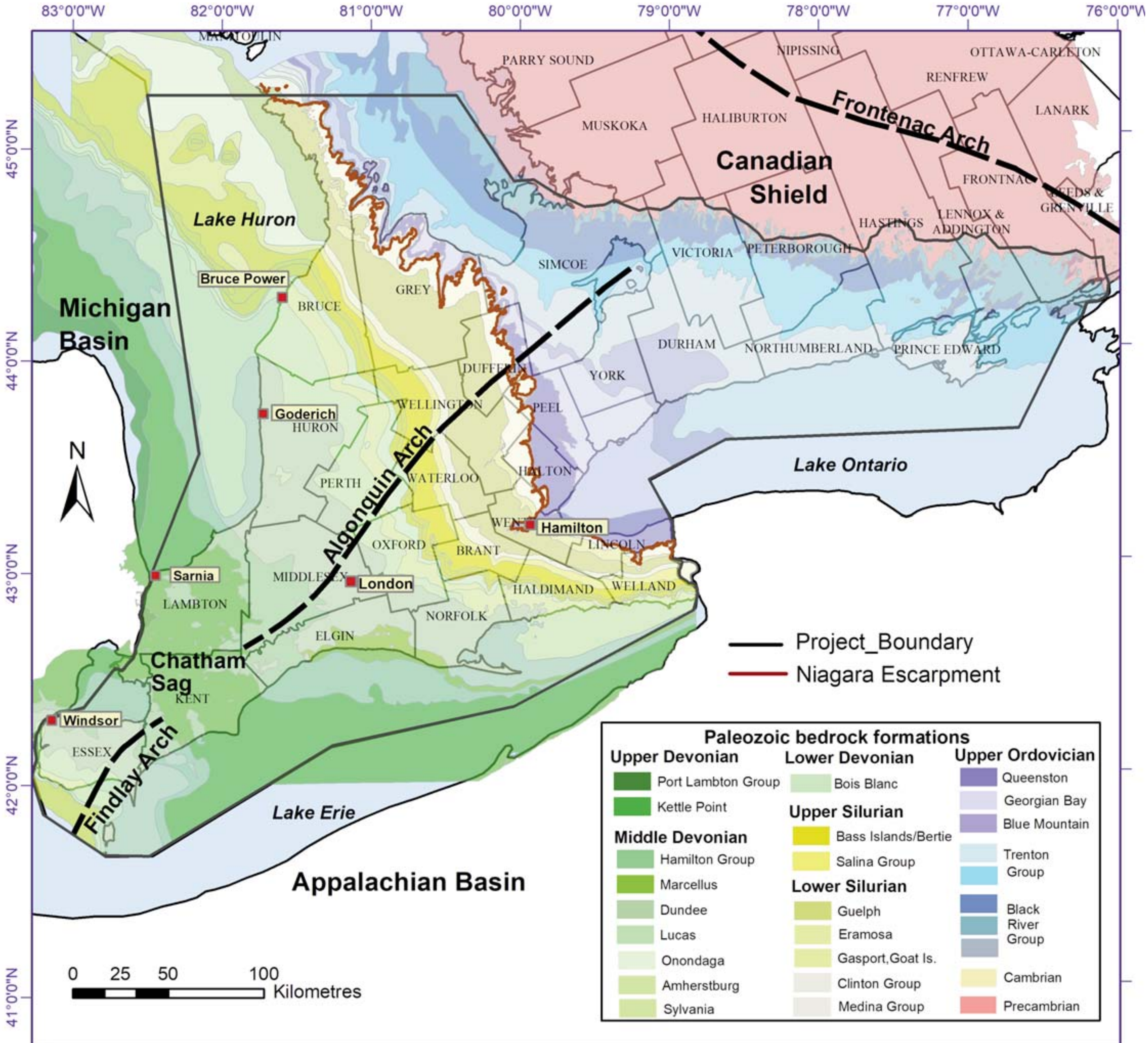

Figure 1. Bedrock geology of southern Ontario showing bedrock formations and groups of formations, structural arches, and basins, adapted from Carter et al. (2019). County boundaries are shown for geographic reference.

(Fig. 2). Near-surface carbonate and evaporite rocks experienced karstic dissolution by acidic surface waters during these exposure episodes. Burial by younger strata during subsequent periods of sea-level rise preserved these paleokarst horizons in the subsurface.

Approximately 250 million years ago tectonic uplift elevated southern Ontario above sea level, beginning an extended period of post-Paleozoic weathering and erosion, forming an angular unconformity between the bedrock and surficial sediments (Johnson et al. 1992).

Physiography, Bedrock Topography and Quaternary Geology

Several episodes of continental glaciation affected southern Ontario from 1.8 million to 10 000 years ago. Twenty thousand years ago all of Ontario was covered by the most recent of these glaciation events, the Laurentide Ice Sheet (LIS) (Barnett 1992). On its retreat, the glaciers left behind a complex terrain of glacial landforms and a wide variety of clastic sediments that range in thickness from a few metres to a maximum of 250 m, averaging tens of metres in thickness (Gao et al. 2006).

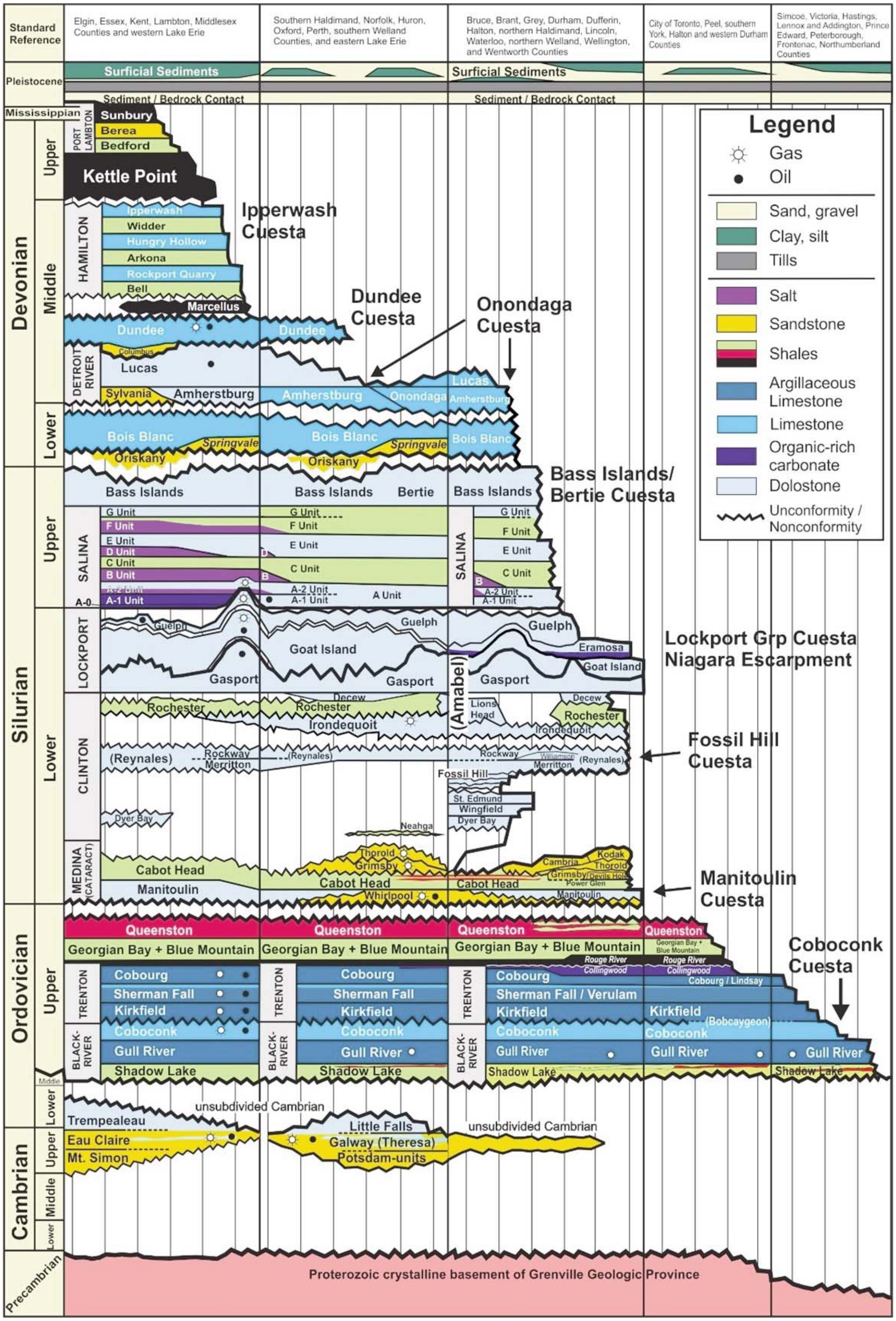

Figure 2. Subsurface Paleozoic stratigraphy of southern Ontario showing named geological formations, their geologic ages, positions of major unconformities (vertical hatch pattern), and principal oil and gas producing intervals (adapted from Carter et al. 2019).

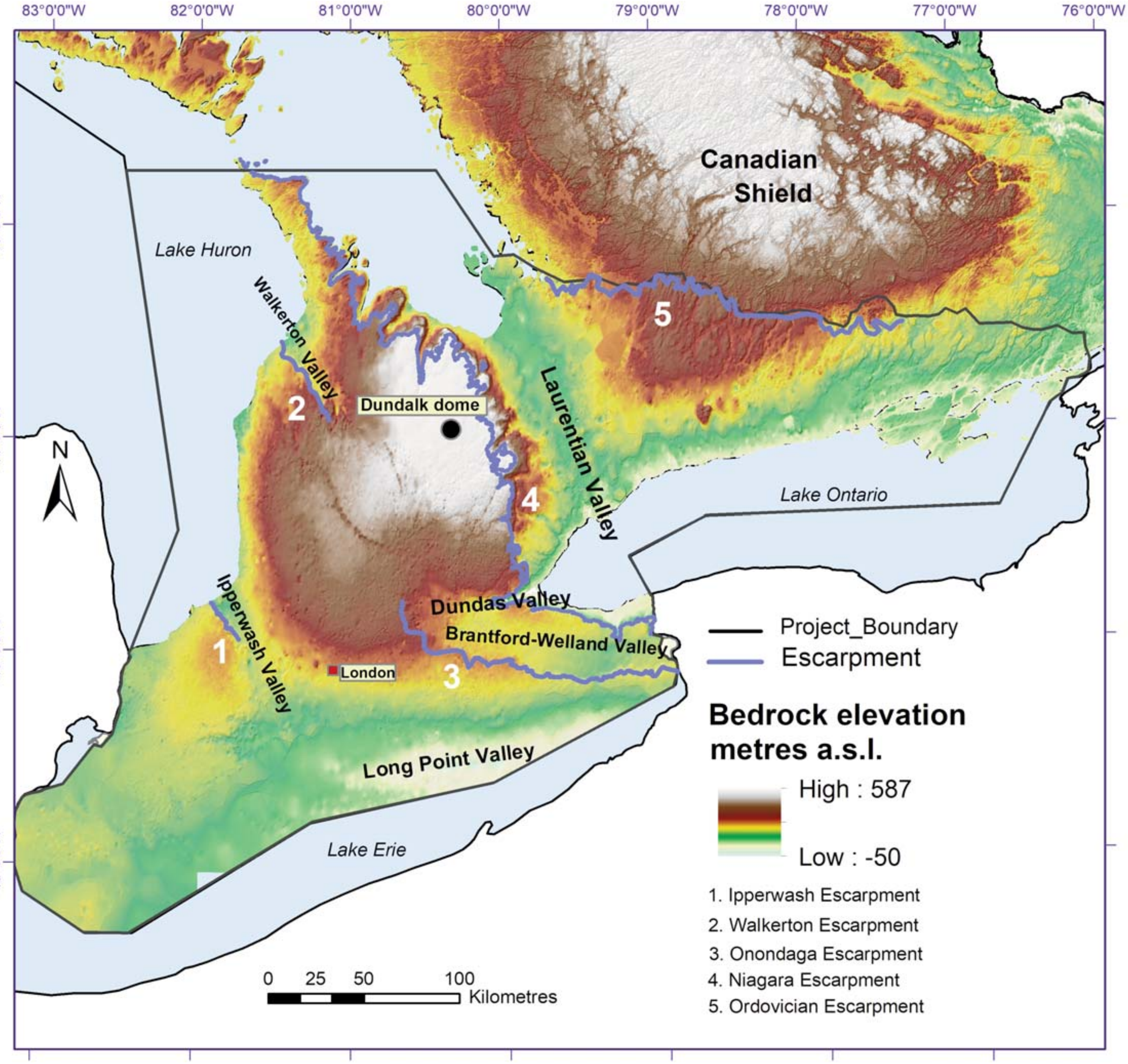

Figure 3. Topography of the bedrock surface in southern Ontario, showing principal named bedrock valleys and bedrock cuestas, derived from Gao et al. (2006), Gao (2011) and Brunton and Dodge (2008). Also shown is the Dundalk dome, a bedrock topographic high in the Lockport Group (Priebe and Brunton 2016; Priebe et al. 2021).

Lateral continuity is generally poor, with rapid lateral facies change. Sediments are thickest in bedrock valleys and beneath major moraines, and thinnest near escarpments, along river valleys and in the Bruce Peninsula (Logan et al. 2020). The ice sheets removed all older unconsolidated sediments and eroded the weathered surface of the bedrock. Estimates of the depths of glacial erosion vary but at least tens of metres and up to 200 m of Paleozoic bedrock was removed in most of the onshore portion of southern Ontario (Hallet 2011).

The bedrock surface reaches its highest elevation on the Dundalk dome, immediately west of the Niagara Escarpment (Fig. 3). Regional slope of the bedrock surface is to the southwest on the western side of the Niagara Escarpment. East of the escarpment the bedrock surface slopes south and west from the highlands of the Canadian Shield into the Laurentian Valley and the Lake Ontario basin. Average regional slopes are approximately 1.5 to 3.2 m/km in both areas, steepening on the sides of bedrock valleys, gorges, and cuestas. A system of glacially-sculpted buried valleys, narrow steep-walled gorges, and bedrock cuestas characterize the present-day bedrock surface (Fig. 3) (Gao 2011). The valleys coincide with the subcrop belts of easily eroded shale of the Hamilton Group, Georgian

Bay Formation and Blue Mountain Formation, or evaporites of the Salina Group. Cuestas have formed on this deeply eroded surface by differential erosion of shale or evaporites undercutting erosion-resistant carbonate rocks along the up-dip edges of the shallow-dipping bedrock formations (Figs. 2, 3). The Niagara Escarpment is the most prominent example, with local relief exceeding 100 m (Figs. 1, 2). Topography of the bedrock surface exerts a controlling influence on water movement at the bedrock−overburden interface.

The Niagara Escarpment forms a significant topographic divide for surface and groundwater movement in southern Ontario. The dolostone cap-rocks forming the escarpment brow are significant sites for groundwater recharge due to stress-relief fracturing and karstification by meteoric water (e.g. Cowell 1976; Brunton and Brintnell 2020).

Karst in Southern Ontario

Large parts of southern Ontario are underlain by carbonate and evaporite bedrock. Following the Pleistocene glaciations there has been extensive karstic dissolution by acidic surface water where these rocks were exposed at or near the surface or in areas of thin overburden, and local reactivation of the paleokarst formed during earlier periods of exposure (Golder Associates Ltd. and Ontario Geological Survey 2008; Brunton and Dodge 2008; Brunton 2013). This is referred to as recent or modern karst in this study. Most shallow modern karst in southern Ontario has only limited depth of penetration of vertical conduits, probably due to erosional removal of the uppermost bedrock during Pleistocene glaciations and infill of karst openings with Quaternary sediments. Documented karst landform features in southern Ontario include karren, shallow caves, sinkholes, sinking streams and large springs. A much more complete description of the regional occurrence and geological relationships of shallow karst in southern Ontario and the history of its study is found in Brunton and Dodge (2008) and Brunton (2013), and for the Bruce Peninsula in Cowell (1976).

"Paleokarst", in the context of this study, is karst that formed in the geologic past during periods of subaerial exposure of carbonate and evaporite bedrock at major disconformities, with subsequent burial and preservation in the subsurface. These paleokarst horizons form regionally extensive intervals of enhanced porosity and permeability within the bedrock strata.

Mapping of modern karst in southern Ontario is compromised by the thick cover of surficial sediments, biasing visual identification of its distribution to areas of exposed bedrock (Brunton and Dodge 2008) (Fig. 4). Carter and Clark (2018) have identified large areas of inferred modern karst beneath surficial sediments using a GIS analysis of water well records from WWIS (Fig. 5). It includes the karst identified by Brunton and Dodge (2008), and also accurately delineates the "breathing well zone" in Huron County, a local karst aquifer in the Lucas Formation described by Freckelton (2012). Hamilton et al. (2017) have inferred the presence of large areas of karst beneath surficial sediments based on ratios of dissolved CO_2 and O_2 in shallow groundwater. Large areas of subcropping carbonate rocks in southern Ontario are identified as inferred or potential karst by Brunton and Dodge (2008) and Brunton (2013) based on their susceptibility to dissolution by meteoric and shallow groundwater. Modern karst has formed a complex shallow system of fresh groundwater, at depths from a few tens of metres to 200 m below the ground surface (Banks and Brunton 2017; Brunton et al. 2017; Priebe et al. 2019; Brunton and Brintnell 2020), the extent of which is still incompletely known.

At intermediate to deep depths within the bedrock, paleokarst horizons are the principal geological control on location of regional confined aquifers in the subsurface Paleozoic bedrock (Carter 2012; Carter and Fortner 2012; Sharpe et al. 2014). The most extensive paleokarst development is along disconformities at the top of the Lucas, Bass Islands, and Guelph formations and the unsubdivided Cambrian.

Joints and Fractures

At shallow depths there are ubiquitous regional stress-relief joints in the uppermost few metres of outcropping and subcropping bedrock especially near the edges of escarpments and bedrock gorges (e.g. Novakowski and Lapcevic 1988; Hancock and Engelder 1989; Eyles and Scheidegger 1995), which enhance permeability in the shallow bedrock (Fig. 6). Open vertical joints in subcropping carbonate strata may penetrate to several tens of metres as a result of solution widening and deepening. In the absence of karst, the apertures of vertical joints narrow rapidly with depth. At the Bruce site, in deeper bedrock, there is a dramatic decline in frequency of all types of fractures below 180 m depth (Intera Engineering Ltd. 2011).

Faults

Both normal faults and strike-slip faults have been identified in the bedrock of southern Ontario (Brigham 1971a, b; Armstrong and Carter 2010). The most prominent faults occur in the Chatham Sag. A fracture framework model developed by Sanford et al. (1985) indicated the Chatham Sag to be more fractured and faulted than the rest of southern Ontario. Maximum vertical displacement on normal faults is 50 to 100 m (Brigham 1971a, b; Carter 1991; Armstrong and Carter 2010). No recent analysis of the styles of faulting and timing of activity relative to regional orogenic events has been completed for southern Ontario.

Faults may form either barriers or pathways for lateral movement of groundwater in the subsurface. In the geologic past some of these faults have acted as pathways for vertical movement of groundwater across formation boundaries in southern Ontario, as indicated by dissolution, near faults, of subsurface salt beds in the Salina Group (e.g. Sanford 1977; Armstrong and Carter 2010). Collapse of younger strata over dissolution voids in subsurface salt beds can fracture the rocks, creating additional potential pathways for groundwater movement. Evidence of past movement of groundwater along a fault does not imply that the fault is currently a pathway for groundwater flow.

Preferential dolomitization of limestone of the Salina A-1 Carbonate and A-2 Carbonate has occurred along vertical

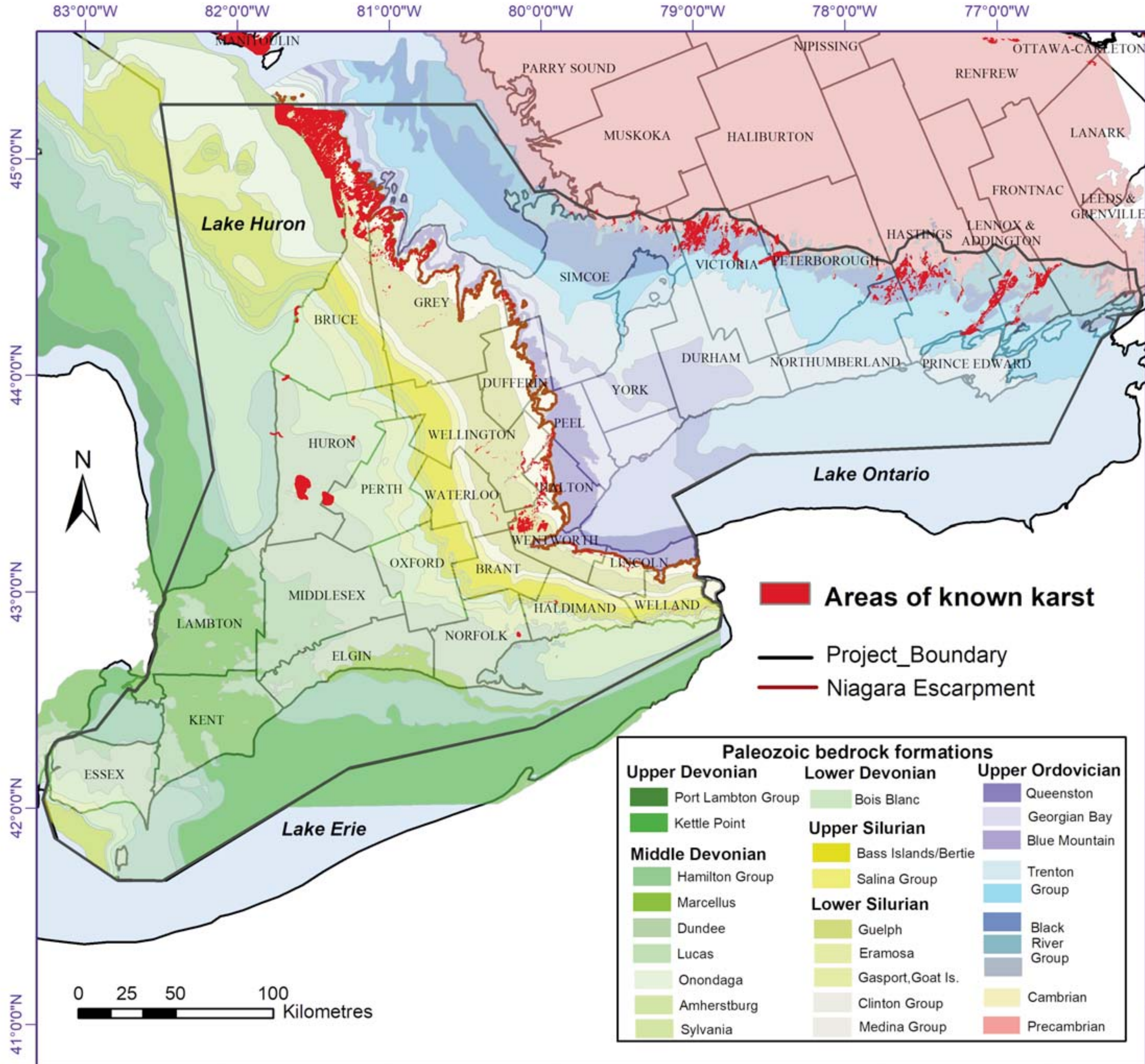

Figure 4. Areas of observed karst in southern Ontario, derived from Brunton and Dodge (2008). The limited mapped extent of karst reflects the masking effect of thick surficial sediments.

faults in Lambton County, presumably as a result of migration of formation water along the faults (Carter 1991). Reservoirs of natural gas occur in these dolomitized zones near the faults. Vertical cross-cutting "chimneys" of dolomite several hundred metres in width and several kilometres in length have formed in regional limestone units of the Trenton Group and Black River Group in Essex and Kent counties in association with vertical wrench faults (Middleton et al. 1993; Coniglio et al. 1994; Haeri-Ardakani 2013). Enhanced porosity and permeability in the dolomite have created reservoirs for crude oil and natural gas (e.g. Davies and Smith 2006, Dorland et al. 2016) and associated oil-field brine. There is no documentation of modern groundwater movement along faults in southern Ontario.

METHODOLOGY AND DATASETS

This study compiles and integrates a wealth of geological, hydrogeological, hydrochemical and isotopic data collected over the past 10 years by the authors and by others, to inform development of a high-level hydrostratigraphic framework for southern Ontario.

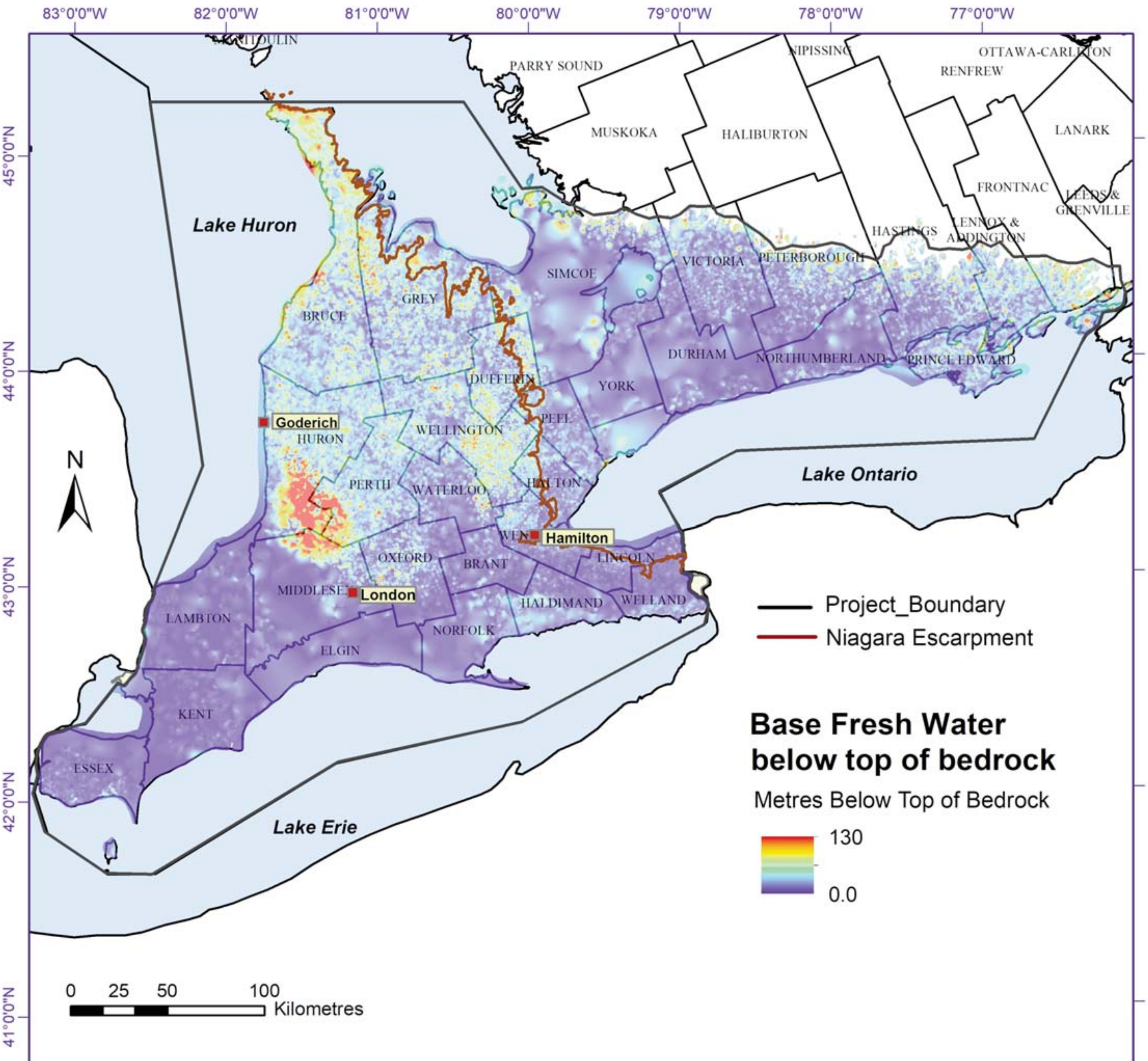

Figure 5. Map of the deepest reported occurrence of fresh water below the bedrock surface as recorded in water well records (from Carter and Clark 2018). Areas in red, green and yellow show fresh water occurring > 5 m below the top of bedrock and are inferred to indicate shallow modern karst. Areas in blue show fresh water at or immediately below the top of bedrock, inferred to represent the contact aquifer. The large red area between London and Goderich delineates the "breathing well zone" (Freckelton 2012) shallow karst aquifer in the Lucas and lower Dundee formations. Shallow karst immediately west of the Niagara Escarpment and in the Bruce Peninsula occurs within the Lockport Group.

The lithostratigraphy of southern Ontario is well-documented and recently updated (Brunton et al. 2017; Carter et al. 2017) and is the foundation for assignment of hydrostratigraphic units (HSU) using the concepts established by Maxey (1964). Unequivocal assignment of the complete thickness or geographic extent of individual lithostratigraphic units as an HSU is problematic in practice due to lateral and vertical inhomogeneity and anisotropy of formations due to facies changes, diagenesis, weathering and karstification, interbedded lithologies, etc. For the same reason there is no precise definition of aquifers or aquitards with respect to hydraulic conductivity. The terms aquifer and aquitard are used in a relative sense in this study, as recommended by Freeze and Cherry (1979). The water interval data from petroleum wells and the calculated probability of water occurrence within individual formations was a key criterion for identification of aquifers in the subsur-

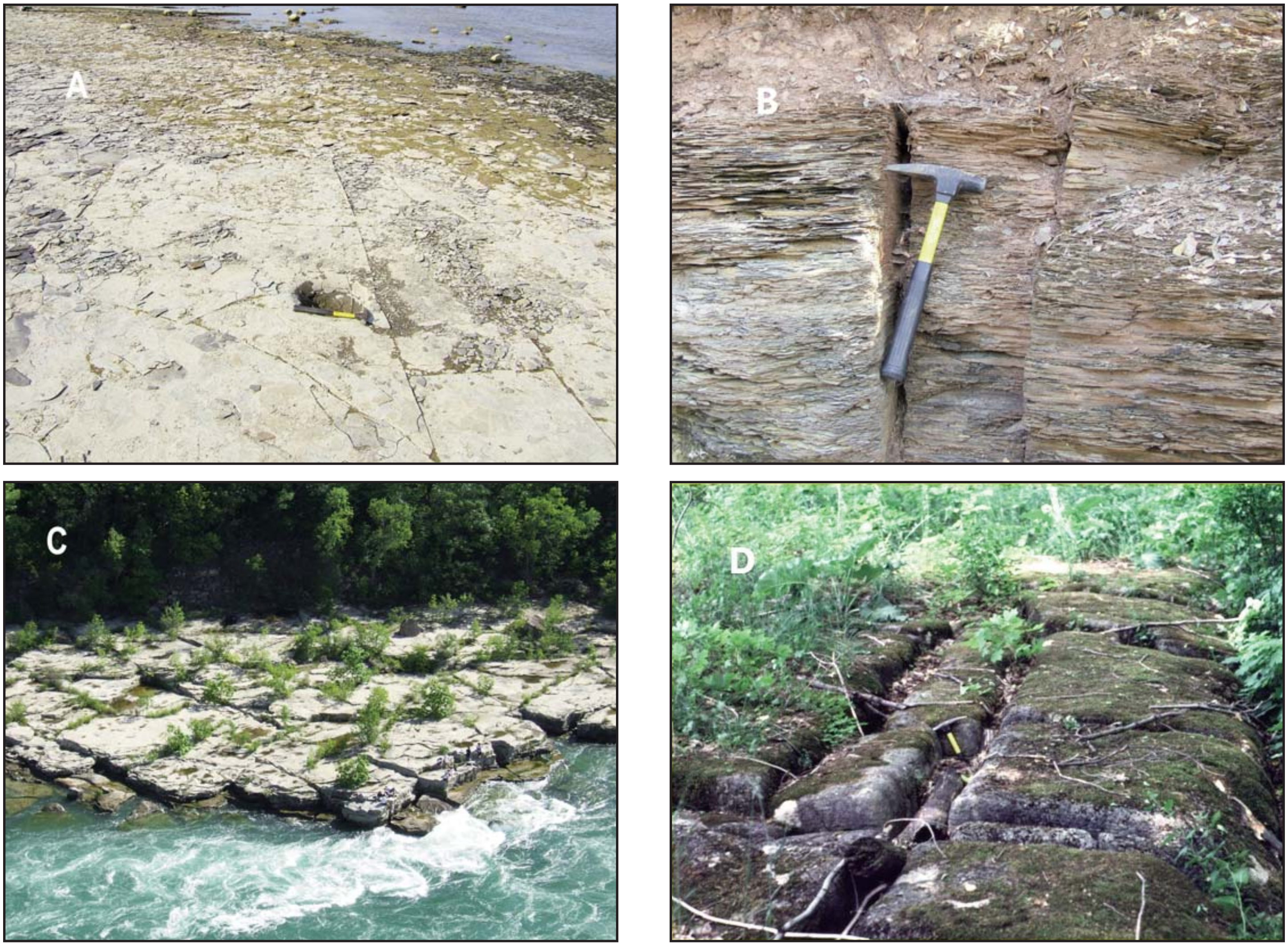

Figure 6. Examples of joints in outcropping bedrock in southern Ontario. A) Joints in black shale of the Kettle Point Formation in Lambton County on the shore of Lake Huron. B) Subvertical joints in Kettle Point shale showing decreasing aperture with depth. C) Widely spaced rectilinear jointing patterns in quartzose sandstone of the Whirpool Formation in the Niagara River. D) Solution widening of joints in Lockport Group dolostone in Bruce County.

face bedrock formations (see Table 1), together with the water interval maps of Carter et al. (2015a, b). In some instances, the available data do not allow an unequivocal assignment, in which case an interpretation has been made based on expert judgement and the weight of available data, subject to future revision. Water type varies with depth within individual aquifers and is not used to subdivide aquifers, but rather to define a regional hydrochemical depth zonation of groundwater within the aquifer systems.

Water interval records for petroleum wells are the principal data set used to identify regional groundwater intervals in the subsurface bedrock, and characterize bedrock formations as aquifers, aquitards or aquicludes. Specific to this study, bedrock formations intersected by petroleum wells drilled by the cable tool method, for which the driller has recorded the entry of water into the wellbore, are considered to be aquifers at the well location, regardless of the volume/flow, water type or commercial value of the water. The Ontario petroleum well database contains 35 000 discrete records of water-bearing intervals within wellbores. Carter et al. (2015a) documented the geographic and stratigraphic occurrence of groundwater by water type, in each of the subsurface Paleozoic bedrock formations in southern Ontario. Carter et al. (2015b) constructed static level maps for the principal bedrock aquifers to interpret regional hydraulic gradients. The approximate base of sulphur water has been interpreted by Carter and Sutherland (2020) using a GIS analysis of petroleum well water interval records.

For this study, groundwater mapping by the Ontario Geological Survey (OGS) is the principal source of information on potable groundwater in the shallow bedrock of southern Ontario. This includes mapping of modern karst aquifers (e.g. Priebe et al. 2012, 2019, 2021; Priebe and Brunton 2016; Brunton et al. 2017; Brunton and Brintnell 2020), and characterization and mapping of the hydrochemistry of shallow groundwater (McIntosh et al. 2014; Hamilton 2015; Hamilton et al. 2015). The base of fresh water in southern Ontario was interpreted by Carter and Clark (2018) using a GIS query of WWIS (Fig. 5).

Table 1. Water interval records from petroleum wells in southern Ontario documenting the number of wells that penetrate each geological formation, and the number of wells, by water type (see Table 2), for which a water interval is reported in the Ontario Petroleum Data System (OPDS). The water probability score represents the percentage of wells which encountered non-potable water and was a key criterion for designation of formations as either aquifers or aquitards. Reported fresh water intervals were excluded to eliminate both the effects of karstic dissolution at shallow depths, and fractured bedrock in the contact aquifer. The formations are in stratigraphic sequence from youngest to oldest, separated by geologic age with horizontal lines. See Carter et al. (2015a) for maps illustrating the geographical distribution of water intervals, coded by water type and formation.

Formation/ Unit	# Wells	# Water Records	Black	Brackish	Fresh	Lost Circ.	Mineral	Salt	Sulphur	Unknown	Water Probability*
Totals by type		34567	1797	112	14005	99	167	4670	12141	1576	
Surficial sediment	18005	5387	18	6	5050	1	10	26	171	105	
Port Lambton	132	27			23			1	2	1	3.0%
Kettle Point	4218	1027	4	1	958			14	27	23	1.6%
Hamilton	7719	944	3	2	636		2	61	121	119	4.0%
Dundee	12079	4311	21	19	1648	1	23	392	2096	111	22.0%
Columbus	2350	607	18	2	24		5	129	415	14	24.8%
Lucas	7236	3647	33	20	375	21	34	406	2640	118	45.2%
Amherstburg	7626	2276	86	5	1227	6	14	17	719	202	13.8%
Sylvania	1012	49	6		7	1	3	1	28	3	4.2%
Bois Blanc	8997	1888	60	15	611	3	12	69	1058	60	14.2%
Bass Islands	12181	3047	385	8	757	22	18	161	1561	135	18.8%
G Unit	9149	143	3	1	48	2	1	11	75	2	1.0%
F Unit	8501	1487	126	2	757	4	6	25	480	87	8.6%
F Salt	1419	9	1		1			3	2	2	0.6%
E Unit	8476	1308	109	3	660	3	3	20	432	78	7.6%
D Unit	3513	2			1	1				0	0.0%
C Unit	8279	378	26		173		3	2	136	38	2.5%
B Unit(B Marker)	6457	467	37		252	1	2	16	131	28	3.3%
B Salt	3257	11						9	1	1	0.3%
B Anhydrite	4142	41	2		19			1	15	4	0.5%
A-2 Carbonate	8542	604	23	2	144		2	247	153	33	5.4%
A-2 Shale	3312	11			2			8	1	0	0.3%
A-2 Anhydrite	6573	20						12	4	4	0.3%
A-2 Salt	2518	8						8		0	0.3%
A-1 Carbonate	7462	520	5	2	50	1	5	318	103	36	6.3%
A-1 Evaporite	3189	17						16	1	0	0.5%
Guelph	15606	4903	805	14	394	4	19	1828	1657	182	28.9%
Goat Island	4213	151			3	1		107	32	8	3.5%
Gasport	3765	148	1		6	1		110	26	4	3.8%
Rochester	12937	74	18		3	1	2	20	21	9	0.5%
Irondequoit	9666	27	3		5			15	1	3	0.2%
RRMF***	4299	53	2		8	1		8	4	30	1.0%
Thorold	2726	13						4		9	0.5%
Grimsby	10172	42			1			19	4	18	0.4%
Cabot Head	10125	26		1	11			10	3	1	0.1%
Manitoulin	2803	11			6			3	1	1	0.2%
Whirlpool	8409	40		2	3			31	3	1	0.4%
Queenston	10253	97	1	3	73		1	10		9	0.2%
Georgian Bay-Blue Mountain	1728	77		2	39			22	6	8	2.2%
Trenton**	1857	58			10		2	30	6	10	2.6%
Cobourg	1857	93	1		7	1		52		32	4.6%
Sherman Fall	1225	54			2	3		31	1	17	4.2%
Kirkfield	1001	32			3	2		17		10	2.9%
Black River**	999	16			2			11	1	2	1.4%
Coboconk	1205	51			2	6		34	1	8	4.1%
Gull River	979	60		2	2	9		37	1	9	5.9%
Shadow Lake	1007	16			1	2		12	1	0	1.5%
Cambrian	896	289			1	1		286		1	32.1%

* % of wells that encountered water, water type ≠ Fresh **unsubdivided ***Reynales-Rockway-Merriton-Fossil Hill

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Published hydraulic conductivity measurements were compiled for this study, as described below, and provide valuable data on flow rates of groundwater within bedrock formations. Published isotopic and hydrochemical data for groundwater in the bedrock were reviewed and supplemented with new data, to provide insights on groundwater types, source, history of evolution, and delineation of groundwater regimes.

Field visits were an important component contributing to geological understanding. All known sulphur water springs west of the Niagara Escarpment were visited and sampled. Quarries provided bedrock exposures facilitating direct observations of the relationships between groundwater flow and stratigraphy. More than 20 quarries west of the Niagara Escarpment were visited, including the McGregor Quarry in Essex County, the Port Dover Quarry in Norfolk County, the St. Marys Quarry in Perth County, the Bowmanville Quarry in Durham County, the Picton Quarry in Prince Edward County, the Guelph Dolime Quarry in Wellington County, all building stone quarries in Bruce County, the Sydenham Quarry in Grey County, the Pelee Island Quarry, the Beachville and Woodstock quarries in Oxford County, the Cayuga Quarry in Haldimand County, the Ridgemount Quarry in Welland County, and the Vineland Quarry and Beamer Quarry in Lincoln County.

Well Databases

Data are available primarily from one of two datasets, the Ministry of Environment, Conservation and Parks water well information system (WWIS) and the Ministry of Natural Resources and Forestry (MNRF) Ontario Petroleum Data System (OPDS) co-managed by the Oil Gas and Salt Resources Library (OGSRL; www.ogsrlibrary.com). WWIS is the principal source of regional data on shallow groundwater in southern Ontario (data.ontario.ca) with records for over 400 000 water wells in southern Ontario, of which 160 000 penetrate bedrock (Carter and Clark 2018). OPDS well records are the principal source of geological and hydrogeological information at deeper depths with records for nearly 27 000 wells (Fig. 7).

Water Type Data in the Ontario Petroleum Data System

The water types reported from petroleum wells are subjective descriptions by drillers of groundwater encountered during drilling and are similar to the types recorded in the WWIS (Table 2). In OPDS, the geological formation within which the water is encountered is identified and recorded, using terminology consistent with Armstrong and Carter (2010).

In this study, description of water salinity uses the terminology of Carpenter (1978) and Freeze and Cherry (1979) (Table 3). The subjective water type identified as salt water (SAL) includes saline water and brine, with no odour of dissolved H_2S. Sulphur water (SUL) is brackish to saline water that has an odour of dissolved H_2S.

OPDS contains records for nearly 35 000 water intervals (Table 1). Drillers record the depth at which water enters the well bore, the subjective water type, and the static level it stabilizes at within the wellbore before the zone is sealed off by casing. For the most part, only wells drilled by the cable tool method have water records as they are drilled in an open system with no hydraulic pressure, which allows groundwater to flow freely into the borehole.

Isotopic and Hydrochemical Data

Geochemical and isotopic characterization of deep groundwater in southern Ontario has been undertaken by several studies (McNutt et al. 1987; Dollar 1988; Dollar et al. 1991; Kaufman et al. 1993; Wilson and Long 1993; Weaver et al. 1995; Husain et al. 1998, 2004; Shouakar-Stash 2008). Skuce (2014) and Skuce et al. (2015a, b) acquired isotopic and geochemical fingerprints of 130 samples of intermediate to deep groundwater in southern Ontario in support of the current study. Most samples from intermediate to deep depths were obtained from active petroleum wells. Additional samples from shallow to intermediate depths were obtained from quarries, springs and artesian flow of water to the surface from orphan petroleum wells or deep water wells. Geochemical parameters analyzed included Na, Ca, Mg, K, Si, Sr, Br, Cl, SO_4, HCO_3, sulphide, and 24 trace elements. The oxygen and hydrogen isotope compositions of water ($\delta^{18}O$ and $\delta^{2}H$, in ‰ relative to Standard Mean Ocean Water – VSMOW) were also measured.

Petrophysical, hydrochemical and isotopic analyses of 1214 samples were obtained from eight deep diamond drill holes in the Paleozoic bedrock at the Bruce site (AECOM Canada Ltd. and Itasca Consulting Canada Inc. 2011; Hobbs et al. 2011; Intera Engineering Ltd. 2011; NWMO 2011; NWMO and AECOM Canada Ltd. 2011; Sykes et al. 2011). These studies included detailed depth profiles of stable isotopic ratios and hydrochemistry of groundwater and pore water in Paleozoic bedrock formations at the site.

As part of a regional ambient water chemistry survey, Hamilton (2015) collected over 900 samples of fresh water from domestic water wells completed in surficial sediments and in shallow bedrock at the interface with the sediments. Samples were analysed for a large suite of parameters, dissolved gases, major ions, trace elements, and stable isotopes of water. An additional 106 samples of fresh water were obtained from water wells completed in a shallow karst aquifer in the Lucas Formation in Huron County (Freckelton 2012).

Hydraulic Conductivity

Hydraulic conductivity measurements have been published for scattered locations in southern Ontario and have been compiled for this study (Table 4) (Novakowski and Lapcevic 1988; Intera Technologies Ltd. 1988; Raven et al. 1990, 1992; Weaver 1994; Golder Associates Ltd. 2003; Intera Engineering Ltd. 2011; Sykes et al. 2011; Beauheim et al. 2014; Priebe et al. 2017). Formations with relatively higher hydraulic conductivity correlate very well with observations of water-bearing intervals in petroleum wells.

Minimum and maximum values for individual formations can vary by several orders of magnitude at the same site. Such variation can be caused by variations in lithology, diagenesis, facies changes, and karst. Most of these measurements were acquired at shallow depths, less than 200 m below the surface.

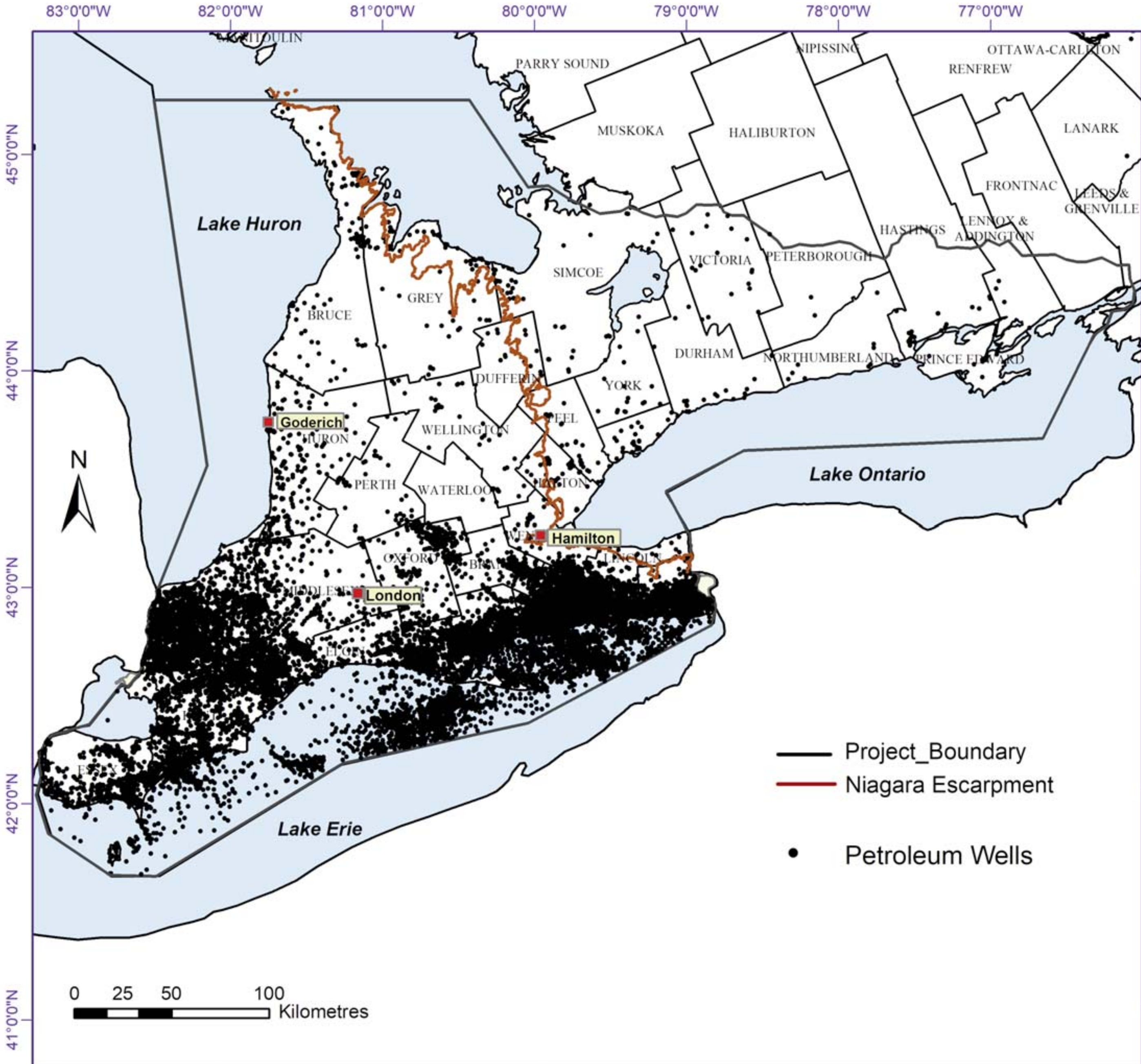

Figure 7. Locations of petroleum wells drilled in southern Ontario showing highly variable well density.

Table 2. Ontario Petroleum Data System (OPDS) water type codes and descriptions.

Water Type Code	Description
BLK	Black
BRA	Brackish
FRE	Fresh
LOS	Loss of circulation
MIN	Mineral
SAL	Salt
SUL	Sulphur

Table 3. Water types classified by salinity, as per Carpenter (1978) and Freeze and Cherry (1979).

Water Type	mg/L TDS
Fresh	0–1000
Brackish	1000–10 000
Saline	10 000–100 000
Brine	> 100 000

https://doi.org/10.12789/geocanj.2021.48.172

Table 4. Hydrostratigraphic units defined in this study, with hydraulic conductivity values and source reference: (a) Priebe et al. 2017; (b) Novakowski and Lapcevic 1988; (c) Intera Technologies Ltd. 1988; (d) Golder Associates Ltd. 2003; (e) Intera Engineering Ltd. 2011, Beauheim et al. 2014; (f) Weaver 1994; (g) Raven et al. 1990, 1992; (h) Sykes et al. 2011; (i) Freeze and Cherry 1979.

Hydrostratigraphic Unit	Included Formations	Water Type	Hydraulic Conductivity m/s	Reference
HSU 1. Surficial Sediment System	Glacial and modern sediments	fresh	10^{-1} to 10^{-12}	i
HSU 2. Contact Aquifer	Interface of surficial sediments & bedrock	fresh, brackish	$1×10^{-5}$	g
HSU 3. Shallow Karst Aquifer System	Carbonate bedrock subcrop/outcrop	fresh	$5×10^{-3}$ to $6×10^{-7}$	a, b, e, g
HSU 4. Devonian Aquitard	Port Lambton Group, Kettle Point, Hamilton Group, Marcellus, upper Dundee	nil	$1×10^{-7}$ to $4×10^{-13}$	c, f, g
HSU 5. Lucas-Dundee Aquifer	lower Dundee, Lucas	sulphur, brackish, saline	$1×10^{-6}$ to $8.4×10^{-8}$	c, f, g, h
HSU 6. Amherstburg-Bois Blanc Aquitard	Amherstburg, Bois Blanc, Springvale, Sylvania, Onondaga	nil	$1×10^{-6}$ to $3.2×10^{-11}$	c, e, g
HSU 7. Bass Islands Aquifer	Bass Islands, Bertie, Oriskany	sulphur, saline, brackish	$1×10^{-4}$ to $1×10^{-7}$	c, e, h
HSU 8. Salina Aquitard	Salina Group	nil	$3×10^{-10}$ to $5×10^{-14}$	e
HSU 9. Guelph Aquifer	Guelph	brine, sulphur	$2.8×10^{-4}$ to $7.9×10^{-9}$	e, g
HSU 10. Lower Lockport Aquitard	Eramosa, Goat Island, Gasport	nil	$4×10^{-8}$ to $2×10^{-12}$	a, b ,g
HSU 11. Clinton-Medina Aquitard	Clinton Group, Medina Group	nil	$5×10^{-12}$ to $9×10^{-14}$	b, e, g
HSU 12. Ordovician Shale Aquiclude	Queenston, Georgian Bay, Blue Mountain	nil	$1×10^{-8}$ to $3×10^{-14}$	b, e, g
HSU 13. Trenton-Black River Aquitard	Trenton Group, Black River Group	nil	$1×10^{-11}$ to $4×10^{-15}$	c, d, e, g, h
HSU 14. Cambrian Aquifer	All Cambrian formations	brine	$3×10^{-6}$ to $1×10^{-9}$	e
HSU 15. Precambrian Aquitard	Precambrian	nil	$1×10^{-9}$ to $1×10^{-12}$	e

At these depths much of the bedrock has been affected by infiltration of meteoric water, with enhancement of porosity and permeability in carbonate and evaporite bedrock by karstic dissolution. At the Bruce site high quality permeability data from the complete Paleozoic stratigraphic sequence was obtained from a total of 88 test intervals for six deep boreholes (Intera Engineering Ltd. 2011; Beauheim et al. 2014). The Bruce dataset is unique in Ontario for the amount and vertical continuity of data available at a single site, and for the depth at which most of the data was obtained, well below the effects of modern or glacial groundwaters.

HYDROCHEMICAL GROUNDWATER REGIMES AND HYDROGEOLOGICAL MODEL

The aquifer and aquitard systems of southern Ontario are developed within a superimposed hydrochemical regime, with zonation by depth consistent with the progression documented by Chebotarev (1955), Sykes et al. (2011), McIntosh and Walter (2006) and Hobbs et al. (2011). A similar hydrochemical depth zonation in sedimentary bedrock in the United States was reported by Stanton et al. (2017). Three groundwater hydrochemical regimes can be recognized in southern Ontario:

1. A **shallow water regime** of predominantly bicarbonate-rich fresh water occurs in the unconsolidated glacial and recent sediments and shallow bedrock to a depth of approximately 100 to 250 m beneath the surface.
2. An **intermediate water regime** of brackish to saline sulphur and sulphate-rich water occurs beneath the shallow zone to a maximum depth of approximately 350 to 400 m.
3. A **deep water regime** of ancient water, dominated by dense Na−Cl and Ca−Na−Cl brine, occurs in the deep bedrock extending to the Precambrian rocks of the Canadian Shield that underlie Paleozoic cover.

Depths of the water regimes vary geographically, influenced by the geomorphology, surficial geology, and outcropping or subcropping bedrock geology. Where shale outcrops or subcrops, brackish to saline water is present within a few metres of the bedrock surface and fresh water is largely confined to the surficial sediments and the interface between the sediments and the bedrock (see Fig. 5). In areas of shallow modern karst, fresh water of the shallow water regime has penetrated much deeper into the bedrock.

A revised and updated hydrogeological model is presented here (Fig. 8). Most of the confined aquifers at shallow to intermediate depths in the bedrock are recharged by meteoric water through shallow modern karst at their outcrop and subcrop edges, with down-dip hydraulic gradients along formation contacts. The depth of penetration of meteoric water depends on the permeability of the formation, including the degree of karstification, the lateral continuity of the permeable horizon, the hydraulic gradient, and the buoyancy effects of saline water and brine in the deeper bedrock formations. Hydrochemistry and $\delta^{18}O$ and $\delta^{2}H$ compositions suggest the original pre-Pleistocene groundwaters in the intermediate regime have mixed with and largely been replaced by both modern and cooler climate fresh waters, probably as a result of enhanced fluid flow and recharge beneath the LIS during the last glacial maximum (Bense and Person 2008; McIntosh et al. 2011), as discussed below. These waters have subsequently been altered by

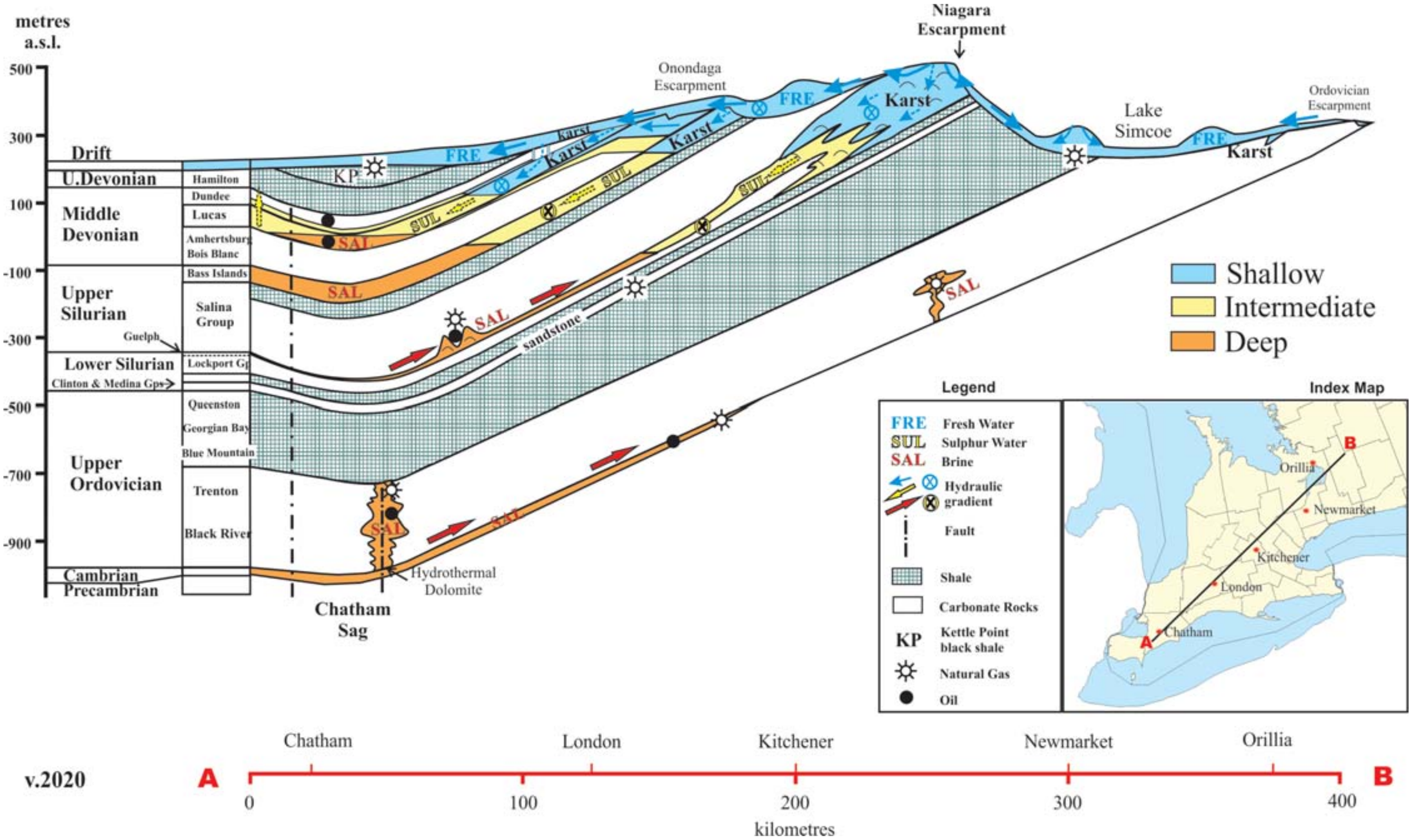

Figure 8. Conceptual model of regional groundwater regimes in the surficial sediments and bedrock of southern Ontario showing hydrochemical depth zonation on a scaled cross-section of southern Ontario. Aquifers are colour-coded as shallow, intermediate, and deep. All other formations are aquitards. Flow directions in the shallow regime are topographically controlled with penetration into subsurface bedrock through shallow modern karst. Hydraulic gradients from the shallow to intermediate regime are down-dip along bedrock paleokarst horizons with only limited active recharge and discharge, and up-dip in the deep brine regime, with no active recharge or discharge.

water−rock interactions and biochemical processes, also discussed below.

Shallow Groundwater Regime

Within the shallow groundwater regime three distinct hydrogeological systems are recognized and designated as hydrostratigraphic units: surficial sediment aquifer−aquitard system, contact aquifer, and shallow karst aquifer. These groundwater systems correspond to the three shallow systems of Sharpe et al. (2014) and are described in more detail below. All domestic water wells in southern Ontario acquire potable groundwater from the shallow groundwater regime.

Flow directions in the shallow groundwater regime above the bedrock−overburden interface are principally down-gradient from topographic highs (Sharpe et al. 2014). Shallow modern karst is the entry point for groundwater penetration into subsurface bedrock, within which regional hydraulic gradients are down the regional dip of porous bedrock formations (Fig. 8).

The deepest reported occurrence of fresh water in water well records is 130 m below the top of bedrock (Fig. 5) and approximately 175 m below the ground surface. Fresh water is reported in petroleum well records at depths of up to 250 m below the surface, approximately 200 m below top of bedrock (Carter and Clark 2018). The variability in the reported depth to the base of fresh water largely reflects the practice of water well drillers to terminate drilling at the shallowest interval from which a fresh water supply can be obtained. Therefore, it is expected that the actual depth to the base of fresh water, at least locally, may be significantly greater than documented in water well records.

Groundwater in the shallow regime is generally fresh and is locally brackish to sulphurous. Water composition is dominated by Ca-HCO_3 and Ca-SO_4, with pH values ranging from 6.2 to 8.8, and a total dissolved solids (TDS) content averaging 770 mg/L (calculated from Hamilton 2015). In a regional shallow groundwater characterization study covering all southern Ontario, the $\delta^{18}O$ and δ^2H compositions of fresh groundwater were determined by Hamilton et al. (2015) for 596 samples from water wells finished at shallow depths into bedrock or at the bedrock−sediment interface. All samples plot on the local meteoric water line for Simcoe, Ontario. The $\delta^{18}O$ values of most of these samples range from –13 to –10‰, similar to modern meteoric-sourced groundwater, with a secondary modal peak at –17‰ which was interpreted as glacial meltwater.

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Figure 9. Sulphur oxidizing bacteria associated with sulphur water discharge: A) Sticky yellowish-white bacterial mat coating vertical face of Dundee Formation limestone at Port Dover Quarry in Norfolk County, beneath sulphur water discharge along horizontal bedding plane parting; B) White filamentous sulphur-oxidizing bacteria in sulphur water spring at contact of Dundee Formation with underlying Onondaga Formation at Hemlock Creek in Norfolk County. Heel of boot is 8 cm wide.

Intermediate Brackish-to-Saline Sulphur Water Regime

Brackish to saline sulphur water (water containing dissolved H_2S) is ubiquitous at intermediate depths varying from a few tens of metres to a maximum of 350 m below ground level (Carter and Sutherland 2020). It occurs in all formations but is particularly prominent in regional bedrock aquifers in the Lucas and lower Dundee, the Bass Islands, and the Guelph formations (Carter et al. 2015a). The deepest occurrence of sulphur water is in areas of modern post-glacial karst where the fresh water regime is also deepest. Hydraulic gradients are down the regional dip of bedrock formations. Sulphur water from the Lucas and lower Dundee formations discharges to the surface in topographic lows at several locations in southern Ontario, including springs, water wells, unplugged petroleum wells, and as seeps in the floor and walls of quarries, indicating a locally active flow system. Regional flow direction is from northeast to southwest, down the regional dip of the bedrock formations.

Groundwater studies in the Midwest Basins and Arches Aquifer System in parts of Indiana, Ohio, Michigan, and Illinois indicate as little as 2% of the shallow fresh groundwater enters the bedrock aquifer system (Eberts and George 2000). Comparable estimates for southern Ontario have not been made but the limited number of known sulphur water discharge sites, with their distinctive and easily detected olfactory signature, suggests that active recharge from the shallow water regime is limited.

Where sulphur water flows to the surface the discharged water is often populated by white filamentous colonies of sulphur-oxidizing proteobacteria and/or sticky yellow bacterial films and mats (Fig. 9) and has a foul rotten-egg odour indicating the presence of dissolved H_2S. Dissolved H_2S is a diagnostic field indicator of the presence of sulphate-reducing delta proteobacteria in the groundwater (Dyer 2003). These bacteria utilize oxygen from dissolved sulphate to oxidize organic matter under anoxic conditions, with H_2S released as a waste product. Microbial DNA analyses of sulphur water samples collected by the first author from the lower Dundee Formation in Norfolk County show abundant and diverse microbial populations dominated by sulphur proteobacteria (J. Neufeld personal communication 2015).

Similar microbial communities were reported by Ruberg et al. (2008) on the floor of Lake Huron near Middle Island in Michigan, where springs of sulphur water from a regional aquifer in the Detroit River Group fill a submerged karst sinkhole. They report long white strands of sulphur oxidizing bacteria and purple microbial mats coating the walls and floor of the sinkhole. The groundwater entering the sinkhole had an average temperature of 10 to 12°C, with elevated concentrations of chlorides, sulphates, and bacteria relative to lake water.

Groundwater in the intermediate regime has pH of 7.2 to 11.7 and is brackish to saline (563 to 43 600 mg/L TDS). Its composition ranges from $Ca-SO_4$ to $Na-Ca-Cl$ to $Ca-Na-Cl$ with generally elevated levels of sulphate relative to the deep brine regime, and generally low levels of other dissolved elements. Isotope ratios of oxygen and sulphur in the dissolved sulphate in samples analyzed by Skuce (2014) range from +12.2 to +53.9‰ $\delta^{34}S_{SO4}$ and +8.7 to +19. 9‰ $\delta^{18}O_{SO4}$, and are consistent with an origin from dissolution of evaporite minerals (anhydrite, gypsum) in the bedrock formations (Skuce 2014; Skuce et al. 2015a, b). They also confirm that bacterially mediated dissimilatory sulphate reduction is active in the shallow groundwater systems (Skuce 2014). The oxygen and hydrogen isotope compositions for the water plot close to the Global Meteoric Water Line of Craig (1961) with values ranging from those typical of modern precipitation in the study area to those more characteristic of Pleistocene glacial meltwater (Skuce 2014; Skuce et al. 2015a, b).

Deep Brine Regime

The confined aquifers in the deep regime contain dense brines with pH values from 3 to 7, and measured salinities from

138 000 to 441 000 mg/L TDS, dominated by sodium and calcium chlorides (Dollar et al. 1991; Hobbs et al. 2011; Skuce 2014; Skuce et al. 2015a, b).

The depth at which the brine system occurs depends on the presence or absence of aquitards in the overlying bedrock and distance down-dip from subcrop. In areas where shale comprises the uppermost bedrock there is very shallow penetration of fresh water and the brine system begins at depths as shallow as 200 m, as confirmed by hydrochemical analyses of formation water (Skuce 2014; Skuce et al. 2015b). In areas of modern shallow karst, petroleum well records indicate that the brine regime does not begin until a depth of 350 m below the ground surface. At depths of > 350 to 450 m petroleum well records indicate that all groundwater in the Paleozoic bedrock is brine. This is corroborated at the Bruce site by analyses of pore water extracted from crushed drill core which show increasing salinity to depths of 350 to 400 m below which a Na−Cl basinal brine exists (Intera Engineering Ltd. 2011). This water is often referred to as formation water.

The $\delta^{18}O$ and $\delta^{2}H$ of the deep brines (Dollar 1988; Dollar et al. 1991; Weaver 1994; Skuce 2014; Skuce et al. 2015a) plot well to the right of the Global Meteoric Water Line of Craig (1961) with unique isotopic compositions for different aquifers having developed over extended periods of geologic time. The isotopic compositions are typical of sedimentary basin brines formed by evaporative concentration of seawater (Holser 1979; Knauth and Beeunas 1986) in a sabkha or salina depositional environment, such as that under which deposition of the Salina Group and Lucas Formation occurred. Such an origin is also consistent with the extremely high salinities.

Flow model simulations (Sykes et al. 2011) indicate that brines have been trapped in these rocks for millions of years. Clark et al. (2013) have calculated a residence time of at least 260 million years for brine trapped as pore water within the Ordovician shale units.

Static level maps prepared using OPDS water interval data indicate up-dip hydraulic gradients for brine in the Guelph Formation and Cambrian units (Carter et al. 2015b) similar to calculated gradients at the Bruce site (Intera Engineering Ltd. 2011). There is no known natural discharge of deep brines to the surface.

EFFECTS OF GLACIATION ON GROUNDWATER

Glaciation of North America had a profound effect on groundwater systems. Greatly increased hydraulic gradients would have been produced by pressurized subglacial meltwater beneath the LIS, resulting in deep penetration of fresh water into porous and permeable bedrock formations, flushing out and/or diluting the original formation waters. Glacial meltwater can be identified by low $\delta^{18}O$ and $\delta^{2}H$. Glacial meltwater $\delta^{18}O$ values compiled by McIntosh and Walter (2006) for Michigan, northern Indiana/Ohio and southern Ontario range from –25 to –11‰, and an average $\delta^{18}O$ of –25.4 ± 2.5‰ is commonly ascribed to the LIS (Ferguson and Jasechko 2015).

Isotopic evidence has been cited to indicate the presence of meteoric water of likely glacial origin in clay-rich glacial sediments (Desaulniers et al. 1981; Aravena at al. 1995), in the contact aquifer (Husein et al. 2004; Skuce 2014; Hamilton et al. 2015), and in the intermediate groundwater regime (Dollar 1988; Skuce 2014; Skuce et al. 2015a). At the Bruce site, at a depth of 340 m, saline pore water from a 4-m thick paleokarst interval in the uppermost Salina A-1 Carbonate Unit had isotopic compositions of $\delta^{18}O$ = –14.4‰ and $\delta^{2}H$ = –104‰ (Intera Engineering Ltd. 2011), suggestive of glacial meltwater. A sub-regional sulphur water interval at the top of the A-1 Carbonate identified by Carter and Sutherland (2020) extending east to the subcrop belt is the likely pathway for down-dip penetration of glacial meltwater, a distance of 25 km.

Sulphur water samples from the lower Dundee Formation, immediately east of the pinch-out edge of the Lucas Formation in Norfolk County, were obtained from seepage into the Port Dover Quarry, within the subcrop belt, and from four unplugged petroleum wells exhibiting artesian flow at the surface in the valleys of Big Creek and Big Otter Creek in Norfolk County, at successively deeper depths down-dip from the subcrop. The $\delta^{18}O$ and $\delta^{2}H$ of the groundwater decrease progressively down-dip and with increasing depth (from 10 to 83 m below ground surface) from –7.8 to –14.8‰ for $\delta^{18}O$ and from –54 to –102‰ for $\delta^{2}H$ (Fig. 10). The values are lowest where the Dundee Formation is overlain by black shale of the Marcellus Formation which forms a barrier to vertical infiltration of modern meteoric water, and highest at the Port Dover Quarry where stripping of unconsolidated sediments has exposed the Dundee Formation at the surface. The hydraulic gradient within the shallow bedrock in this area is down-dip, from north to south, with active flow as indicated by the artesian discharge. The results are interpreted to indicate the

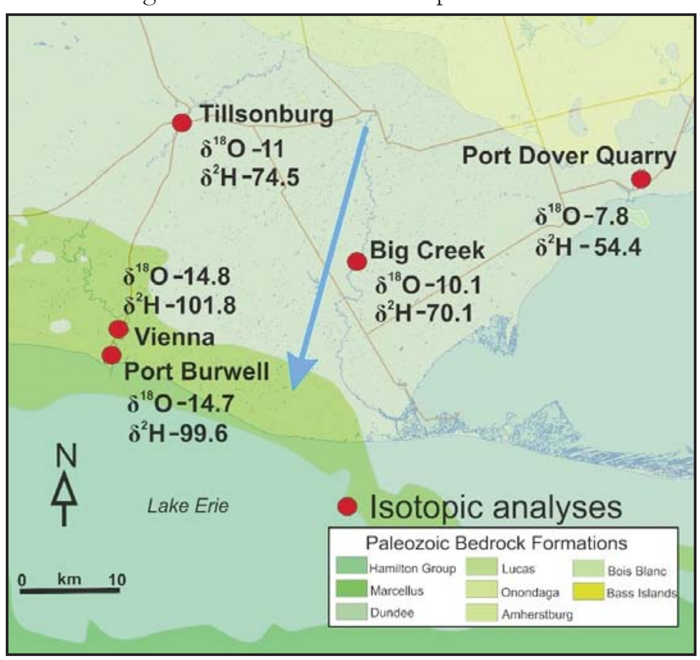

Figure 10. Isotopic results for sulphur water samples from the Lucas Formation and lower Dundee Formation, Norfolk and Elgin counties, southern Ontario, showing progressively lower $\delta^{18}O$ and $\delta^{2}H$ (‰, VSMOW), with increasing depth, in a down-dip direction, interpreted to indicate a transition from modern meteoric water to water of likely glacial origin over a down-dip distance of 20 to 25 km. Arrow shows regional dip of bedrock formations and regional groundwater flow direction.

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down-dip penetration of glacial meltwaters into the deeper portions of the lower Dundee Formation, with more recent infiltration of modern meteoric water at shallow depths.

These observations are consistent with studies by McIntosh and Walter (2006) and McIntosh et al. (2012) documenting extensive large-scale infiltration of Pleistocene glacial meltwaters into Silurian−Devonian carbonate aquifers around the margins of the Illinois and Michigan basins. Finite-element model simulations of groundwater flow beneath the LIS demonstrate the potential for deep penetration of dilute glacial meltwaters into the carbonate aquifers of the Michigan Basin and displacement of saline formation waters (McIntosh et al. 2011).

HYDROSTRATIGRAPHIC UNITS (HSU)

Following hydrostratigraphic protocols and nomenclature of Maxey (1964) and Seaber (1988) hydrostratigraphic units (HSU) are referenced by the names of their host lithostratigraphic units, are predominantly either aquifers or aquitards, and have unique lithology, sedimentary structures and facies, and hydrogeological properties. In this study, hydrostratigraphic assignment and classification is primarily based on hydrogeological properties of the rocks at intermediate to deep intervals in the subsurface in order to isolate the effects of modern karstic dissolution in the shallow regime. Except within paleokarst horizons, carbonate and evaporite rocks usually form aquitards and even aquicludes in the intermediate to deep subsurface, but at shallow depths these same rocks may form shallow karstic fresh water aquifers. These up-dip transitions from aquitard to aquifer make unequivocal assignment of hydrostratigraphic units problematic. Further, some of these transitions must be inferred or interpreted due to gaps in borehole coverage and data collection.

The definition of a HSU as an aquifer is not meant to imply an active flow system. In most cases they probably are not active but we note that it is not possible to identify unique recharge and discharge at the scale of the study. As discussed above, in the deep groundwater system the basinal brines are static, with no modern discharge or recharge. In the intermediate system there is local evidence of recharge, in particular by glacial meltwater, but only limited discharge to the surface. Flow systems in karstic bedrock can be identified in the shallow groundwater regime but they are generally local or subregional with dominant flow directions directed along strike rather than down-dip (e.g. Priebe et al. 2021).

Water interval records from petroleum wells are the primary source of data for assignment of lithostratigraphic units as either aquifers or aquitards. Maps showing the geographic distribution of the reported water intervals by water type for each formation have been prepared by Carter et al. (2015a). As discussed above, for all bedrock formations, fresh water is encountered in the subcrop belts. This water occurs within near-surface unconfined or partially confined aquifers, within either the contact aquifer or shallow karst aquifer system. Within confined bedrock aquifers in the intermediate to deep groundwater regimes, drillers have not reported the occurrence of fresh water.

A regional, generalized assignment of lithostratigraphic units as aquifers, aquitards, and aquicludes is presented as a hydrostratigraphic chart in Figure 11. The chart is synthesized from all the stratigraphic, hydrogeological, isotopic and hydrochemical data and geological observations discussed above. Fifteen regional hydrostratigraphic units are proposed in this study (Table 4).

For clarity, there is no inference that hydrostratigraphic units classified as aquifers are uniformly porous and permeable. As documented below, in some aquifers water flow may be concentrated along a few very thin intervals, such as solution-widened bedding plane partings, which may be only a few millimetres or centimetres in thickness. Hydrostratigraphic units comprised of interbedded rock types and exhibiting lateral facies changes may have considerable variation in permeability. A HSU classed as an aquitard may include formations with such low hydraulic conductivity that they can be considered as aquicludes (see HSU 13).

HSU 1: Surficial Sediment Aquifer/Aquitard System

Details on the surficial sediment groundwater system are beyond the scope of this study, but a brief summary is provided as over 90% of the area is covered by surficial sediment and it is a critical component of the Contact Aquifer. The surficial sediment system comprises all the unconsolidated glacial and modern sediments that overlie the Paleozoic bedrock and forms a complex system of aquifers and aquitards. Deposits can be up to 250 m thick (Gao et al. 2006; Gao 2011) and consist of a mixture of clastic sediments in a variety of low-relief glacial landforms with rapid changes in thickness and poor lateral continuity. This leads to complex local groundwater flow patterns that can vary significantly over lateral distances of 100s or 1000s of metres (Singer et al. 2003; Sharpe et al. 2014). Coarse-grained sediments (gravel, sand) generally form aquifers and very fine-grained sediments (mud, clay) form aquitards. Therefore, aquifers within the overburden generally have limited geographic extent and predictability compared to bedrock aquifer systems.

Unconsolidated sediments usually exhibit much greater porosity than bedrock formations with pore space of up to 40 to 50% in coarse gravel and sand deposits (Sharpe et al. 2014). Areas of thick sediments in glacial moraines and buried bedrock valleys have the largest groundwater storage capacity. Typical rates of flow exhibit a very large range, from ~1000 to 0.00001 mm per day (Sharpe et al. 2014). The irregular topography also slows runoff and contributes to percolation of rainfall into the subsurface. The water is generally fresh, with local quality constraints.

Precipitation readily penetrates these sediments except in thick deposits of clayey till and glaciolacustrine clay and silt. In these clay-rich areas vertical flow velocities are so low that much of the groundwater originated during the late Pleistocene (Desaulniers et al. 1981; Aravena et al. 1995).

HSU 2: Contact Aquifer System

The Contact Aquifer HSU occurs at the contact between bedrock and surficial sediments and consists of the first few

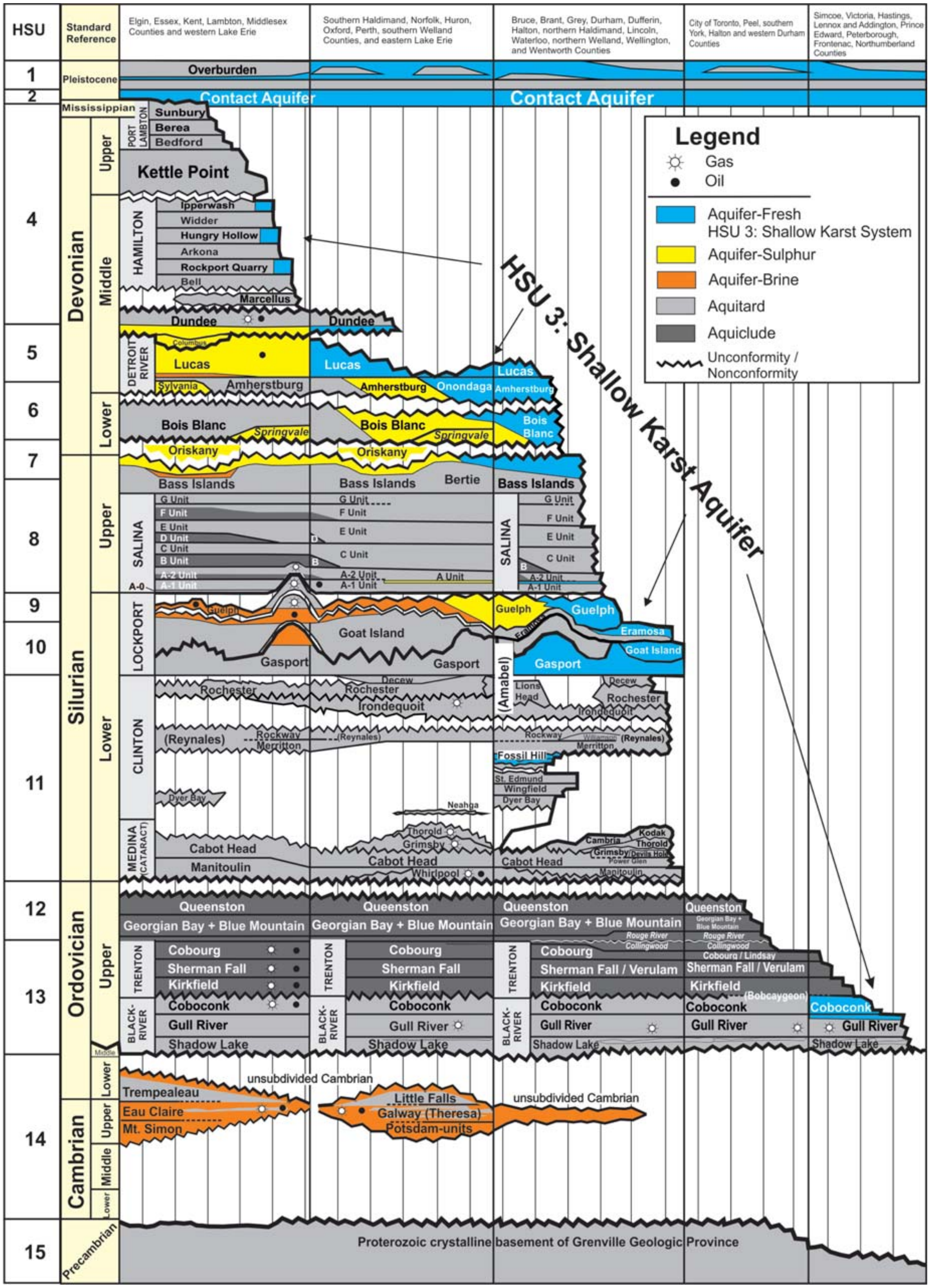

Figure 11. Hydrostratigraphic chart showing generalized assignment of bedrock lithostratigraphic units as regional aquifers, aquitards and aquicludes, and their HSU designations. The shallow karst aquifer system includes all fresh water aquifers in the subcropping carbonate bedrock, with the exception of the contact aquifer. Not included are isolated accumulations of brine in oil and gas reservoirs. The close relationship between regional disconformities and aquifers is directly related to the development of paleokarst at these intervals.

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metres of fully saturated jointed and fractured bedrock and the lowermost few metres of overlying sediment (Fig. 12). The water in the jointed bedrock and surficial sediment are in hydraulic communication and form one HSU with two quite different porosity systems: fracture porosity in the bedrock versus intergranular porosity in the sediment (e.g. Dillon Consulting Ltd. and Golder Associates Ltd. 2004; Husain et al. 2004; Strynatka et al. 2007; Carter and Fortner 2012). Records in WWIS indicate 40% of water wells in southern Ontario are drilled a few metres into the bedrock, terminating in either the contact aquifer or in the shallow karst aquifer system (Carter and Clark 2018). The contact aquifer is discordant to bedrock formation dips and underlies most of southwestern Ontario from Windsor to the Niagara Peninsula as far north as London and underlies most of the area east of the Niagara Escarpment to the edge of Paleozoic cover (Fig. 5).

The measured hydraulic conductivity of the Contact Aquifer HSU at a well in the Sarnia area was 1×10^{-5} m/s (Raven et al. 1990), but a considerable range of values is likely to be encountered. Regional water flow directions are controlled by the dip of the bedrock surface with local control by buried erosional cuestas and bedrock valleys. Topographic gradients drive recharge. The water within HSU 2 is generally potable, with local quality constraints, and mostly of modern meteoric origin, with several residual accumulations of glacial meltwater (Husein et al. 2004; Hamilton et al. 2015). Water compositions are dominated by $Ca-HCO_3$ and $Ca-SO_4$ with TDS averaging 770 mg/L (calculated from Hamilton 2015), and pH values ranging from 6.2 to 8.8. Groundwater chemistry is locally controlled by bedrock lithology (Singer et al. 2003).

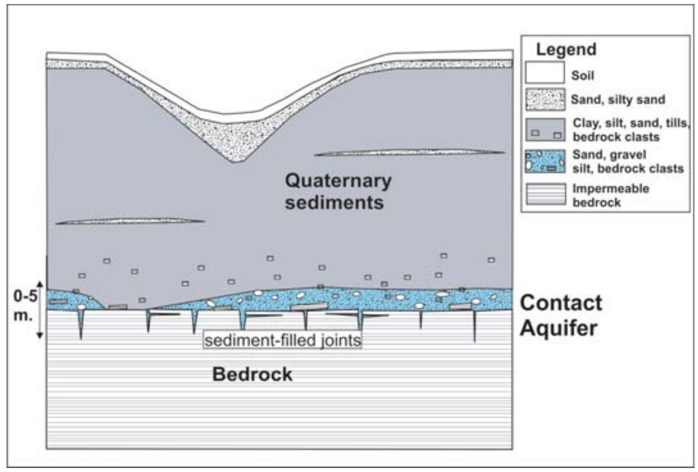

Figure 12. Conceptual model of the contact aquifer in the Chatham Sag, southwest of London, showing hydrogeological relationships relevant to areas where Kettle Point shale forms the top of bedrock.

HSU 3: Shallow Karst Aquifer System

A complex shallow system of fresh groundwater in carbonate, and less frequently evaporitic, bedrock has developed across large areas of southern Ontario due to karstic enhancement of porosity and permeability by meteoric water. This system is best developed at or near the subcrop surface of carbonate rocks in areas of thin overburden, along cuestas and near buried bedrock valleys. Stress-relief fracturing associated with these features further enhances the penetration of meteoric water (Cole et al. 2009; Priebe et al. 2019; Brunton and Brintnell 2020). Shallow karstic aquifers occur in the subcropping edges of most carbonate formations, including the Ipperwash, Hungry Hollow and Rockport Quarry formations in the Hamilton Group; the Dundee, Lucas, Amherstburg, Onondaga, Bois Blanc, Bass Islands, Fossil Hill, Gull River and Coboconk formations; and the Lockport Group. The most extensive shallow karst aquifers are developed in subcrops of the Lucas Formation and lower Dundee Formation and in the Lockport Group.

Shallow karstic aquifers in the Lockport Group subcrop belt are an important source of potable water in the area north of Brant County as described in detail by Brunton and Brintnell (2020) and Priebe et al. (2021). There is considerable geographic variation in aquifer development, with potable water found in the Guelph, Goat Island and Gasport formations, and locally the Eramosa Formation. Regional groundwater flow is to the southwest and northwest, downgradient from the topographic high formed by the Niagara Escarpment and a local bedrock topographic high known as the Dundalk dome, and parallel to the regional strike of the Lockport Group carbonate units (Priebe and Brunton 2016; Priebe et al. 2021).

Within shallow inferred karst in carbonate bedrock the deepest fresh water intervals recorded in water well records are 130 m below the bedrock surface. It should be noted that water well drillers generally do not drill deeper than the first water interval capable of providing a reliable supply. Fresh water is locally reported in petroleum well records at depths of up to 250 m below the ground surface (Carter and Clark 2018).

Lucas and lower Dundee Formations

In HSU 3 the Lucas Formation is susceptible to karst development in subcrop and outcrop (Fig. 13), and also at shallow depths beneath the subcrop edge of the lower Dundee Formation, where solution-widened joints in the Dundee provide pathways for deep penetration of meteoric water. The presence of interbeds of soluble anhydrite and locally halite increases the susceptibility of the Lucas to karst development (Fig. 14). Evaporite dissolution is believed to have played a significant role in formation of the "breathing well zone", a local karstic aquifer in Huron County (Brunton and Dodge 2008; Freckelton 2012) (see Fig. 5).

Some of the largest and most extensive sinkhole fields in southern Ontario occur in areas of thin overburden in the subcrop belts of the Lucas and Dundee formations in Huron County and western Perth County (Brunton and Dodge 2008; Hurley et al. 2008). Meteoric water can be observed flowing into solution-widened joints in outcrop exposures of the Dundee Formation after heavy rainfall events. Immediately east of Goderich, in central Huron County, elliptical patches of dark water in aerial photographs mark the location of "black holes" in the bed of the Maitland River (Fig. 15). The black holes are sinkholes 10 m or more in depth in the bedrock which provide entry points for infiltration of water from the Maitland River into the Lucas Formation. Fresh water from

Figure 13. Large vugs in reactivated paleokarst zone in uppermost Lucas Formation, Colborne Riverside Park, Maitland River valley, Huron County. Cliff exposure is approximately 3 metres in height.

Figure 15. Aerial photograph of the Maitland River west of Goderich showing "black holes" in bed of Maitland River marking location of submerged sinkholes that are over 10 m deep in the Dundee and Lucas formations. The sinkholes provide entry points for infiltration of meteoric water into the bedrock.

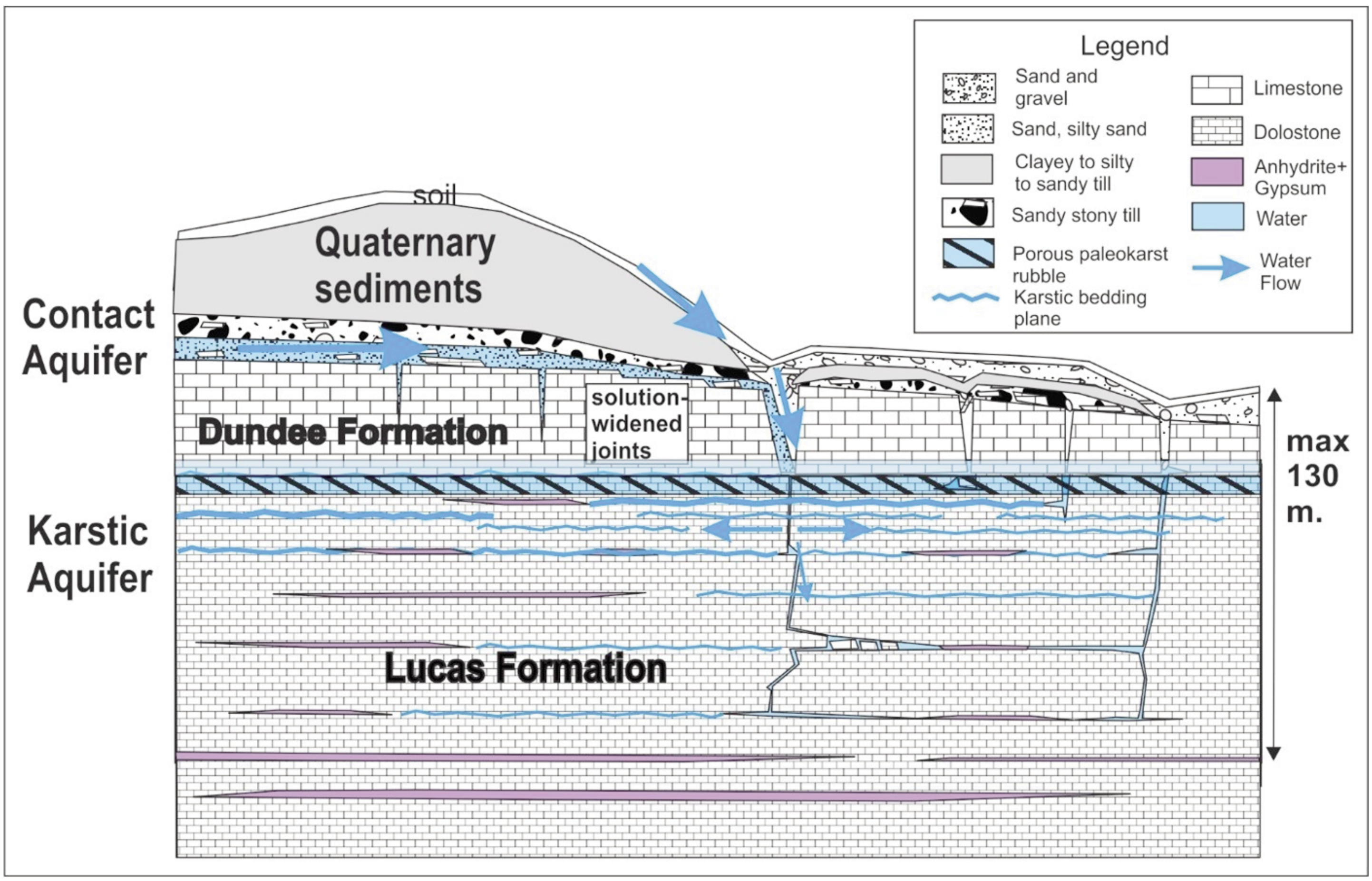

Figure 14. Conceptual model of shallow karst aquifer developed in subcropping limestone of the lower Dundee Formation and dolostone of the Lucas Formation, showing inferred flow directions. Based on field observations in outcrop and quarries (see Figures 15–18).

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the shallow karst aquifer recharges HSU 5, the confined Lucas–Dundee Aquifer, at intermediate depths down-dip from the subcrop belt. At the Bruce site, at a depth of 20 m below the surface, Intera Engineering Ltd. (2011) reported average hydraulic conductivity for the Lucas Formation in HSU 3 as 1×10^{-6} m/s.

Lockport Group

The Lockport Group in HSU 3 is composed of carbonate rocks of the Gasport, Goat Island, Eramosa, and Guelph formations. These rocks are susceptible to karstification and development of fresh water aquifers where they are exposed at surface or in subcrop beneath shallow overburden, particularly in proximity to the Niagara Escarpment (e.g. Brunton 2013; Banks and Brunton 2017; Priebe et al. 2019; Brunton and Brintnell 2020). The City of Guelph relies primarily on groundwater from the Gasport Formation for its municipal water supply and to a lesser extent from the Guelph Formation. Flow zones occur at karst-enhanced stratigraphic breaks, bedding plane partings, and/or lithologic contrasts, which usually represent formation contacts (Priebe et al. 2017). North of Hamilton, Banks and Brunton (2017) have documented flow zones located at sequence and stratigraphic breaks in crinoidal grainstone and packstone of the Gasport and Goat Island formations, with others defined in the Eramosa and Guelph formations. The presently documented extent of the Gasport Aquifer is an area of approximately 10 000 km^2 northwest of the City of Hamilton (Priebe and Brunton 2016; Banks and Brunton 2017; Priebe et al. 2017, 2019).

From 23 different monitoring wells in the vicinity of the City of Guelph, Priebe et al. (2017) reported hydraulic conductivities for formations of the Lockport Group in HSU 3 ranging from 6×10^{-7} to 5×10^{-3} m/s, at depths of 17 to 100 m below the surface. The wide range of reported conductivities is directly related to depth below the present-day surface and the presence or absence of karst or solution-widened bedding plane partings. At shallow boreholes near the Niagara Gorge, Novakowski and Lapcevic (1988) measured hydraulic conductivity ranging from 5.5×10^{-4} to 7.8×10^{-11} m/s in the Goat Island and Gasport formations, and a range from 2.8×10^{-4} to 1.4×10^{-8} m/s for the Guelph Formation. Raven et al. (1992) reported a range from 2×10^{-5} to 3.2×10^{-9} m/s for the Goat Island Formation. The higher k values in these shallow boreholes are indicative of the effects of post-glacial karstification.

Regional hydraulic gradient from the shallow karst aquifer into the subsurface is down-dip from the subcrop belt (Carter et al. 2015b) and is interpreted to be the likely pathway for penetration of glacial meltwater in the geologic past, and possibly modern meteoric water, into HSU 9 at intermediate depths. In the area of the subcrop belt north of Hamilton, recent mapping has established that flow is radially outward to the south, southwest and northwest from the Dundalk dome, a topographic high in the bedrock immediately west of the Niagara Escarpment (see Fig. 3), with flow directions parallel to the regional strike (Priebe and Brunton 2016; Priebe et al. 2021). Proximal to the Niagara Escarpment groundwater flow is to the east due to capture by solution-widened stress-relief joints and a network of shallow karst caves (e.g. Cowell and Ford 1983; Brunton and Dodge 2008).

HSU 4: Devonian Aquitard

HSU 4 consolidates in ascending stratigraphic order the upper portion of the Middle Devonian Dundee Formation, the Middle Devonian Marcellus Formation and Hamilton Group, the Upper Devonian Kettle Point Formation, and the Upper Devonian to Mississippian Port Lambton Group. These units form the uppermost bedrock beneath an onshore area of approximately 12 000 km^2 in southern Ontario (Fig. 1), with cumulative thickness of 130 to 180 m. Starting from the upper Dundee Formation the HSU is composed of limestone that is disconformably overlain by organic-rich black shale of the Marcellus Formation, and then by calcareous shale and interbedded limestone of the Hamilton Group, in turn overlain disconformably by black, organic-rich shale of the Kettle Point Formation, and very locally by sandstone and shale of the Port Lambton Group.

Petroleum well drillers do not report significant amounts of water when drilling through this HSU (Carter et al. 2015a). Hydraulic conductivities are low, with reported values for the Kettle Point Formation of 3×10^{-9} (Weaver 1994) and less than 1×10^{-10} m/s (Raven et al. 1990). Measured values for the Hamilton Group shale are 2.2×10^{-11} (Weaver 1994) and 1×10^{-12} m/s (Raven et al. 1990). For the upper Dundee Formation Raven et al. (1990) reported measured hydraulic conductivity of 1×10^{-11} m/s.

HSU 5: Lucas–Dundee Aquifer

HSU 5 consists predominantly of the Lucas Formation, the Columbus Formation and the lowermost few metres of the Dundee Formation, and is a major regional, confined aquifer in the intermediate subsurface. It underlies a land area of approximately 22 000 km^2 with a combined thickness of 40 to 110 m. The aquifer is well known in the Ontario petroleum industry for the almost ubiquitous occurrence of sulphur water and the corrosive effect of this water on steel well casings. These same formations have produced over 45 million barrels of oil from oil reservoirs in Lambton County (Carter et al. 2016).

Water in the aquifer demonstrates a gradational increase in salinity down-dip from the shallow karst aquifer from brackish water to saline water containing elevated SO_4 and dissolved H_2S at intermediate depths, to local occurrences of dense brine in the deepest part of the aquifer. In southern Ontario salinities vary from 1300 to 44 000 mg/L TDS in the intermediate zone at depths from 50 to 180 m below the surface (Dollar et al. 1991; Weaver et al. 1995; Skuce et al. 2015b) with Na–Ca–Cl–SO_4 composition, and maximum SO_4 content of 2000 mg/L. In the state of Michigan, down-dip into the Michigan Basin, the aquifer reaches depths of 620 to 1560 m, and Wilson and Long (1993) reported Ca–Na–Cl brines with TDS of 125 000 to 387 000 mg/L.

Artesian flow of sulphur water is encountered by petroleum wells and deep water wells that intersect this aquifer in topographic lows such as Big Otter Creek and Big Creek in

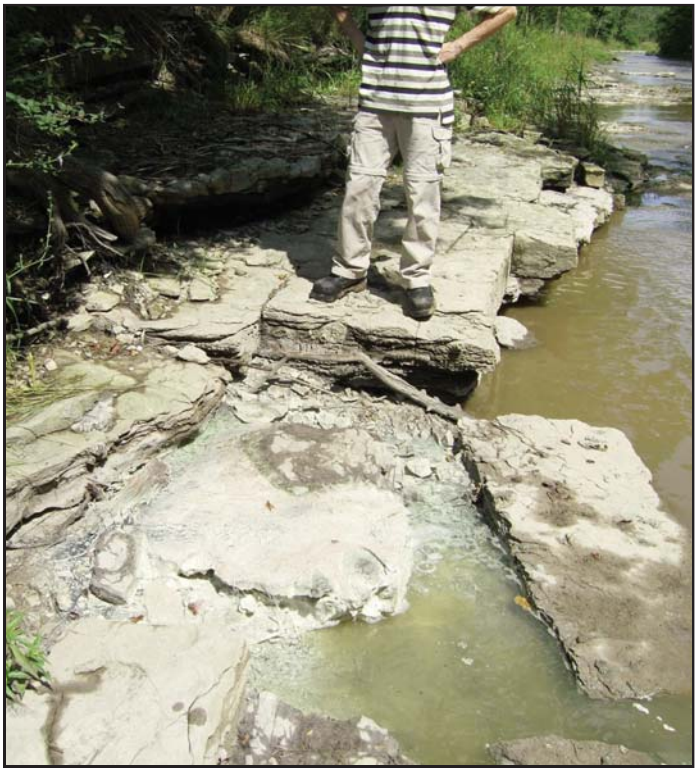

Figure 16. Sulphur water spring flowing into Hemlock Creek, 600 m north of Lake Erie. The spring flows out of a bedding plane parting in limestone at the contact of the Dundee Formation with the underlying Onondaga Formation.

Figure 17. Inflow of sulphur water along bedding plane partings in the Lucas Formation on the southern face of the McGregor Quarry. Inactive zones are marked by white residue immediately below the bedding plane. The red staining on the lower bench marks an active inflow with a rotten egg smell, indicative of the presence of sulphur-oxidizing bacteria. Exposed bedrock thickness is approximately 40 m. Photograph taken October 18, 2013.

Figure 18. Water inflow along a horizontal bedding plane parting in limestone of the lower Dundee Formation, Port Dover Quarry. Yellow slime covering the quarry walls is a vigorous population of sulphur-oxidizing bacteria.

Norfolk County and along the Lake Erie shoreline, where it constitutes a drilling hazard. Sulphur water also locally discharges into quarries and from natural springs (Figs. 16, 17, 18). As noted above microbial DNA analyses show abundant sulphur proteobacteria in artesian flow from the lower Dundee Formation in Norfolk County (Fig. 10).

On the Michigan Basin side of the Algonquin Arch, the Lucas Formation is the principal water-bearing unit in HSU 5. It is composed of fine-grained to very fine-grained restricted-marine limestone and dolostone with anhydrite and gypsum beds in the lower half of the formation, and beds of quartzose sandstone in the upper portion. Occasional halite beds occur near Lake Huron and the St. Clair River. In Ontario, the Lucas Formation averages 25 to 40 m in thickness, reaching a maximum of 90 m in the Chatham Sag. It thins eastwards to its pinch-out edge in Norfolk County. Karstic dissolution of evaporite rocks and stromatolitic beds greatly enhances horizontal permeability. Petroleum wells have encountered severe loss-of-circulation and incompetent bedrock within the Lucas Formation during drilling in Lambton, Kent, and Huron counties. An unusual microporous dolomite is locally common (Hamilton 1991), which may also have a significant role in groundwater storage and movement. In the McGregor Quarry in Essex County, groundwater flow in the Lucas Formation is controlled by horizontal bedding plane partings a few millimetres wide (Fig. 17), which have been enhanced by karstic dissolution. Measured hydraulic conductivity in the Lucas Formation varies considerably from 1×10^{-6} to 2×10^{-9} m/s (Raven et al. 1990; Intera Engineering Ltd. 2011) due to the varying sample depths, the differing degrees of karstic dissolution, and the presence or absence of horizontal fractures.

The Dundee Formation disconformably overlies the Lucas Formation and is composed of up to 45 m of fossiliferous limestone, of which only the lower few metres is considered, with the Lucas, as an aquifer. Petroleum wells consistently encounter water in the lower few metres of the formation, and in Lambton County the lower Dundee Formation is the principal oil-producing interval in Devonian oil reservoirs. East of the Algonquin Arch and the pinch-out edge of the Lucas Formation in central Norfolk County (see Fig. 1), the basal Dundee Formation becomes the principal aquifer. Water flow into the Port Dover Quarry in Norfolk County is confined along bedding plane partings in the Dundee Formation (Fig. 18). At a deep monitoring well drilled through the Dundee, Lucas and Amherstburg formations near Sarnia, Raven et al. (1990) reported measured hydraulic conductivity of 1×10^{-8} to 1×10^{-9} m/s for the lowermost few metres of the Dundee, versus 1×10^{-11} m/s for the upper Dundee. Weaver (1994) reported hydraulic conductivity of 8.4×10^{-8} m/s.

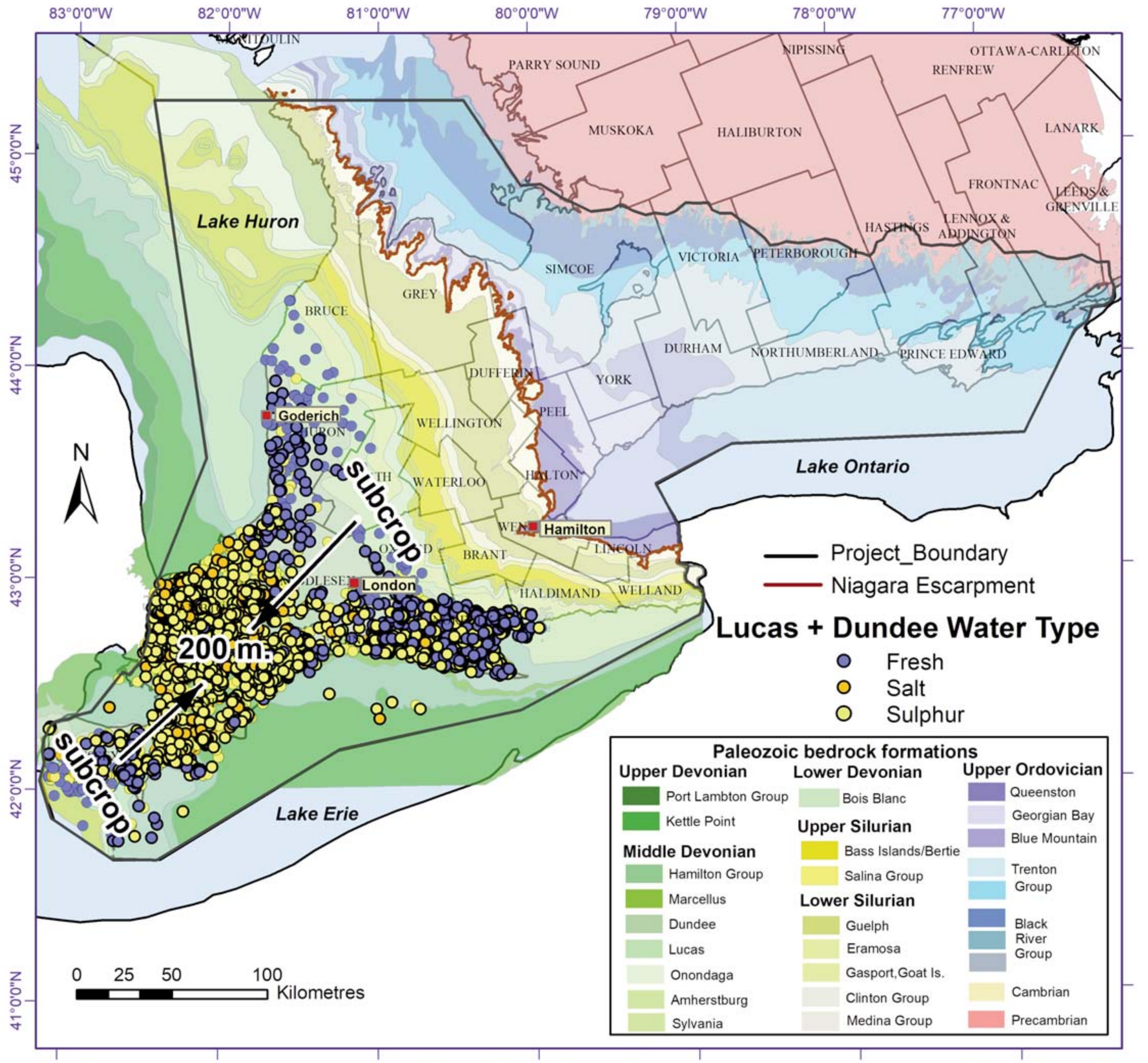

Figure 19. Map showing water-bearing intervals, by water type, encountered by petroleum wells while drilling through the Lucas Formation and Dundee Formation (from Carter et al. 2015a). There is a down-dip gradation from fresh water, to sulphur water, to saline water. Arrows show regional dips and depth to top of the Lucas Formation. Similar maps have been constructed for 35 formations and/or groups of formations, including all aquifers (adapted from Carter et al. 2015a).

Recharge

Recharge of the Lucas-Dundee Aquifer is from HSU 3, the Shallow Karst Aquifer, in subcrop exposures of the Lucas and lower Dundee formations. Hydraulic gradients are down-dip from HSU 3 towards the Chatham Sag and Lakes Huron and Erie, as indicated by hydrochemical zonation (Carter et al. 2015a) (Fig. 19), static level mapping (Carter et al. 2015b) (Fig. 20) and down-dip decreases in the water's $\delta^{18}O$ and $\delta^{2}H$ (Fig. 10). Water type mapping indicates a transition from fresh to sulphur water approximately 20 to 35 km down-dip from the subcrop belts of the Lucas and Dundee formations (Fig. 19) (Carter et al. 2015a). Isotopic data collected in Norfolk County for this study indicate a transition from modern meteoric water to water of likely glacial origin at similar distances (Fig. 10).

HSU 6: Amherstburg–Bois Blanc Aquitard

HSU 6 comprises the Bois Blanc, Amherstburg and Onondaga formations, including the Sylvania Formation and the Springvale Member of the Bois Blanc Formation and underlies a land area of ~23 000 km^2. Thickness ranges from 40 to 90 m, thick-

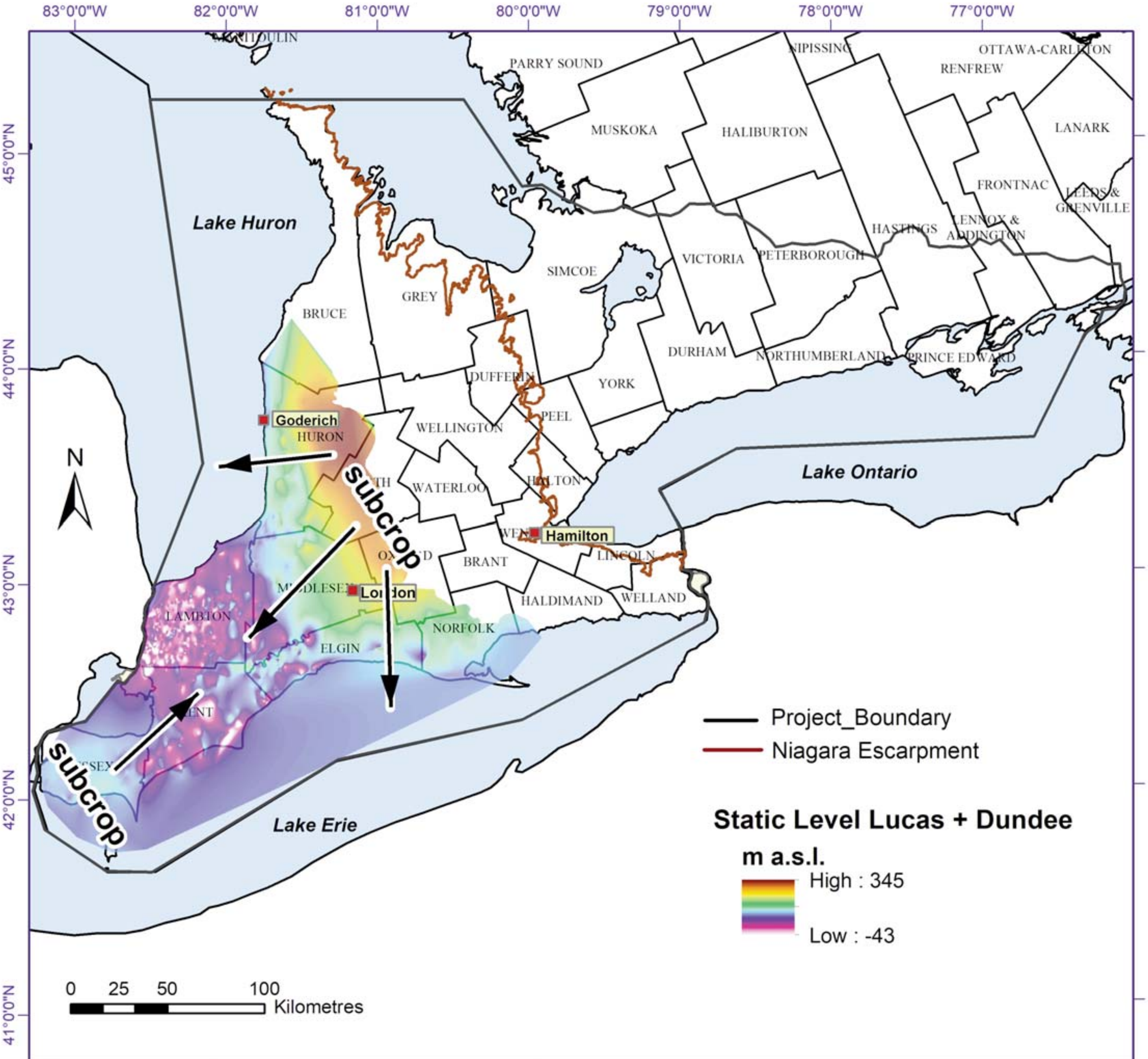

Figure 20. Static level map for fresh and sulphur water in the Lucas Formation and the lower Dundee Formation, showing down-dip hydraulic gradient from HSU 3 in the subcrop belt into HSU 5 (adapted from Carter et al. 2015b).

ening into the Chatham Sag and westwards into the Michigan Basin.

Conformably underlying the Lucas Formation, the Amherstburg Formation consists of 20 to 60 m of limestone and dolostone. In Norfolk County and farther east, the Amherstburg Formation, together with the Lucas Formation, is transitional into cherty limestone of the Onondaga Formation (Armstrong and Carter 2010; Sun 2018). Raven et al. (1992) measured hydraulic conductivity of 3.2×10^{-11} to 7.9×10^{-9} m/s in the Amherstburg Formation at Sarnia. Sykes et al. (2011) reported hydraulic conductivity of 1×10^{-6} to 1×10^{-7} m/s at both the Windsor and Goderich salt mines. These considerable variations are directly related to depth, with the higher conductivity values occurring at depths of less than 150 m. Thick lenses of quartz sandstone of the Sylvania Formation underlie the Amherstburg Formation in the southwest corner of Essex County but no hydraulic conductivity data are available.

The Bois Blanc Formation consists of cherty fossiliferous limestone 3 to 50 m in thickness, locally with 3 to 10 m of glauconitic sandstone of the Springvale Member at the base.

Measured hydraulic conductivity of 1×10^{-8} to 1×10^{-9} m/s was reported at the Nanticoke tunnel (Intera Technologies Ltd. 1988).

HSU 7: Bass Islands Aquifer

HSU 7 comprises the upper half of the Silurian Bertie and Bass Islands formations, and the Devonian Oriskany Formation, in ascending order. It underlies a land area of approximately 24 500 km^2 with a thickness from 10–70 m, thickening westwards into the Michigan Basin and the Chatham Sag, with local thickening over salt dissolution/subsidence features in the underlying Salina Group (Sanford 1969; Bailey Geological Services Ltd. and Cochrane 1985).

Dolostone beds of the Upper Silurian Bass Islands Formation have a continuous distribution in the subsurface of southern Ontario southwest of the subcrop edge. The underlying Bertie Formation dolostone only occurs beneath Welland County and eastern Haldimand County and easternmost Lake Erie. The upper contact of the Bass Islands Formation is a major unconformity and is the principal water-bearing horizon in HSU 7. Paleo-karstification of this surface has created solution-widened joints, many of which are locally filled with quartz sand of the Oriskany Formation, resulting in greatly enhanced porosity and permeability. The Oriskany Formation forms small outliers of calcareous quartz sandstone preserved within paleo-depressions on the surface of the Bass Islands Formation related to subsidence over salt dissolution features in the underlying Salina Group. At the Bruce site, the Bass Islands Formation has measured horizontal hydraulic conductivity varying from 1×10^{-4} to 1×10^{-5} m/s for the upper 20 m and 1×10^{-5} to 1×10^{-6} m/s for the lower 25 m (Intera Engineering Ltd. 2011). At the Goderich salt mine Intera Technologies Ltd. (1988), as cited by Sykes et al. (2011), reported values of 1×10^{-6} to 1×10^{-7} m/s. There are insufficient groundwater samples from HSU 7 at intermediate to deep depths to characterize its hydrochemistry.

HSU 8: Salina Aquitard

HSU 8 comprises the Salina Group and the lower half of the overlying Bass Islands Formation. It underlies a land area of approximately 31 000 km^2 with a maximum thickness of 420 m in the Chatham Sag thinning easterly to 120 m. The Salina Group is dominated by evaporite rock types, including halite, anhydrite, gypsum and lime/dolomudstone. Thick beds of halite occur in the Salina A-2 Unit, B Unit, D Unit and F Unit west of the Algonquin Arch, and locally in the A-1 Unit in Huron County, exhibiting an eastward facies change to anhydrite and carbonate rocks, and an increase in shaliness east of the arch, and a corresponding decrease in thickness.

The zero edge of the salt beds, particularly in the B-Salt, is very abrupt, thinning from tens of metres to zero in as little as 1 km and is interpreted to be a dissolution front. When dissolution occurred after deposition and lithification of younger strata the overlying formations collapse into the dissolution voids and in drill core intersections the bedrock is observed to be fractured and brecciated (Armstrong and Carter 2010). This may have created pathways for subsequent downward or lateral movement of water, but this is conjectural. Underground observations of collapse breccia in salt mines in Ontario indicate no evidence of active groundwater infiltration.

At the Bruce site, the Salina Group formations have hydraulic conductivity varying from 3×10^{-10} m/s in the A-2 Unit to 5×10^{-14} m/s in the F Unit (Intera Engineering Ltd. 2011). Pore water composition varies from Ca–SO_4 with 30 000 mg/L TDS in units of the upper Salina Group, to a dense Na–Cl brine averaging 370 000 mg/L in the Salina A-1 and A-2 units (Intera Engineering Ltd. 2011). At a depth of 510 m in the Goderich Salt mine, two samples of Ca–Na–Cl brine obtained from dewatering boreholes drilled into the A-2 Carbonate immediately above the A-2 Salt contained 375 000 to 391 000 mg/L TDS (Skuce et al. 2015b).

In the subsurface, the presence of intact salt beds is proof of lack of groundwater movement through these rocks subsequent to deposition, and in these areas the Salina Group can be considered as an aquiclude. At the Bruce site, an anomalous water-bearing paleokarst horizon occurs in the uppermost 3.5 m of the A-1 Carbonate (Intera Engineering Ltd. 2011) at a depth of 340 m. Two water samples contained 26 760 mg/L and 30 455 mg/L TDS, typical of the intermediate groundwater regime, but inconsistent with the dense porewater brines in the enclosing formations of the Salina Group. The water also has an anomalous $\delta^{18}O = -14.4‰$ and δ^2H of $-104‰$, suggestive of glacial meltwater. Flow direction was determined to be to the northwest, down-dip towards the Michigan Basin. Petroleum well data indicates the continuity of this paleokarst horizon to the subcrop belt, as discussed above. Horizontal hydraulic conductivity for this zone, as measured at the Bruce facility, averaged 2×10^{-7} m/s.

HSU 9: Guelph Aquifer

HSU 9 consists primarily of dolostone of the Guelph Formation, and locally the uppermost few metres of the underlying Goat Island Formation. It underlies a land area of approximately 38 000 km^2 and varies from 2 m to over 100 m in thickness.

The Lockport Group, of which the Guelph Formation is the uppermost formation, forms a gently dipping layer, thickening from west to east, and underlies all of southern Ontario west of the Niagara Escarpment. A distinctive series of lithofacies belts is preserved in the Guelph Formation as a result of a complex depositional, erosional, and diagenetic history, consisting of a carbonate platform in the east with carbonate banks/reefs, a regional paleokarst to the west, and an intervening pinnacle belt with inter-pinnacle karst (Fig. 21). There are considerable differences in hydrogeological characteristics of the Guelph Formation in the different lithofacies belts.

The regional paleokarst is a porous and permeable breccia or paleosol rubble (Fig. 22), 2 to 8 m thick, extending downward into the uppermost Goat Island Formation (Smith 1990; Carter et al. 1994; Brunton and Brintnell 2020). Within the eastern extent of the paleokarst is a 50-km wide belt of pinnacles of thickened Gasport, Goat Island and Guelph carbonate rocks, separated by the same paleokarst breccia. The "pinnacles" have heights exceeding 100 m above the regional inter-

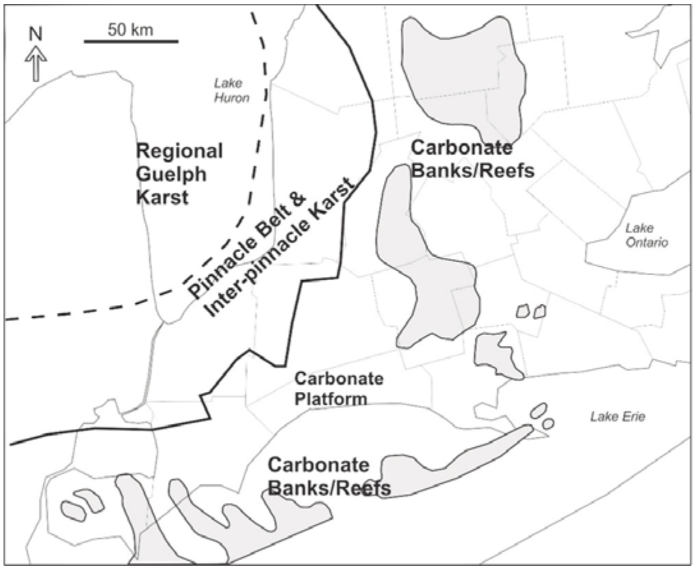

Figure 21. Lithofacies belts of the Guelph Formation in southern Ontario, showing carbonate banks or reefs on a southeast-dipping carbonate ramp and regional paleokarst and inter-pinnacle karst to the west. Revised from Sanford (1969) and Carter et al. (1994), using data from Bailey Geological Services Ltd. and Cochrane (1988), 3-D visualization (Carter et al. 2019) and paleoenvironmental interpretations of Brunton and Brintnell (2020).

Figure 22. Dark brown to black, dolostone paleokarst rubble in the inter-pinnacle Guelph Formation, 800.5 m below rig floor. Drill core from petroleum well Tec. Dow 4, Moore 21-XII, in Lambton County, well licence #T007290, core # 996 at the OGSRL. This paleokarst rubble forms a regional brine aquifer in the regional karst and inter-pinnacle karst belts in southern Ontario.

pinnacle Guelph surface, and shorter build-ups known as incipient mounds are commonly less than 30 m. The pinnacles are interpreted as "karst towers" by Brunton and Brintnell (2020) and Brunton et al. (2012), but most previous workers have considered them to be pinnacle reefs (e.g. Sanford 1969; Gill 1977; Sears and Lucia 1979; Grimes 1987; Smith et al. 1988; Smith 1990; Charbonneau 1990a, b; Carter et al. 1994, 1996; Coniglio et al. 2003).

Both the pinnacles and the incipient mounds exhibit varying degrees of karstification. The resulting enhancement of porosity and permeability, and the vertical and lateral seal provided by the Salina Group, has created prolific reservoirs of oil and natural gas and natural gas storage reservoirs. Average measured porosity in storage reservoirs is 7.7% with some thin intervals exceeding 30% porosity with maximum horizontal permeability of 1000 to 10 000 millidarcies (Carter et al. 1996). Where no hydrocarbons are present the pinnacles and incipient mounds are filled with brine or the pore space has been infilled by secondary halite. The regional karst and inter-pinnacle karst are occupied by dense brines.

East of the pinnacle belt individual carbonate banks or reefs have a maximum Guelph Formation thickness of 100 m (Sanford 1969; Brintnell 2012) with 20 to 50 m of relief on the Guelph Formation surface (Bailey Geological Services Ltd. and Cochrane 1988; Carter et al. 2019). Natural gas reservoirs occur in the banks or reefs beneath Lake Erie, and in the absence of hydrocarbons these structures are filled with brine.

In the deep brine regime salinities range from 153 000 to 441 000 mg/L TDS for pinnacles (Dollar et al. 1991; Skuce et al. 2015b) at depths of 354 to 770 m, and 365 000 to 375 000 mg/L for inter-pinnacle karst (Intera Engineering Ltd. 2011) at a depth of 390 m. There is an up-dip transition from brine to saline to brackish groundwater at intermediate depths (Carter and Sutherland 2020), and to fresh water in shallow modern karst in the subcrop belt. Horizontal and vertical hydraulic conductivity of the inter-pinnacle Guelph is 3×10^{-8} m/s at the Bruce site (Intera Engineering Ltd. 2011). Raven et al. (1992) recorded measurements of 6.3×10^{-5} to 7.9×10^{-9} m/s at Niagara Falls.

Hydraulic gradient in the shallow and intermediate regimes is down-dip from the subcrop belt, from northeast to southwest (Carter et al. 2015b). Groundwater in the deep brine regime exhibits hydraulic gradients up-dip from both the Appalachian Basin (Carter et al. 2015b) and from the Michigan Basin (Intera Engineering Ltd. 2011). The degree of connectivity and mixing between the intermediate and deep groundwater regimes in HSU 9 is unknown.

HSU 10: Lower Lockport Aquitard

HSU 10, the lower Lockport Aquitard, underlies 41 000 km^2, is 20 to 110 m thick, and comprises, in ascending order, dolostone of the Gasport, Goat Island and Eramosa formations of the lower Lockport Group. In the intermediate to deep subsurface of most of southern Ontario, where they are confined beneath the Salina Group, these formations are aquitards. Within the subcrop belt these same formations are porous and permeable and are included in HSU 3. In the deep subsurface at the Bruce site, far below the influence of surface water, at a depth of 378.6 m, the Goat Island Formation has a measured hydraulic conductivity of 2×10^{-12} m/s (Intera Engineering Ltd. 2011).

HSU 11: Clinton–Medina Aquitard

HSU 11, the Clinton–Medina Aquitard, consists of the combined Clinton and Medina groups (Fig. 2) and underlies a land area of 42 000 km^2 with a thickness averaging 40 to 70 m. Shale of the Cabot Head Formation of the Lower Medina Group forms a major confining bed throughout all of southern Ontario west of the Niagara Escarpment, with no fresh water found below this stratigraphic level (Brunton and Brintnell 2020).

The upper part of this succession is dominated by limestone and dolostone: the DeCew, Irondequoit, Rockway (Reynales), Fossil Hill, and Merritton formations. The Rochester Formation forms a wedge of calcareous shale thinning to the northwest from a maximum of 24 m beneath eastern Lake Erie to its pinch-out along a line between Hamilton and Goderich. It transitions laterally to dolostone of the Lions Head Formation (Brunton and Brintnell 2020) on the Bruce Peninsula. The lower part of the succession is dominated by clastic sedimentary rocks east of the Algonquin Arch, including shale of the Neahga and Cabot Head formations, quartzose sandstone of the Thorold and Whirlpool formations, and interbedded shale, siltstone and quartzose sandstone of the Grimsby Formation. Sandstone contains natural gas throughout its distribution with sufficient permeability to support gas production where shale content is low (Carter et al. 2016). Small amounts of Na–Ca–Cl brine occur in association with natural gas production, with salinity ranging from 181 000 to 407 000 mg/L at depths of 226 to 572 m (Dollar et al. 1991; Skuce et al. 2015b). At the Bruce site the measured hydraulic conductivity of the formations comprising HSU 11 is low to very low, ranging from 5×10^{-12} m/s for the Lions Head and Fossil Hill formations to 9×10^{-14} m/s for the Cabot Head Formation (Intera Engineering Ltd. 2011).

HSU 12: Ordovician Shale Aquiclude

HSU 12, the Ordovician Shale Aquiclude, underlies a land area of 48 000 km^2, is up to 500 m thick, thinning northeast to under 175 m in Bruce County and erosional truncation in outcrop east of the Niagara Escarpment. It comprises the Upper Ordovician Queenston, Georgian Bay, and Blue Mountain formations. The three formations are comprised primarily of shale with subordinate siltstone and sandstone and limestone interbeds. The Queenston Formation is characterized by its distinctive red colour. For grey shale of the Georgian Bay and Blue Mountain formations the gradational contact, non-uniqueness of composition, and lack of distinct wireline log response make differentiation difficult.

At the Bruce site the Ordovician shale has a horizontal hydraulic conductivity of 2×10^{-14} to 3×10^{-14} m/s and is significantly underpressured with uniform pore water composition of Na–Cl brine averaging 300 000 mg/L (Intera Engineering Ltd. 2011). These characteristics, in combination with the lack of water intervals reported from petroleum wells, indicate no significant fluid flow has occurred within HSU 12, supporting its designation as an aquiclude. Novakowski and Lapcevic (1988) reported values of 1×10^{-8} to 1×10^{-11} from deep boreholes at Niagara Falls.

HSU 13: Trenton–Black River Aquitard

HSU 13 is the Trenton–Black River Aquitard which underlies a land area of approximately 65 000 km^2 with a maximum thickness of nearly 250 m beneath west-central Lake Erie. It occurs at a depth of 850 m or more in the Windsor area, thinning to the northeast, and subcrops east of Toronto. It comprises all the formations of the Trenton and Black River groups.

The base of the aquitard is the predominantly argillaceous Shadow Lake Formation, which is generally 2 to 3 m thick, ranging to a maximum of 15 m. It has an angular unconformable lower contact with either Cambrian sandstone and dolostone or Precambrian crystalline basement rocks. It is generally non-porous and non-permeable, with local exceptions, and forms a caprock to reservoirs of oil and natural gas in the underlying Cambrian formations. The Shadow Lake is conformably overlain by a cyclical sequence of lime mudstone, wackestone, packstone and bioclastic grainstone comprising the rest of the Trenton and Black River groups. North of London (see Fig. 5), the uppermost 1–10 m of HSU 13 consists of black, organic-rich shaly limestone and calcareous shale of the Collingwood Member of the Cobourg Formation. Where the Collingwood Member is absent the uppermost few metres of the Cobourg Formation is dolomitized (Armstrong and Carter 2010).

Hydraulic conductivity for the Shadow Lake Formation ranges from 1.0×10^{-8} to 4.0×10^{-14} m/s (Raven et al. 1992; Golder Associates Ltd. 2003). At the Bruce site, limestone of the Trenton Group has an average porosity of 2.4% and an average horizontal hydraulic conductivity of 4×10^{-15} to 1×10^{-14} m/s. It is significantly underpressured with pore water composition of Na–Cl brine varying from 285 000 mg/L at the top to 230 000 mg/L at the base (Intera Engineering Ltd. 2011). Black River Group limestone has an average porosity of 1.5%, with an average horizontal hydraulic conductivity of 2×10^{-11} to 1×10^{-12} m/s. Golder Associates Ltd. (2003) obtained similar hydraulic conductivity values for the Trenton Group and Black River Group from deep boreholes along the northern shore of Lake Ontario. They are normally pressured to overpressured with pore water composition of Na–Cl brine varying from 200 000 mg/L to 230 000 mg/L in the Gull River Formation (Intera Engineering Ltd. 2011). These characteristics, combined with the general lack of water documented in petroleum wells (Carter et al. 2015a), indicate that HSU 13 is an aquitard. The Trenton Group has been classified as an aquiclude by Intera Engineering Ltd. (2011) and Al et al. (2015) and is labelled as such on Fig. 11.

Local exceptions to the impermeable character of the Trenton and Black River groups occur where limestone has been dolomitized along vertical faults and fractures, principally in Kent and Essex counties (Middleton et al. 1993; Coniglio et al. 1994; Haeri-Ardakani 2013). This dolomite is porous and permeable with additional connectivity provided by fractures associated with the faults. These "hydrothermal dolomite" chimneys may be several kilometres in length, up to 1200 m in width and may extend vertically for over 100 m through the entire thickness of the Trenton and Black River groups (Davies and Smith 2006; Dorland et al. 2016). The structures are confined beneath shale of the Blue Mountain Formation. These dolomite reservoirs are prolific producers of oil and natural gas in Kent and Essex counties and the adjacent portions of Lake Erie in Ontario, and in southern Michigan. Dense Na–Ca–Cl brines occur in the basal portions of these reservoirs or, in the absence of hydrocarbons, occupy the full vertical extent of the hydrothermal dolomite zones. Salinities

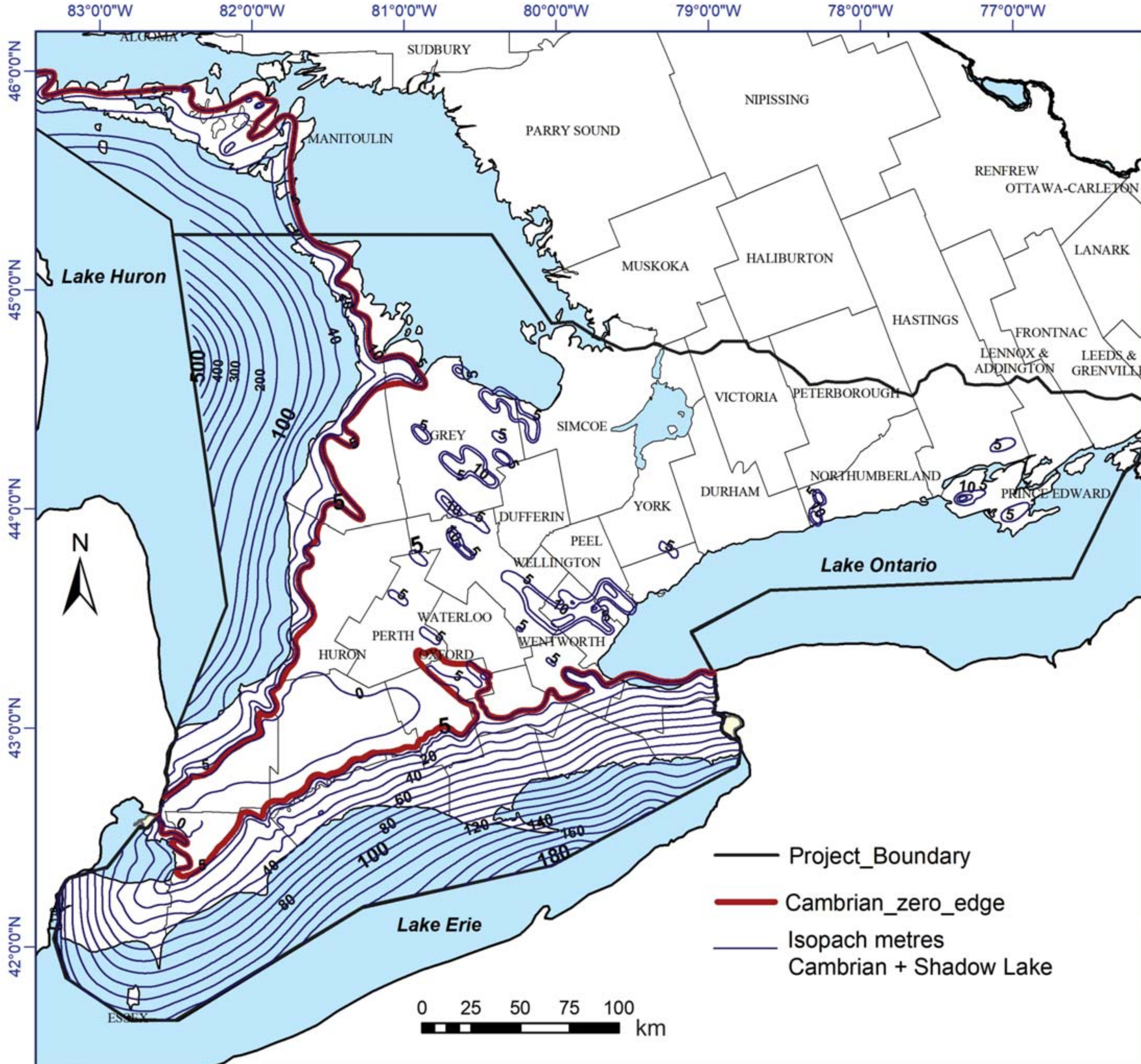

Figure 23. Isopach map of the combined Cambrian formations and Shadow Lake Formation and zero edge of the Cambrian strata, compiled from Sanford and Quillian (1959), Bailey Geological Services Ltd. and Cochrane (1984), Trevail (1990) and Ontario Geological Survey (2011). The Shadow Lake Formation underlies all southern Ontario except for a small area in Lambton and Middlesex counties. Cambrian units do not subcrop within the study area. Contour spacing is variable.

vary from 136 000 to 403 000 mg/L TDS (Dollar et al. 1991; Skuce et al. 2015b).

HSU 14: Cambrian Aquifer

HSU 14 is the Cambrian Aquifer which underlies a land area of 18 500 km^2 and most of Lake Huron and Lake Erie and is composed of all the Cambrian age formations in the subsurface of southern Ontario (Fig. 2). Cambrian strata are absent over the crest of the Algonquin Arch and thicken into the respective flanking basins to as much as 500 m beneath Lake Huron and 180 m beneath Lake Erie (Fig. 23).

Cambrian formations are dominated by sandstone in most of the onshore portion of southern Ontario. Beneath Lake Erie and Lake Huron it consists of quartzose sandstone and dolostone. The Cambrian strata experienced a prolonged period of exposure and erosion at the end of the Early Ordovician, as indicated by an extensive and intensive paleokarst horizon at the Knox Unconformity (Mussman and Read 1986;

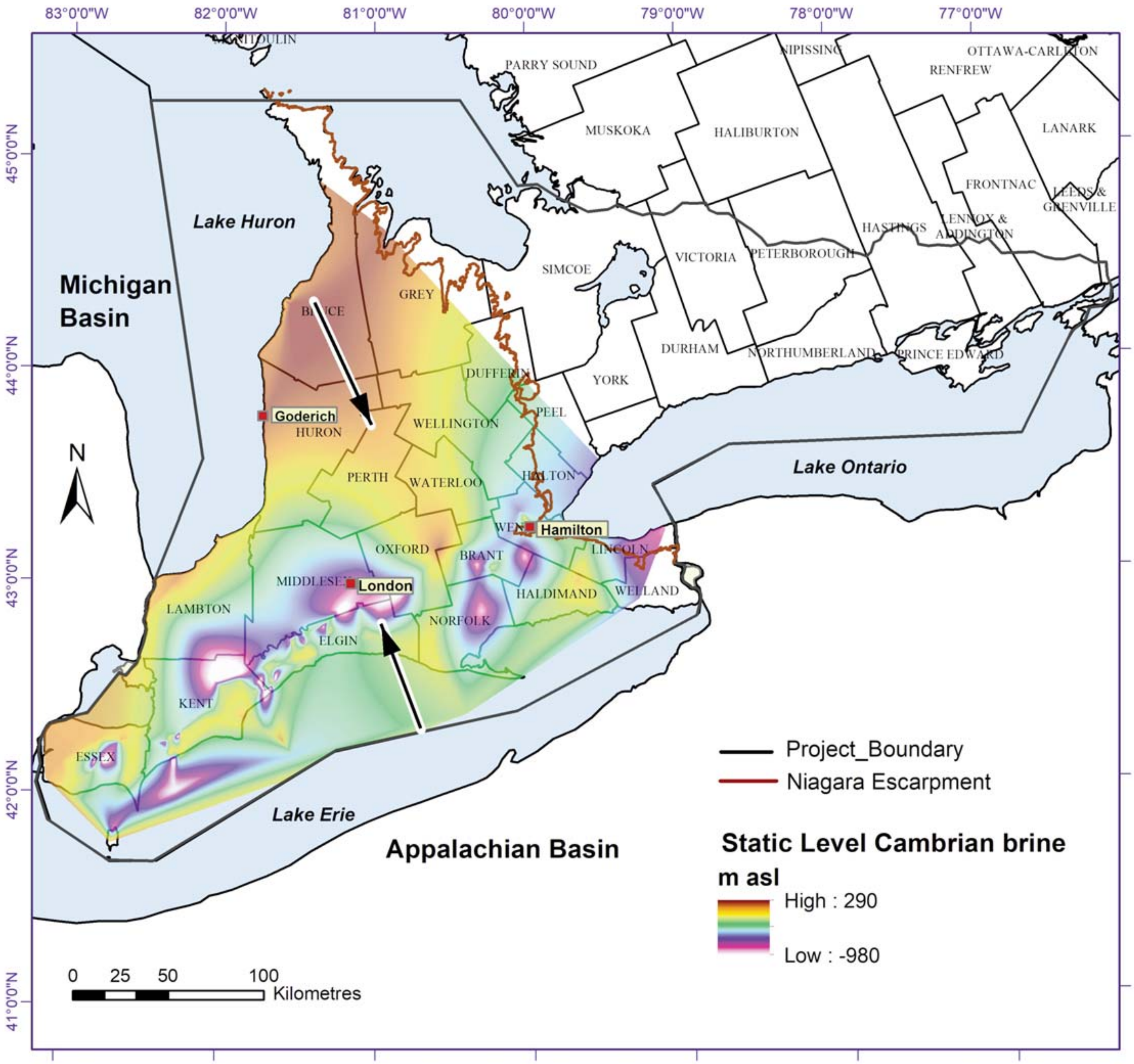

Figure 24. A potentiometric surface map for Cambrian brine encountered by petroleum wells. There are insufficient data to correct for density differences, but available data shows brine density is generally consistent. Indicated hydraulic gradient is to the northwest, up-dip from the Appalachian Basin, and southeast, up-dip from the Michigan Basin (Carter et al. 2015b).

Trevail 1990) and erosional removal over the crest of the Algonquin Arch (Johnson et al. 1992).

Groundwater in the Cambrian Aquifer is exclusively dense Na−Ca−Cl and Ca−Na−Cl brine ranging from 174 000 to 423 000 mg/L TDS (Dollar et al. 1991; Intera Engineering Ltd. 2011; Skuce et al. 2015b) in southern Ontario, similar to values obtained by Al-Aasm and Crowe (2018) for fluid inclusions in calcite and dolomite in deep drill core from the Bruce site. Measured hydraulic conductivity is 3×10^{-6} m/s (Intera Engineering Ltd. 2011). Petroleum industry core analyses show average porosity of 9.2 to 11.8% to a maximum of 20% (Dorland et al. 2016). Hydraulic gradients are up-dip from both the Michigan Basin and the Appalachian Basin (see Fig. 24). At the Bruce site it is highly overpressured, with a formation pressure of 11 000 kPa and a calculated static level of 350 m asl (165 m above ground level; Intera Engineering Ltd. 2011).

HSU 15: Precambrian Aquitard

Crystalline Precambrian metamorphic rocks of the Canadian Shield unconformably underlie the Paleozoic sedimentary rocks in southern Ontario. These rocks are gneiss of granitic, monzonitic, and tonalitic compositions (Armstrong and Carter 2010) all of which were affected by the Grenville Orogeny approximately 1 billion years ago (Easton 1992). This Grenville gneiss was subsequently peneplained by a prolonged period of erosion lasting upwards of 450 million years (R.M. Easton personal communication 2021).

Drillers do not report water-bearing zones in these rocks. The uppermost few metres of the Precambrian bedrock have been altered in southern Ontario and throughout the midcontinent of North America by warm basinal brines that migrated along the unconformity in response to Appalachian orogenic events (Lidiak and Ceci 1991; Harper et al. 1995; Ziegler and Longstaffe 2000a, b). Primary igneous minerals have been altered to illite, chlorite, albite, muscovite and calcite with pervasive occurrence of authigenic K-feldspar. Most of the wells that penetrate the Precambrian in southern Ontario reach total depth within the alteration zone and do not penetrate unaltered Precambrian bedrock (Armstrong and Carter 2010). Measured hydraulic conductivity of the alteration zone is 1×10^{-10} to 1×10^{-9} (Intera Engineering Ltd. 2011). A review of data from analogous unaltered Precambrian rocks elsewhere in the Canadian Shield by Intera Engineering Ltd. (2011) indicates hydraulic conductivity of 1×10^{-12} m/s and porosity of 0.5%.

DISCUSSION

The purpose of this work is to provide a high-level hydrostratigraphic classification of the groundwater systems of southern Ontario as a foundation for 3-D modeling of the hydrostratigraphy. The focus is on groundwater systems in the intermediate to deep subsurface, which are usually ignored in groundwater studies as they do not contain potable water. The Paleozoic lithostratigraphy and the hydrogeological characteristics of the bedrock formations is the foundation for the hydrostratigraphic framework, and so it has been described in some detail. Understanding the geology is the key to understanding the hydrostratigraphy and being able to predict the occurrence of groundwater in the subsurface.

The proposed framework is amenable to further subdivision to accommodate local variability both geographically and stratigraphically (e.g. Intera Engineering Ltd. 2011). It is also subject to improvement, particularly at intermediate depths where the supporting data are relatively sparse. For the most part, the interpreted hydrostratigraphic units comply with the definition of Maxey (1964). The Shallow Karst Aquifer (HSU 3) and the Contact Aquifer are unconventional in that they cross formation boundaries rather than being confined within the lithostratigraphic framework. The defining characteristic of HSU 3 is confinement within shallow karstic carbonate rocks, and for HSU 2 it is the bedrock–surficial sediment interface. These two hybrid hydrostratigraphic units occur at the interface between the confined aquifers in the bedrock and the much more complex and fragmented aquifer systems in the overburden.

A considerable amount of hydrochemical and isotopic data is available from deep bedrock penetrations by oil and gas wells, mostly at depths greater than 250 m. Conversely, most studies of fresh groundwater, and the drilling of water wells, are limited to shallow depths, generally less than 100 m, due to the increase of salinity and other groundwater quality issues with depth. Data are sparse at depths from 100 to 250 m, creating uncertainty about the interaction of shallow fresh groundwater with deeper saline and sulphurous groundwater. Water interval data from petroleum wells indicate a transition from fresh water to brackish to saline sulphur water occurs consistently at approximately 20 to 35 km down-dip from the subcrop edges of all bedrock aquifers, corresponding to a depth of approximately 100 m. Down-dip decrease in $\delta^{18}O$ and $\delta^{2}H$ (‰, VSMOW) over a similar distance, in Norfolk County, suggests that this transition indicates the presence of glacial meltwater in the intermediate groundwater regime. Further investigation is warranted.

Exposure of carbonate and evaporite strata to meteoric water at regional unconformities in the geologic past has resulted in development and enhancement of porosity and permeability at the unconformities. These “paleokarst” horizons are the principal geological control on groundwater occurrence in the bedrock of southern Ontario and host all the regional bedrock aquifers in the intermediate to deep subsurface. Recognition of these paleokarst horizons is key to understanding groundwater (paleo)flow in the bedrock. At shallow depths these paleokarst horizons may be reactivated and enhanced by modern (Quaternary) meteoric water. This knowledge has been used to guide exploration for new sources of groundwater (e.g. Banks and Brunton 2017).

Subsurface groundwater flow (paleo?) pathways in the intermediate to deep groundwater systems are stratabound along the regional unconformities and associated paleokarst. There is considerable evidence of dissolution of salt beds in the geologic past by cross-formational groundwater flow along faults (Sanford 1977; Armstrong and Carter 2010), but there is no evidence of present-day flow along faults. There have been no detailed studies of the timing of salt dissolution along faults, salt dissolution and collapse features related to faults, or direct impacts of faulting on modern groundwater flow. More fundamentally, there have been no comprehensive studies or interpretation of faulting in southern Ontario since the work of Brigham (1971a, b) with the exception of a recent lineament analysis (Béland-Otis 2020). An improved understanding of fault locations, geometry and potential for groundwater movement associated with faults is of particular significance for Ontario’s two underground salt mines, at Windsor and Goderich.

Mapping of active groundwater flow systems in the shallow bedrock is beyond the scope and intent of this study and the reader is referred to recent work by the Ontario Geological Survey, e.g. Brunton and Brintnell (2020), Hamilton et al. (2015) and Priebe et al. (2021). The present study suggests that most groundwater movement in the shallow fresh groundwater system, HSU 1, 2 and 3, is subparallel to the gradient of the ground surface or the top of bedrock, with discharge back to the surface, including the beds of lakes Erie and Huron. Isotopic and hydrochemical data indicate that HSU 3, the shallow karst aquifer system, was a pathway for penetration of glacial meltwater into the intermediate groundwater system. No data are available on the volume or proportion of modern meteoric water that recharges from HSU 3 into the intermediate groundwater system. Depth of down-dip penetration is limited by density gradients created by the increasing salinity at depth and low regional topographic gradient, implying a major component of flow parallel to regional strike and discharge back to the surface. Down-dip decreases in the $\delta^{18}O$ and $\delta^{2}H$ of the groundwater, down-dip increase in salinity over relatively short distances, and the relatively few known sulphur water seeps and springs, suggest that modern recharge volumes to the intermediate groundwater regime are small, probably due to limited discharge pathways. This idea requires further investigation.

This study establishes a regional geological context for groundwater occurrence and pathways for groundwater flow in the bedrock. Flow systems with identifiable recharge and discharge can only be inferred in the intermediate regime with currently available data and do not presently exist in the deep regime.

Additional data on porosity and permeability of Paleozoic bedrock formations at intermediate to deep depths are available in core analysis data from 485 petroleum wells compiled by the OGSRL from MNRF regulatory submissions. Most of these cores were acquired within oil and natural gas reservoirs and, consequently, may not be regionally representative. Compilation and interpretation of core analysis data for the Lockport Group is the subject of current study by one of the authors (see Sun et al. 2020) with the goal of improving our understanding of the relationship between depositional and diagenetic facies and permeability within and between facies belts of the Lockport Group within the intermediate to deep subsurface, and possible connections to the shallow groundwater regime.

CONCLUSIONS

Thirty-five thousand (35 000) water interval records from the MNRF petroleum well database are the key source of information for hydrostratigraphic unit assignments in the subsurface Paleozoic bedrock of southern Ontario. Spatial analysis of these data has enabled the delineation of regional aquifers and aquitards in southern Ontario west of the Niagara Escarpment, identification of hydrochemical depth zonation of groundwater, and interpretation of regional groundwater hydraulic gradients in the intermediate to deep subsurface. Supporting information includes hydrochemical and stable isotope analyses of groundwater samples, field observations in outcrops and quarries, published hydraulic conductivity data from test wells and field studies, observations and interpretations of faults and fractures, microbial DNA analyses, and published geological, hydrochemical, karst and groundwater studies.

Hydrostratigraphic units occur within three groundwater hydrochemical regimes: a shallow fresh water regime, an intermediate brackish to saline sulphur water regime, and a deep brine regime. Flow directions in the shallow groundwater regime (HSU 1, 2) are down-gradient from topographic highs (Sharpe et al. 2014). Shallow karst (HSU 3) is the entry point for groundwater recharge down-dip into the intermediate regime, with paleo-recharge by glacial meltwater and limited recent recharge by meteoric water at subcrop edges. In the deep brine regime hydrostatic gradient is up-dip, at least for the Guelph Formation and Cambrian formations, but there is no evidence of groundwater movement except for induced flow near petroleum wells in response to extraction of oil and natural gas and associated brine.

Fifteen hydrostratigraphic units have been recognized, of which 7 are aquifers. The hydrostratigraphic units are named on the basis of the principal lithostratigraphic units within which they are contained. Most potable groundwater in southern Ontario is found in the Surficial Sediment Aquifer/Aquitard System (HSU 1), the Contact Aquifer (HSU 2), and the Shallow Karst Aquifer System (HSU 3) within the shallow fresh water regime, which extends to depths of 100 to 250 m below the surface. Notably HSU 3 includes the up-dip edges of formations that at depth may be aquitards but in subcrop have enhanced porosity and permeability due to karstification by exposure to acidic meteoric water. This complicates unequivocal assignment of lithostratigraphic units to hydrostratigraphic units and extrapolation of aquitards and aquifers from the deep subsurface to subcrop. Identification of groundwater flow systems within the shallow fresh water regime is beyond the scope and intent of this study.

Hydrostratigraphic units within the intermediate and deep regimes include: Devonian Aquitard, Lucas–Dundee Aquifer, Amherstburg–Bois Blanc Aquitard, Bass Islands Aquifer, Salina Aquitard, Guelph Aquifer, Lower Lockport Aquitard, Clinton–Medina Aquitard, Ordovician Shale Aquiclude, Trenton–Black River Aquitard, Cambrian Aquifer, and the Precambrian Aquitard (Table 4, Fig. 11). Intermediate and deep regime aquifers are confined within thin, regionally extensive paleokarst horizons, separated by thick aquitards. The intermediate hydrochemical regime can extend from a few metres below the bedrock surface in shale units to depths of 350 m, and locally 450 m, and is closely correlated with recharge pathways for down-dip penetration of surface water and potential mixing with older formation fluids, particularly under subglacial hydraulic pressure. The deep hydrochemical regime is dominated by relatively immobile basinal brines that are calculated to be greater than 260 Ma in some low permeability shale units (Clark et al. 2013). Where sufficient data are available, hydrostatic gradient is indicated to be up-dip in deep brine aquifers, but there is no evidence of groundwater movement except in response to extraction of oil, natural gas and associated brine.

Hydrostratigraphic units designated as aquifers are not uniformly porous and permeable. At intermediate depths principal flow zones are confined to karst-enhanced bedding plane partings only a few millimetres to centimetres in thickness.

The hydrostratigraphic units proposed here provide a regional framework subject to continual modification and improvement as new information becomes available. Additional complexity and detail at a local scale can and should be incorporated.

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Since 1998, the Oil, Gas and Salt Resources Library has executed a critical role in maintaining and enhancing Ontario petroleum well data using funding provided by the petroleum and salt industries of Ontario. This work has included very large undertakings of quality control and quality assurance of the data stored by MNRF in OPDS. This study could not have been completed without these data.

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