Geoscience Canada
Journal of the Geological Association of Canada
Journal de l'Association Géologique du Canada

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Volume 47, Number 3, 2020

URI: https://id.erudit.org/iderudit/1072472ar
DOI: https://doi.org/10.12789/geocanj.2020.47.161

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Publisher(s)

The Geological Association of Canada

ISSN

0315-0941 (print)
1911-4850 (digital)

Explore this journal

Cite this article

van Staal, C. & Zagorevski, A. (2020). Accretion, Soft and Hard Collision: Similarities, Differences and an Application from the Newfoundland Appalachian Orogen. *Geoscience Canada*, *47*(3), 103–118. https://doi.org/10.12789/geocanj.2020.47.161

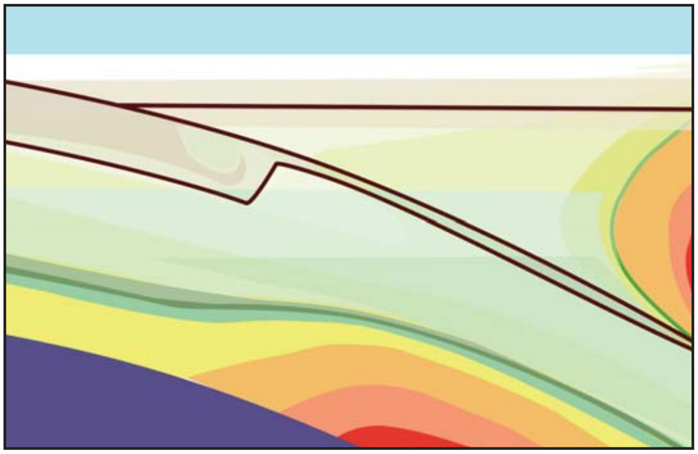
Article abstract

We argue there is no distinction between accretion and collision as a process, except when accretion is used in the sense of incorporating small bodies of sedimentary and/or volcanic rocks into an accretionary wedge by off-scraping or underplating. There is also a distinction when these terms are used in classifying mountain belts into accretionary and collisional orogens, although such classifications are commonly based on a qualitative assessment of the scale and nature of the accreted terranes and continents involved in formation of mountain belts.

Soft collisions occur when contractional deformation and associated metamorphism are principally concentrated in rocks of the leading edge of the partially pulled-down buoyant plate and the upper plate forearc terrane. Several young arc-continent collisions show evidence for partial or wholesale subduction of the forearc such that the arc is structurally juxtaposed directly against lower plate rocks. This process may explain the poor preservation of forearcs in the geological record. Soft collisions generally change into hard collisions over time, except if the collision is rapidly followed by formation of a new subduction zone due to step-back or polarity reversal. Thickening and metamorphism of the arc's suprastructure and retro-arc part of upper plate due to contractional deformation and burial are the characteristics of a hard collision or an advancing Andean-type margin. Strong rheological coupling of the converging plates and lower and upper crust in the down-going continental margin promotes a hard collision.

Application of the soft–hard terminology supports a structural juxtaposition of the Taconic soft collision recorded in the Humber margin of western Newfoundland with a hard collision recorded in the adjacent Dashwoods block. It is postulated that Dashwoods was translated dextrally along the Cabot-Baie Verte fault system from a position to the north of Newfoundland where the Notre Dame arc collided ca. 10 m.y. earlier with a wide promontory in a hyperextended segment of the Laurentian margin.

ANDREW HYNES SERIES: TECTONIC PROCESSES



Accretion, Soft and Hard Collision: Similarities, Differences and an Application from the Newfoundland Appalachian Orogen

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Cees van Staal received the 2019 GAC Logan Medal; this paper is contribution number 6 of the Journal's Logan Medallist series.

SUMMARY
We argue there is no distinction between accretion and collision as a process, except when accretion is used in the sense of incorporating small bodies of sedimentary and/or volcanic rocks into an accretionary wedge by off-scraping or underplating. There is also a distinction when these terms are used in classifying mountain belts into accretionary and collisional orogens, although such classifications are commonly based on a qualitative assessment of the scale and nature of the accreted terranes and continents involved in formation of mountain belts.

Soft collisions occur when contractional deformation and associated metamorphism are principally concentrated in rocks of the leading edge of the partially pulled-down buoyant plate and the upper plate forearc terrane. Several young arc-continent collisions show evidence for partial or wholesale subduction of the forearc such that the arc is structurally juxtaposed directly against lower plate rocks. This process may explain the poor preservation of forearcs in the geological record. Soft collisions generally change into hard collisions over time, except if the collision is rapidly followed by formation of a new subduction zone due to step-back or polarity reversal. Thickening and metamorphism of the arc's suprastructure and retro-arc part of upper plate due to contractional deformation and burial are the characteristics of a hard collision or an advancing Andean-type margin. Strong rheological coupling of the converging plates and lower and upper crust in the downgoing continental margin promotes a hard collision.

Application of the soft–hard terminology supports a structural juxtaposition of the Taconic soft collision recorded in the Humber margin of western Newfoundland with a hard collision recorded in the adjacent Dashwoods block. It is postulated that Dashwoods was translated dextrally along the Cabot-Baie Verte fault system from a position to the north of Newfoundland where the Notre Dame arc collided ca. 10 m.y. earlier with a wide promontory in a hyperextended segment of the Laurentian margin.

RÉSUMÉ
Nous soutenons qu'il n'y a pas de distinction entre l'accrétion et la collision en tant que processus, sauf lorsque l'accrétion est utilisée dans le sens d'incorporer de petits corps de roches sédimentaires et/ou volcaniques dans un prisme d'accrétion par raclage ou sous-placage. Il y a également une distinction lorsque ces termes sont utilisés pour classer les chaînes de montagne en orogènes d'accrétion et de collision, bien que ces classifications soient généralement basées sur une évaluation qualitative de l'échelle et de la nature des terranes accrétés et des continents impliqués dans la formation des chaînes de montagnes.

Des collisions molles se produisent lorsque la déformation par contraction et le métamorphisme associé sont principalement concentrés dans les roches du front de la plaque chevauchante partiellement abaissée et du terrane d'avant-arc de la plaque supérieure. Plusieurs jeunes collisions arc-continent montrent des preuves d'une subduction partielle ou totale de l'avant-arc de telle sorte que l'arc est directement structurellement juxtaposé contre les roches de la plaque inférieure. Ce processus peut expliquer la mauvaise préservation des avant-arcs dans les archives géologiques. Les collisions molles se transforment généralement en collisions dures au fil du temps, sauf si la collision est rapidement suivie de la formation d'une nouvelle zone de subduction en raison d'un recul ou d'une inversion de polarité. L'épaississement et le métamorphisme de la suprastructure de l'arc et de la partie rétro-arc de la plaque supérieure dus à la déformation par contraction et à l'enfouissement sont les caractéristiques d'une collision dure ou d'une marge de type andin en progression. Un fort couplage rhéologique des plaques convergentes et de la croûte inférieure et supérieure dans la marge continentale descendante favorise une collision dure.

L'application de la terminologie molle-dure corrobore une juxtaposition structurelle de la collision molle taconique enregistrée dans la marge de Humber de l'ouest de Terre-Neuve avec une collision dure enregistrée dans le bloc de Dashwoods adjacent. Il est postulé que le bloc de Dashwoods a été déplacé de manière dextre le long du système de failles Cabot-Baie Verte à partir d'une position au nord de Terre-Neuve où l'arc Notre Dame est entré en collision environ 10 m.a. plus tôt avec un large promontoire dans un segment en hyper-extension de la marge laurentienne.

Traduit par la Traductrice

INTRODUCTION

Subduction of oceanic lithosphere ultimately leads to the amalgamation of allochthonous (exotic) terranes with buoyant, unsubductable lithosphere and formation of orogenic belts. The actual process of amalgamation is described in the literature using a variety of terms, including docking, suturing, accretion, and collision. Whereas docking and suturing are commonly used as non-genetic descriptors of amalgamation of terranes, collision and accretion commonly carry different connotations to different authors. Accretion and collision have been used to classify mountain belts into accretionary and collisional orogens (e.g. Windley 1992; Cawood et al. 2009), suggesting to some (e.g. Wang et al. 2006) that accretion and collision of terranes represent fundamentally different processes. In Windley's (1992) view, accretion results in mountain belts characterized by significant addition of new juvenile crust, whereas collision generally does not. Collisions have been further subdivided into 'soft' and 'hard' by some workers (see below). The terminology used in analyzing orogenic belts is compounded by numerous other classifying schemes, based on tectonic (e.g. Şengör and Natal'in 1996; Şengör et al. 2018) or metamorphic characteristics (e.g. Brown 2009). Such classifications can be useful for purposes of comparative orogenesis and whether there were any secular changes in tectonic processes (e.g. Stern 2005; Brown 2007), but it is important to keep in mind that they are arbitrary and commonly depend on the scale of studies (see following).

In this contribution, we review and examine some of the common terminology and classifications that are used in orogenic analysis. We discuss the differences in terminology and assess their implications for tectonic analyses of some orogenic belts. In addition, we present an application from the Newfoundland Appalachians where a distinction between soft and hard collision helps in the tectonic analysis of the Ordovician Taconic–Grampian orogen.

Accretion Versus Collision

Accretionary orogens mainly form by tectonic addition of exotic allochthonous terranes such as island arcs, continental ribbons, oceanic plateaus and oceanic crust to continental margins or relatively stable, isolated terranes, prior to terminal closure of oceans. The growing accretionary orogen is more or less viewed as a large-scale accretionary orogenic wedge. Within this orogenic wedge, allochthonous terranes sequentially accrete to cratonized lithosphere, analogous to scraped-off sedimentary and volcanic rocks in accretionary prisms. In contrast, collisional orogens are commonly thought to form where an ocean fully closes between two converging continent-size terranes. The large size of the collided continental terranes generally prevents tectonic reworking of the intervening accreted terranes by any new subduction set-up outboard of the collisional orogen after termination of convergence between the continental colliders. Reworking is more common in an accretionary orogen, because the accreted terranes are generally relatively small and hence, more prone to be overprinted by subsequent tectonism following the rapid renewal of subduction by stepping outboard behind the accreted terrane. Hence, scale can play a significant role in discriminating between accretionary and collisional 'endmembers' of this classification system. Transfer of smaller sedimentary and volcano-plutonic packages from the downgoing plate to the overlying accretionary wedge by scraping-off, clipping-off or underplating is generally considered to be accretion (e.g. Kimura and Ludden 1995). This commonly occurs below sea level and does not typically form emergent mountains. The individual accretionary events are commonly too short and localized to identify them as distinct events in the ancient geological record. Nonetheless, 'steady-state' accretion or episodic accretion of larger underplated rocks or terranes can result in significant uplift and deformation in modern settings (Fig. 1A, B; e.g. Platt et al. 1985; Brandon et al. 1998; Soh et al. 1998) and can leave their footprint in the form of structures and metamorphism in the geological record (e.g. van Staal et al. 2008; Wells et al. 2014; Zagorevski et al. 2015).

The perspective of the authors can play a significant and rather arbitrary role in the distinction between accretion and collision. For example, docking of the Ontong Java plateau with the Solomon arc along the Vitiaz trench (Fig. 1C) led to imbrication of the Ontong Java plateau, local emergence of islands (Malaita and Santa Isabel), and a subduction reversal along the Solomon trench (Taira et al. 2004). This event is generally viewed as a collision (Mann and Taira 2004). Similarly, docking of the Crescent-Siletzia terrane to North America along the Cascadia subduction zone (Fig. 1B) led to imbrica-

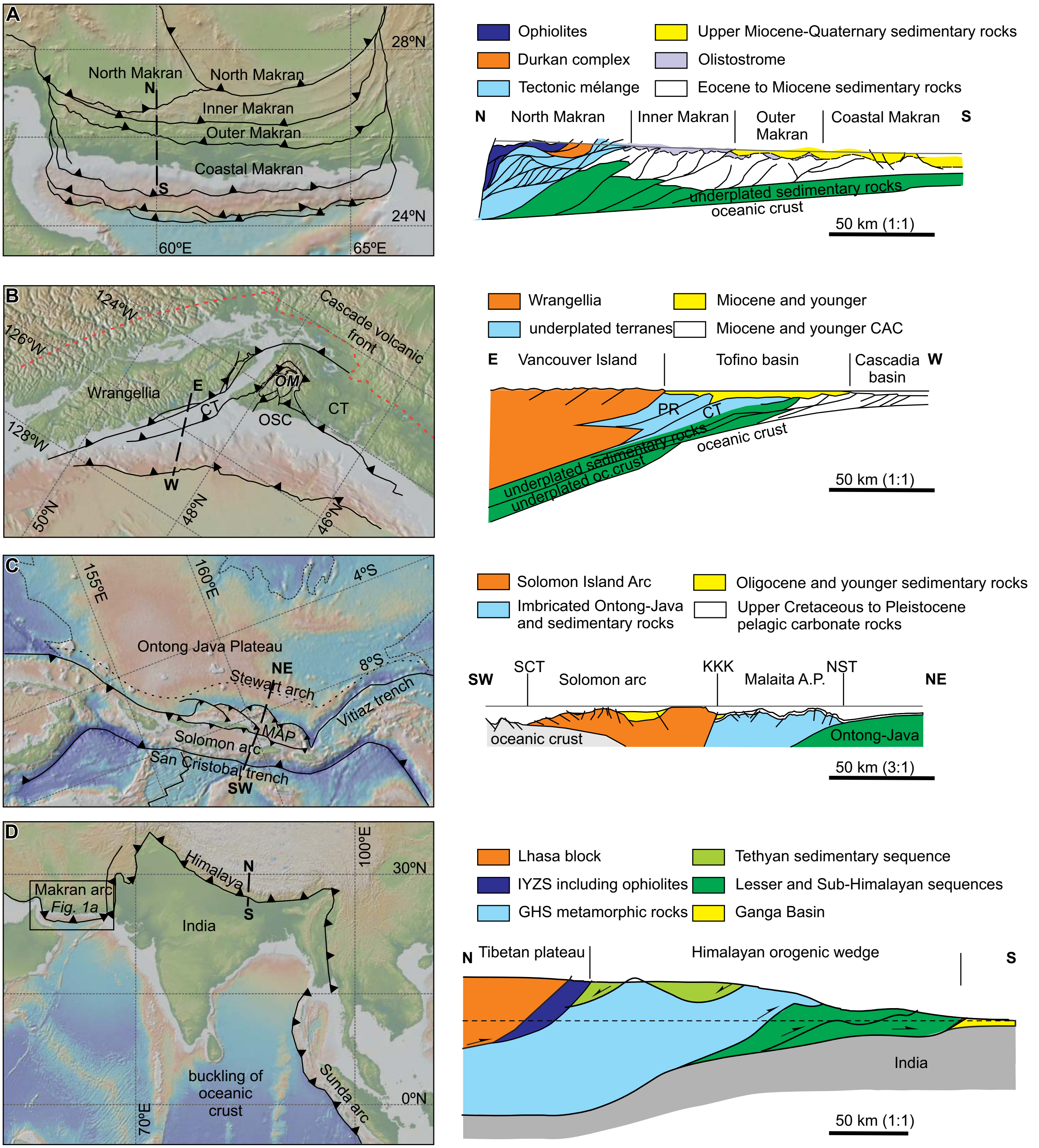

Figure 1. Figures showing the simplified geometries of: (A) the Makran subduction zone immediately west of the India–Eurasia collision zone (modified after Burg 2018). Location of the Makran with respect to India and the Himalayan mountain belt is shown in Fig. 1D, (B) the Cascadia subduction complex along the west coast of British Columbia and Washington (modified after Calvert 1996 and Brandon et al. 1998; CAC – Cascadia accretionary complex; CT – Crescent terrane and equivalents; OM – Olympic Mountains; OSC – Olympic Subduction Complex), (C) the Ontong Java–Solomon arc collision zone (modified after Mann and Taira 2004 and Taira et al. 2004; KKK Kia-Kaipito-Korigole fault zone MAP – Malaita Accretionary Prism, NST North Solomon trench; SCT – San Cristobal trench), and (D) the Himalayan India–Eurasia collision zone (modified after Godin et al. 2018; GHS – Greater Himalayan sequence; IYZS – Indus-Yalung Zangbo Suture zone; location of Figure 1A outlined). Background images and some plate boundaries were generated from www.geomapapp.org.

tion of the partly subducted and underplated Crescent-Siletzia terrane and rocks in the overlying and emerging forearc terrane (e.g. Wells et al. 2014). Yet this is considered an accretionary event by most workers (e.g. Calvert 1996; Groome et al. 2003) rather than a collisional event, although some use these terms interchangeably (e.g. Wells et al. 2014), because it occurred along a continental margin, resulted in growth of an accretionary wedge and continued subduction by stepping back behind the accreted terrane.

Temporal evolution and lateral differences can also play significant roles in the distinction between accretion and collision, which is illustrated in the following thought experiment. The Himalayan mountain belt is generally considered as the type example of a collisional orogen that formed following the closure of the Neotethys Ocean and ongoing India–Eurasia collision (Fig. 1D). However, there is still ongoing subduction of the Indian Ocean beneath the Makran arc to the west and the Sunda arc to the southeast (Fig. 1D). Hence, continental collision occurred only along a relatively short segment of the Neotethys Ocean between India and Eurasia, whereas accretion is ongoing in the adjacent Makran and Sunda accretionary prisms. The India–Eurasia collision generated large intraplate compressive stresses within the subducting Indian plate, which are transferred southwards into the oceanic lithosphere south of India where they are causing large scale buckling and crustal-scale thrust faulting (Fig. 1D; e.g. Beekman et al. 1996). Continued convergence may result in either lateral propagation of the Makran subduction zone along the continental margin of western India or initiation of new subduction south of India along one of the crust-penetrating thrust faults in the deformed oceanic lithosphere along this nascent plate boundary (Coudurier-Curveur et al. 2020). If this occurs, the Himalayan orogenic belt could be viewed as part of an accretionary rather than a collisional orogenic system, albeit one that accreted continental scale, cratonized terranes.

In terms of the process itself, there is no concrete distinction between processes of subduction-induced accretion and collision and hence, these two terms can be used interchangeably. Both of these processes refer to amalgamation of terranes and/or continents following the subduction of the intervening oceanic lithosphere.

Constraining Collision/Accretion Events

The onset of collision or accretion of a continent, an arc or an oceanic plateau to another tectonic element is commonly difficult to constrain and may vary among collision zones. The initiation of collision or accretion occurs when the two converging terranes and/or continents make first contact and the leading edge of the terrane or continent on the downgoing plate enters the foredeep (trench; Fig. 2A). This foredeep, situated between the upper and lower plates, evolves into a foreland basin as tectonic loading leads to flexural subsidence of the leading edge of the underthrust terrane (Fig. 2B). In some collision zones, strong coupling between the forearc and the subducting plate leads to forearc subduction (see following). In these cases, the forearc will experience a similar syn-collisional history to the underthrust terrane.

The onset of collision can result in a number of changes in the upper and lower plates including continental contamination and cessation of arc magmatism (e.g. Huang et al. 2006; Harris 2011), uplift of the upper plate and/or accretionary prism (e.g. Dorsey 1992; Soh et al. 1998; Liu et al. 2001; Lin et al. 2003; Huang et al. 2008), development of fold and thrust belt (Byrne et al. 2011) and flexural subsidence of the lower plate (e.g. Saqab et al. 2017). Continental contamination and/or cessation of arc magmatism (e.g. Huang et al. 2006) are not always a reliable indicator for the onset of collision because arc magmatism may continue for some time and there may be only a short time gap between arc and post-collisional magmatism (Mann and Taira 2004; Harris 2011). Similarly, the record of uplift is typically incomplete and preferentially records the final stages (Soh et al. 1998; Byrne et al. 2011). The deformation record also may be incomplete, lithology-dependent and is commonly difficult to date.

In contrast, the stratigraphy, provenance, and deformation of the syn-collisional foreland and forearc basins can provide some of the best constraints on the initiation of the collision and the evolution of the growing orogen. Foreland basins have an excellent preservation potential and initiate by rapid subsidence of the downgoing plate (Soh et al. 1998; Byrne et al. 2011; Saqab et al. 2017). As the collision progresses, the syn-collisional basins receive detritus from the emerging orogen, starting with uplift and exhumation of the accretionary prism (sedimentary provenance), progressing to the arc upper crust (volcanic and/or ophiolitic provenance), arc middle crust (plutonic provenance), and deeply exhumed orogen (metamorphic provenance). This sedimentary provenance progression provides a detailed record of exhumation of the mountain belt (e.g. Stevens 1970; Nelson and Casey 1979; Dewey and Mange 1999; Huang et al. 2006; Waldron et al. 2012). Careful analysis of the syn-collisional basins therefore is an important tool in orogenic research.

Collisional Styles

The modifiers 'soft and hard' are commonly used qualitatively with respect to collisions in orogenic research by tectonicists outside of the Americas (e.g. Pubellier et al. 1991; Mann and Taira 2004; Matte 2006; Brown 2009; Burg and Bouilhol 2019) with a few exceptions in the Americas (e.g. Zagorevski and van Staal 2011; Iturralde-Vinent et al. 2016). These modifiers have not been defined or described in detail by anybody as far as we know, although attempts have been made (Zagorevski and van Staal 2011). John Dewey introduced these terms in 1996 to the first author who was a visiting scientist in Oxford at the time. Although Dewey never explicitly explained what he meant with these modifiers, it was obvious that he referred to the scale of the structural 'damage' done to the colliding elements, not the rheology of the rocks. 'Soft' referred to collisions where the deformation was relatively light and localized mainly in rocks of the lower plate, and at least in part occurred below sea level. In contrast, hard collisions implied intense penetrative deformation in wide cross-sections of both the lower and upper plates caught up in the damage zone, while the progressively emerging mountains supplied ample sediment to the

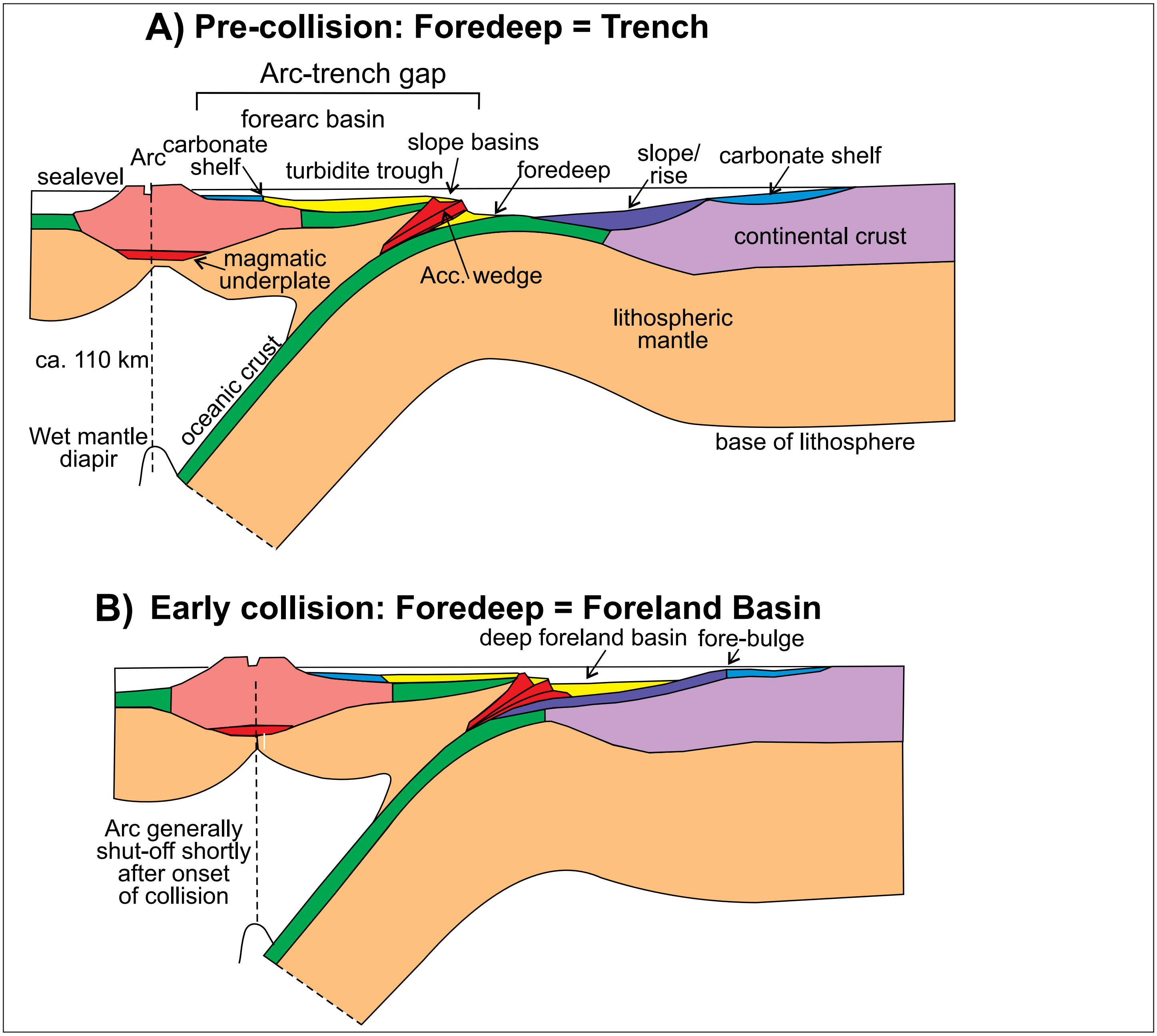

Figure 2. Diagrams showing the tectonic elements usually involved in an arc–continent collision. Collision starts when the leading edge of the approaching continent enters the trench and starts being pulled down beneath the upper plate forearc. At this stage, the foredeep (trench) becomes a foreland basin.

adjacent syn-tectonic basins (e.g. Dewey and Ryan 2016; Ryan and Dewey 2019). This qualitative definition implies that a soft collision could change into a hard collision over time. A collision could remain soft when it is rapidly (< 10 m.y.) followed by subduction step-back and/or subduction polarity reversal, releasing the compressive stresses generated in the collision zone and transferring convergence to a new outboard subduction zone (Dewey 2005). On the other hand, a collision could become 'hard' due to the entrance of progressively more buoyant crust, slowing down of convergence, and increasing coupling and compression between the plates, resulting in widening of the collisional damage zone into the overriding plate (Boutelier and Chemenda 2011; Willingshofer et al. 2013).

The use of soft and hard collision, however, varies somewhat among tectonicists. For example, Matte's (2006) use of 'soft' in his interpretation of the southern Urals was largely based on the absence or low degree of tectonometamorphism of the volcanic and sedimentary rocks of the Magnitogorsk arc and arc-adjacent basins. In contrast, Ryan and Dewey (2019) linked soft collision to the stage when the Grampian orogen in Ireland was still largely below sea level as a result of subduction of a hyperextended margin (Dewey and Ryan 2016), although this model also implies that the upper plate arc terrane was not shortened, internally deformed and thickened at this stage. The degree and nature of the internal shortening, imbrication and burial metamorphism of the upper plate supracrustal rocks of the arc and immediately adjacent basins are thus a potential parameter that can aid in the separation of soft and hard collisions (Zagorevski and van Staal 2011).

Soft Collisions

A review of recent arc–continent collisions (see below), indicates that the early stages of a collision generally localize deformation into the supracrustal rocks of the downgoing plate and overlying, onlapping foreland basin. Together with a pre-collisional accretionary prism, if present, these rocks commonly become imbricated and folded (e.g. Saqab et al. 2017) forming the initial collisional orogenic wedge. Mélanges are common and part of the upper plate forearc terrane, including the accretionary prism, may become (re)deformed internally as a result of a growing and readjusting orogenic wedge (e.g. Westbrook 1982; Harris 2011). The suprastructure of the arc may be faulted and rifted during this stage, but as a rule, the arc is not internally shortened and thickened significantly by imbrication and/or folding. Hence, it is not metamorphosed by structural burial. In our opinion, this tectonic stage best describes a soft collision. Soft collisions are well represented in the recent geological record including segments of the Luzon arc–South China (Huang et al. 2006), Banda arc–Australia (Harris 2011), and Semail ophiolite–Arabian margin collisions (Searle and Cox 1999) as well as others, such as the Melanesian arc–Ontong Java plateau (Mann and Taira 2004), the Honshu arc–Izu-Bonin–Mariana arc (Soh et al. 1998) and Sanghile arc–Halmahera arc collisions (Pubellier et al. 1991).

The Luzon arc–South China collision (Fig. 3A) represents a transition from soft to early stages of a hard collision. This ongoing collision is propagating southward into the South China Sea but is complete in the north. In southern Taiwan, the collision is still in its early stages, parts of the forearc are preserved and there is little or no internal deformation of the Luzon arc suprastructure. The early stage collision in southern Taiwan thus could be described as soft. The initial stages of collision are dated at ca. 6 Ma, largely based on the arrival of non-volcanogenic quartz-rich turbidites derived from the uplifted and exhumed accretionary prism in the forearc and the oldest foreland basin sediments deposited on the passive margin of South China (Huang et al. 2006; Byrne et al. 2011 and references therein).

The more advanced stage collision in central Taiwan is characterized by local deformation of the arc volcanic rocks adjacent to the orogenic wedge and thus represents the start of a transition to a hard collision, although the Luzon arc is not yet pervasively deformed or metamorphosed due to structural burial. Large parts of the forearc were subducted and deformed during this stage of the collision (Tang and Chemenda 2000; McIntosh et al. 2005; Malavieille and Trullenque 2009) and the arc suprastructure became the immediate hanging wall to the orogenic wedge in central Taiwan (Byrne et al. 2011). Parts of the subduction complex (Yuli belt) are being actively exhumed in the footwall of the steeply east-dipping Longitudinal Valley fault system (Brown et al. 2015), which represents the suture between the accreted Luzon arc and the South China margin.

The south-facing Banda/Sunda arc–Australia collision (Fig. 3B) is another young (< 8 Ma) example of a diachronous collision that has reached a relatively mature stage at the longitude of Timor but has not yet taken place farther to the west where oceanic subduction is still ongoing in the Sunda trench (Harris 2011). Continuing convergence in the Banda collision zone is in part taken up by the south-dipping Wetar and Flores thrusts in the Banda Sea, which could be viewed as the initiation of a subduction polarity reversal (Silver et al. 1983; Price and Audley-Charles 1987; Hamilton 1988; Supendi et al. 2020). The Banda collision mainly involved highly deformed (imbricated) and uplifted rocks of the underthrusted Australian margin, structurally overlain respectively by tectonic mélange and a large nappe derived from the Banda forearc (Banda terrane of Harris 2011). Rutherford et al. (2001) proposed that the Banda arc–Australia collision started as early as ca. 16 Ma to explain the westward escape of the Sumba forearc block, but this is inconsistent with the stratigraphic evidence from the foreland and forearc basins. Flexural uplift of the Australian margin and analysis of the foreland basin suggest that underthrusting of the leading edge of the Australian margin beneath the Banda arc–Australia collision started at ca. 6 Ma (Saqab et al. 2017), which would equate with the onset of the soft collision stage. Harris (2011) put the onset of collision slightly earlier ca. 8 Ma), based on the age of the youngest passive margin rocks incorporated in the accretionary wedge, but neither analysis supports an older collision onset as proposed by Rutherford et al. (2001). In addition, contamination of Banda arc volcanic rocks by continental crust took place no earlier than ca. 5 Ma (Harris 2011), which also supports a Late Neogene onset of collision. Volcanism persisted until ca. 2.5–1.3 Ma. Hence, arc volcanism, unlike Taiwan, continued for some time during the advancing collision. Gravity modelling and tomography suggest that part of the forearc was subducted with the Australian lower plate (Harris 2011; Supendi et al. 2020), similar to central Taiwan, whereas part of the arc complex may have been translated to the north, suggesting that the advanced collisional stage in Timor, like in central Taiwan, records a transition from soft to hard collision.

Obduction of the relatively intact suprasubduction zone Semail ophiolite (Fig. 4) can be viewed as a Late Cretaceous collision between the infant oceanic Lasail arc and the Arabian margin (Pearce et al. 1981; Searle and Cox 1999). The onset of collision is constrained by the late Coniacian–Campanian sedimentation in the foreland basin recording underthrusting of the leading edge of the Arabian margin beneath the ophiolite (Robertson 1987). Subduction- and exhumation-related penetrative deformation and burial metamorphism are principally localized in rocks that form part of the downgoing Arabian margin. There are narrow obduction-related shear zones and serpentinite mélanges at the base of the ophiolite which is locally also imbricated and broken up in fault-bounded blocks (Searle and Cox 1999), but penetrative internal deformation and metamorphism related to overthrusting and regional

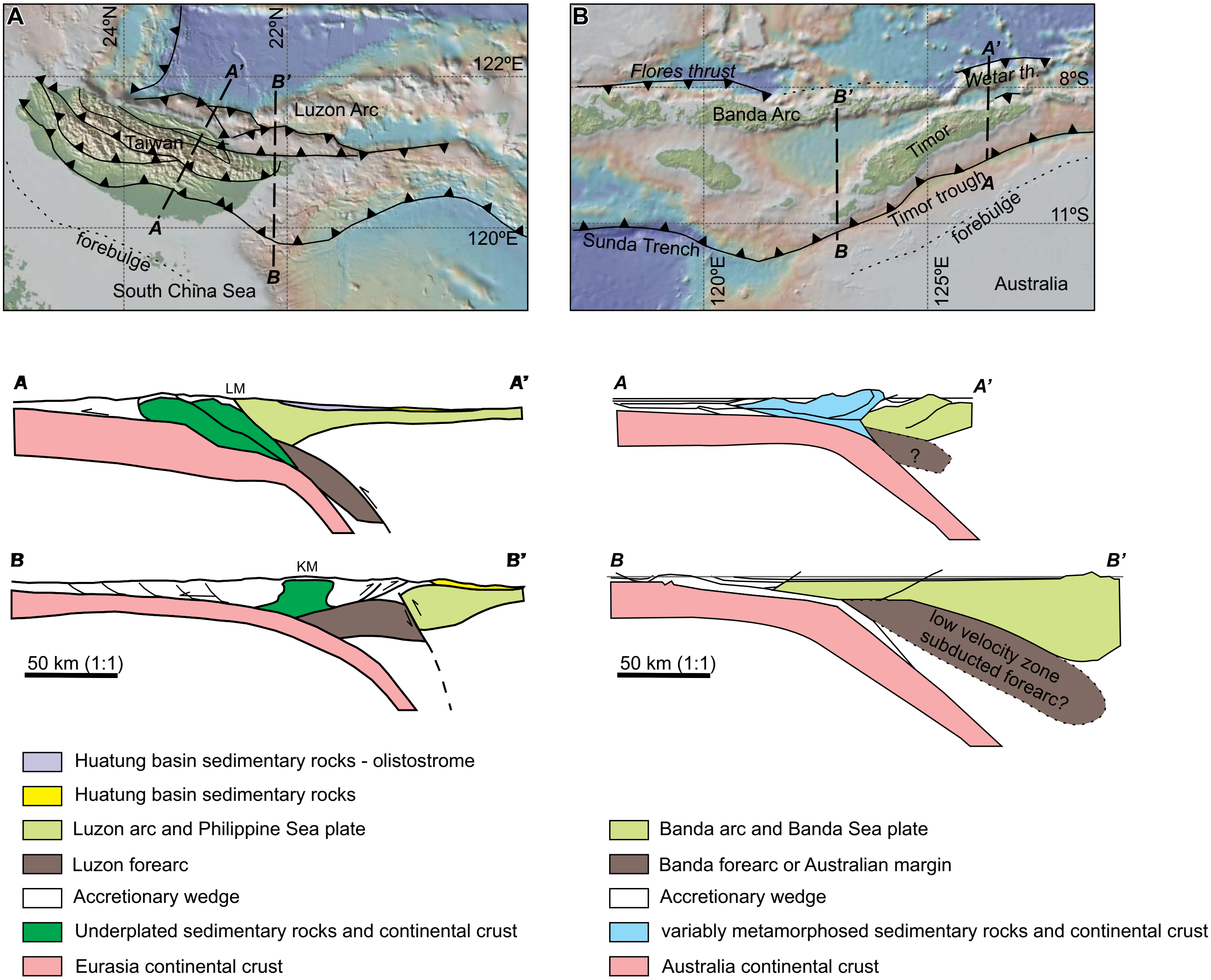

Figure 3. Maps and cross-sections showing the tectonic setting of (A) the China–Luzon arc (modified after McIntosh et al. 2005; LM – Lichi Mélange; KM – Kenting Mélange), and (B) Australia–Banda arc collisions (near surface simplified from Harris 2011, deep crust and mantle modified from Supendi et al. 2020). Background images and some plate boundaries were generated from www.geomapapp.org.

shortening is largely absent in the ophiolite. This collision thus never went beyond the soft collision stage.

Hard Collision

Orogenic belts where lower plate, forearc and significant parts of the upper plate arc and/or retro-arc hinterland are deformed and incorporated into the collisional orogenic wedge are characteristic of hard collisions. Most old orogenic belts on Earth preserve segments that have characteristics of hard collisions. This is not simply a product of deeper level of erosion, as the metamorphic histories of these orogens indicate significant thickening of the upper plate. The Scandian Caledonides in Greenland and Baltica are a good example of a hard collision that resulted in a bivergent orogenic wedge. The pro-wedge preserves Taconic deformed rocks and upper plate arc rocks in the highest east-directed nappes in western Norway (Roberts et al. 2007, 2019), whereas west-directed nappes of the retro-wedge occur in eastern Greenland (Higgins et al. 2004). The nappe stack in the Swiss–Italian Alps comprises penetratively deformed and metamorphosed rocks of both the lower European as well as the upper Adrian plates, elegantly illustrated and described in the kinematic-geometric evolutionary reconstructions made by Escher and Beaumont (1997). The geometry of the orogen with the main detachments nucleating along the interface between upper and lower crust implies a degree of decoupling of the shallow/middle crust from the lower crust and lithospheric mantle (Schmid et al. 1996). Rocks of the upper Adrian plate were also pulled down and incorporated into the evolving nappe stack, recording widening of the deformation channel into the hanging wall of the subduction zone, which was not associated with an arc. The Alps is one of the few orogens where no arc formed dur-

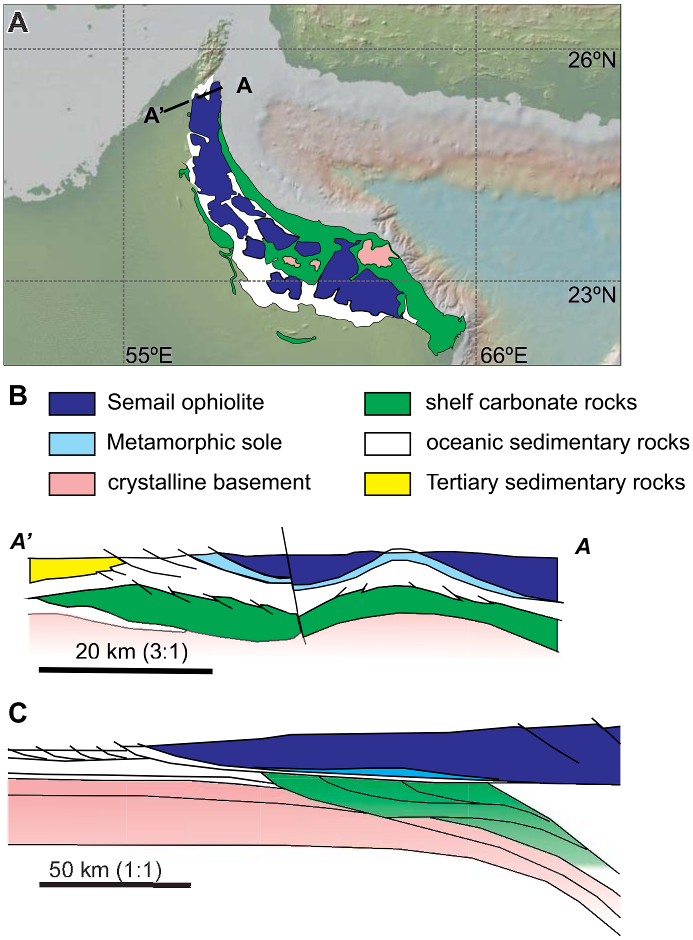

Figure 4. Simplified geological map (A) and a cross-section (B) of the Semail ophiolite and structurally underlying rocks of the Arabian margin. (C) Tectonic model of the Upper Cretaceous obduction the Semail ophiolite. Modified from Searle and Cox (1999). Background image in (A) was generated from www.geomapapp.org.

ing the slow subduction that consumed the narrow Piedmont Ocean (Schmid et al. 1996).

The Himalayan mountain belt is commonly considered as the type example of a collisional orogen (Fig. 1D; Cawood et al. 2009). Like the Alps, the geometry of the Himalaya suggests decoupling of the crust, although there is no incorporation of Eurasian upper plate rocks in the asymmetric orogenic thrust wedge, made up solely of Indian plate rocks. Nevertheless, the various phases of Paleogene–Neogene shortening, which produced foreland- and hinterland-directed thrusting in the upper plate terranes of Tibet (e.g. Lhasa and Qiangtang terranes) that can be linked mechanically to deformation in the south-directed Himalayan thrust belt formed in Indian rocks, conform to the characteristics of a hard collision. However, the gravitational potential energy stored in the thickened crust and resultant body forces in highly elevated parts of southern Tibet formed during the earlier Late Cretaceous–Paleogene collision between the Lhasa and Qiantang terranes, may have inhibited penetrative upper crustal shortening in favour of deformation localized at lower elevations in northern Tibet (e.g. Kapp et al. 2007 and references therein).

Distinction between Soft and Hard Collisions and their Relationship to Accretionary and Collisional Orogens

There are many factors that influence the tectonic style of a collision, but detailed studies of many old and young orogenic belts reveal that a distinction between soft and hard collisions are best made on the nature and tectonometamorphic characteristics of the arc and its upper plate hinterland. Soft collisions are those where the overriding arc and retro-arc hinterland were not significantly shortened and/or penetratively deformed and metamorphosed. Penetrative deformation is basically restricted to the downgoing plate and parts of the forearc of the upper plate, suggesting limited coupling between the upper and lower plates (Willingshofer et al. 2013).

Most hard collisions were preceded by a soft collisional stage(s), because closing oceans commonly contain various isolated buoyant terranes that will accrete to the upper plate before terminal closure. Strong overprint by structures related to the final hard collision may destroy evidence for earlier soft collisional stages. Hence, accretionary orogens are expected to contain the best-preserved remnants of soft or transitional collisions. Several young arc–continent collisions studied in detail, such as Taiwan and Banda, show a transitional character and preserve evidence for subduction of significant parts of the forearc beneath the arc (Fig. 3). Subduction of the forearc may be common in arc–continent collisions. Forearc subduction may explain the absence of well-preserved forearc terranes in accretionary orogens mainly formed by arc accretions (e.g. Zagorevski and van Staal 2011). In contrast, obduction of forearc and trailing arcs such as the Semail ophiolite, may occur if these are thermally immature, extensional, and hence thin (Ryan and Dewey 2019), and the downgoing margin is thin and hyperextended (Reston and Manatschal 2011). Narrower, less extended rifted margins may choke subduction early and instead cause enhanced structural thickening of the margin by inversion of the older, rift-related structures (Reston and Manatschal 2011). In general, hyperextended margins may promote development and preservation of a soft collisional stage preceding the terminal hard collision such as in the Alps and parts of the Taconic–Grampian orogen, because they may be less buoyant than normal continental lithosphere and hence are more easily pulled down and steepen the subduction zone, favouring less coupling with the overriding plate. However, the relative buoyancy of the hyperextended margin is dependent on the degree of serpentinization of the exhumed mantle and volume of mafic magmatism erupted during rifting. It is the leading edge of the downgoing hyperextended margin that is favoured to be pulled down to eclogite-facies depths and to form a complex imbricate stack of high-pressure metamorphic nappes, easily mistaken as a mélange (Beltrando et al. 2010). A hyperextended margin with a thick sequence of rift-related sedimentary rocks on the downgoing plate, on the other hand, may cause thermal blanketing, which will reduce the overall strength of the lithosphere (Reston and Manatschal 2011) and promote thickening and more distributed deformation of the crust in the downgoing plate and increased coupling with the overriding plate.

Structural thickening of the arc and/or retro-arc hinterland typify hard collisions, although such a tectonic style can also form during flat-slab subduction and/or where the upper plate and its arc advances towards the trench, such as in the Andes (Dewey 1980). Andean-style orogenic belts caught up later in a subsequent terminal collisional orogen, may therefore be difficult to separate from the later collision-related structures without careful combined structural and geochronological studies.

Mechanical Control on Orogenic Architecture

Physical analogue and numerical thermo-mechanical models (Willingshofer et al. 2013; Vogt et al. 2017) provide important insights into what controls the distribution of strain during subduction and collision, and its outward propagation from the lower plate into the upper plate (e.g. retro-wedge development); hence, what promotes soft versus hard collisions. Low plate coupling and decoupling between a strong lower and weaker upper continental crust on the downgoing plate, cold initial geotherms and high convergence rates promote formation of highly asymmetric, wide orogens and strain localization in the upper crust of the downgoing plate close to the contact with the upper plate during collision. A foreland-propagating fold and thrust belt forms in the weak upper crust of the lower plate, while the stronger lower crust subducts with the underlying lithospheric mantle (Vogt et al. 2017). Deformation in the overriding plate tends to be minimal and only a weak retro-wedge may develop, if at all (Willingshofer et al. 2013), which corresponds with the orogenic architecture produced by a soft or a transitional collision described above in young arc–continent collisions in southeast Asia (Figs. 1A–C, 3, 4). Hard collisions form where plate coupling between the plates, and the lower and upper crust of the lower plate, become stronger due to a reduced strength contrast and higher geotherms, which both may promote outward propagation of the deformation into the upper plate and formation of doubly vergent orogenic wedges. Slowing down of convergence, relaxation of geotherms and progressive thermal weakening of the orogenic wedge as a result of an ongoing prolonged collision thus could drive an early soft collisional stage to a terminal hard collision. Only short-duration collisions (< 10 m.y.), where convergence-related shortening is terminated due to a subduction polarity reversal or step-back, are settings where a hard stage may not develop.

Application of Soft/Hard Terminology in Orogenic Analysis

The 'soft versus hard' terminology has rarely been used in orogenic studies in the Americas, but can be used as a tool to identify displaced terranes in orogenic reconstructions. This utility is illustrated by the Taconic Appalachians in western Newfoundland (Fig. 5). The Taconic–Grampian orogen in the Appalachian–Caledonian mountain belt records a complex Ordovician collision between Laurentia and an outboard northwest-facing arc with its associated suprasubduction zone (SSZ) ophiolites (van Staal et al. 2007). The collision displays marked changes in tectonic style and architecture along its length (e.g. Ryan and Dewey 2019). Some segments solely preserve evidence of a soft collision, whereas others have characteristics of an earlier soft stage that is overprinted by a hard collision (van Staal et al. 1998, 2009; Dewey and Ryan 2016).

In the Canadian Appalachians, the sediment-dominated Humber margin (Fig. 5 inset) facilitated Mid Ordovician obduction of thin, young SSZ ophiolite sheets in western Newfoundland (e.g. Bay of Islands ophiolite, Cawood and Suhr 1993; Waldron and van Staal 2001) and southern Quebec (e.g. Thetford Mines ophiolite, Tremblay and Pinet 2016). This collision did not result in penetrative contractional deformation and burial metamorphism of the obducted SSZ ophiolites (Suhr and Cawood 1993). Deformation was largely restricted to the ophiolitic sole and underthrusted Humber margin strata that formed thrust sheets, mélanges and folds (e.g. Waldron et al. 2003; Pinet 2013). Metamorphism of the underthrusted Humber margin rocks was mainly low grade, and generally did not exceed greenschist facies (e.g. Castonguay et al. 2001, 2007). The Fleur de Lys Supergroup metasedimentary rocks that were deposited near the leading edge of the Humber margin are preserved in the Corner Brook Lake block (Fig. 5) and record higher grade amphibolite-facies metamorphism that was previously thought to represent Taconic tectonism. However, dating of this Barrovian metamorphism consistently showed it to be Silurian (Salinic) and younger (Cawood et al. 1994; Lin et al. 2013), hence Taconic metamorphism must have been low grade along this part of the margin, consistent with a soft collision. Localization of deformation and low grade metamorphism of the underthrusted sedimentary rocks of the pulled down continental margin, combined with the lack of penetrative deformation of the obducted SSZ ophiolites are hallmarks of a soft collision, analogous to the lack of obduction-related internal deformation of the Semail ophiolite in Oman (Pinet and Tremblay 1995).

The evidence of a soft Taconic collision in western Newfoundland and Quebec is distinctly different from the adjacent Dashwoods block (Fig. 5). The Dashwoods block is a composite terrane, comprising: (i) the Mid to Late Cambrian (509–495 Ma) Lushs Bight oceanic tract (LBOT), which is dominated by island arc tholeiitic mafic rocks and probably represent an arc ophiolite (Swinden et al. 1997), (ii) the Early to Mid Ordovician magmatic and epiclastic rocks of the ensialic first phase of the Notre Dame arc (e.g. ca. 478 Ma Brighton gabbro, Fig. 5), which intruded the LBOT (van Staal et al. 2007), and (iii) a large volume of strongly metamorphosed and deformed sedimentary rocks of various ages, into which the Early Ordovician arc plutons intruded into the oldest part (van Staal et al. 2007). The Dashwoods block is separated from the adjacent Laurentian margin by a highly attenuated narrow belt of late Cambrian (ca. 490 Ma) SSZ ophiolites of the Baie Verte oceanic tract (BVOT), such as the Advocate complex in Baie Verte Peninsula (Fig. 5, van Staal et al. 2009; Skulski et al. 2010). This tectonic boundary is generally referred to as the Baie Verte–Brompton Line (BBL), which coincides with the Cabot Fault in central and southern Newfoundland (Fig. 5). The Dashwoods block and its entrained slivers of LBOT (Fig. 5) record polyphase Taconic deformation and Barrovian metamorphism, locally up to granulite facies (Lissenberg et al. 2006;

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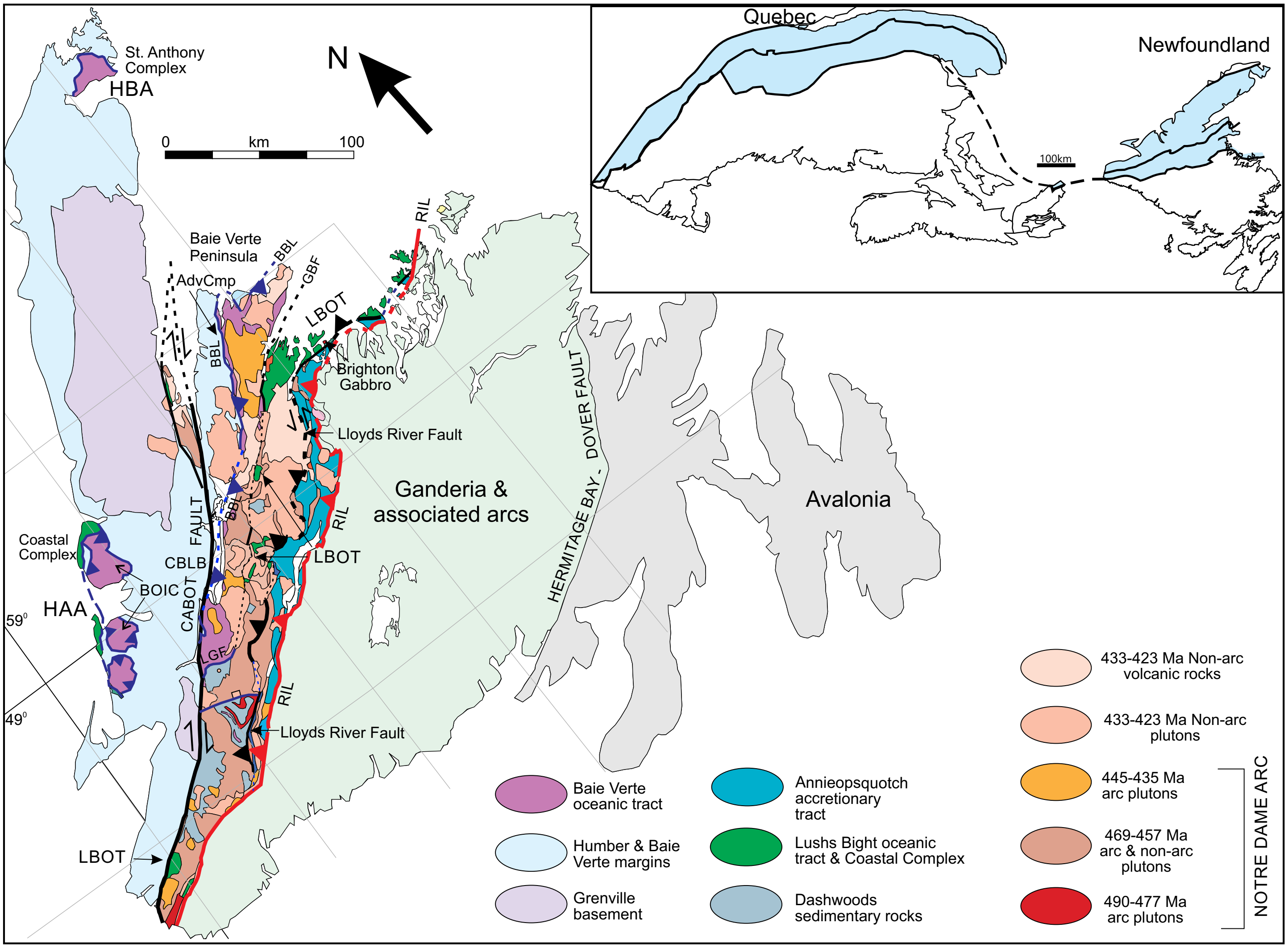

Figure 5. Geology of the Laurentian Humber and Baie Verte margins, and juxtaposed Dashwoods block (modified from van Staal et al. 2007). Note that the Lushs Bight oceanic tract (LBOT) continues as a trail of small blocks and slivers engulfed and/or surrounded by a sea of granitoid rocks (mainly tonalite and quartz diorite) of the Notre Dame arc all the way to its southern extension. Inset shows rocks of the Laurentian margin and associated offshore pericratonic terranes involved in the Taconic orogeny in Newfoundland and southern Quebec. AdvCmp – Advocate Ophiolite Complex;; BBL – Baie Verte–Brompton Line; BOIC – Bay of Island Ophiolite Complex; CBLB – Corner Brook Lake block; GBF – Green Bay fault; HAA – Humber Arm allochthon; HBA – Hare Bay allochthon; LGF Little Grand Lake Fault; LBOT – Lushs Bight oceanic tract; RIL – Red Indian Line.

van Staal et al. 2007). In contrast to the Corner Brook Lake block, the Laurentian Fleur de Lys Supergroup metamorphic tectonites on the Baie Verte Peninsula between the Cabot Fault and the irregular and curving belt of tectonized BVOT ophiolitic slivers (Fig. 4) record Taconic tectonometamorphism, including formation of eclogite, ranging in age between 483 and 460 Ma (Castonguay et al. 2014; de Wit and Armstrong 2014).

The marked contrast in tectonic style suggests the Dashwoods block and the Baie Verte Peninsula were moved from a site where the Taconic arc–Laurentia collision was hard and emplaced into their current position by strike-slip translation along the steeply dipping Cabot Fault and Baie Verte–Brompton Line system (Fig. 6). The lithosphere-cutting Cabot Fault–Baie Verte Line system (van der Velden et al. 2004) accommodated ca. 250 km of dextral displacements during the Late Paleozoic (Waldron et al. 2015) and older, poorly constrained transcurrent movements since the Middle Ordovician (Brem et al. 2007; Lin et al. 2013). The Dashwoods block and the Baie Verte Peninsula thus originated somewhere to the north of Newfoundland (Fig. 6). The site where Dashwoods collided with Laurentia, herein referred to as the Baie Verte margin, is now largely situated below sea level somewhere north of Newfoundland and so cannot be directly investigated.

The Taconic collision displays significant diachroneity along the Baie Verte and Humber margins (Fig. 6). It started between 488 and 480 Ma in the Baie Verte Peninsula and Dashwoods, based on the ages of arc magmatic rocks contaminated by continental crust, metamorphism and the Laurentian provenance of detrital zircon occurring in the Floian Kidney Pond conglomerate near the base of the Snooks Arm Group (van Staal et al. 2007, 2009, 2013; Skulski et al. 2010; Castonguay et al. 2014; de Wit and Armstrong 2014; Willner et al. 2014), at ca. 470 Ma in central Newfoundland (Waldron and

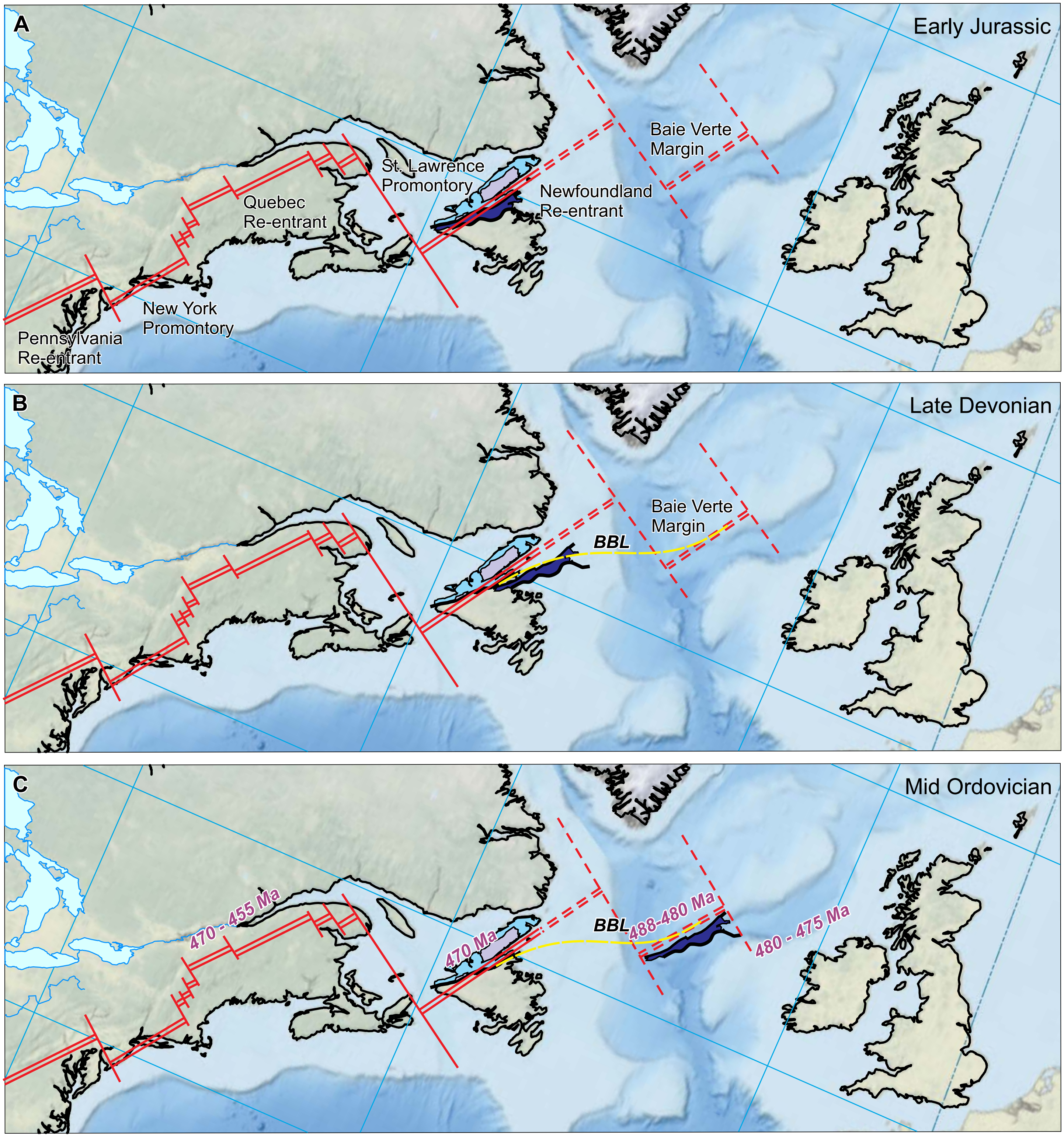

Figure 6. Superimposition of the promontories and re-entrants of Thomas (2005) and the inferred Paleozoic translations of Dashwoods on a landmass reconstruction of the Appalachian–Caledonide connection between Newfoundland and British Isles before Mesozoic opening of the North Atlantic Ocean. North Atlantic restoration includes de-stretching of areas which were subjected to significant stretching and gives an outline of shelf and deeper off-shelf areas. Restoration is based on the reconstruction of Verhoef and Roest (1993). The dashed promontory–re-entrant configuration in the North Atlantic is inspired by the pre-opening bathymetry Late Devonian position of Dashwoods, based on Waldron et al. (2015). BBL – Baie Verte–Brompton Line with its postulated trace across the pre-Atlantic opening restoration to connect with the Clew Bay suture in the west of Ireland. Ages of diachronous Taconic–Grampian arc–continent collision are indicated in (C).

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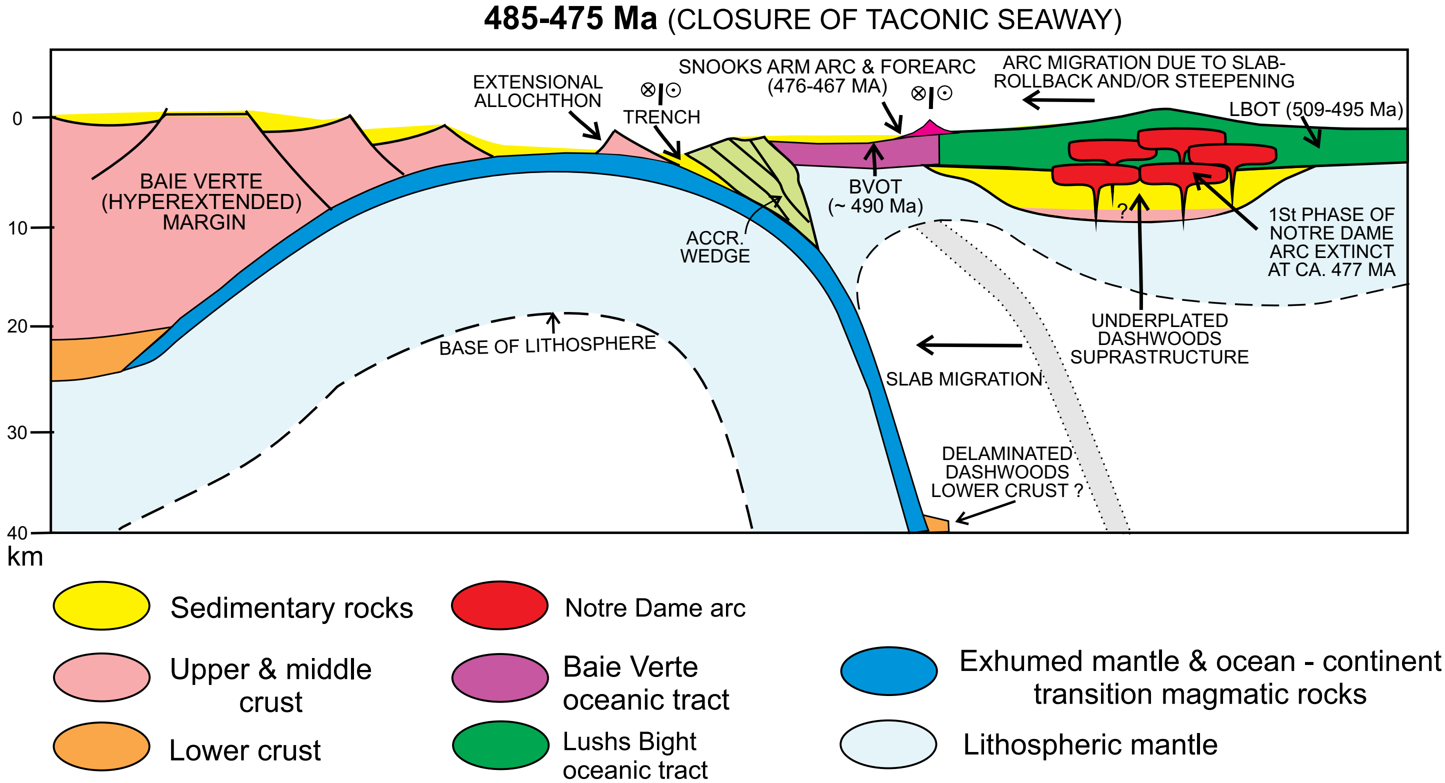

Figure 7. Closure of the Taconic seaway after Dashwoods suprastructure has been underplated to part of the Mid–Late Cambrian Lushs Bight oceanic tract (LBOT) with its lower crust (if there was any) delaminated and pulled down with the subducting plate, which in the Taconic seaway mainly comprised exhumed mantle and mafic magmatic rocks formed during hyperextension (ocean–continent transition). The Coastal Complex in Figure 5 is probably an oceanic arc correlative of the LBOT (van Staal et al. 2007), but never experienced underthrusting by Dashwoods at the latitude it formed; it has a non-exotic, relationship with the BOIC (Cawood and Suhr 1992; Suhr and Cawood 1993). Slab rollback and/or steepening of the subduction zone caused arc migration shortly after the leading edge of the hyperextended Baie Verte margin entered the trench. Figure modified from van Staal et al. (2013).

van Staal 2001) and between 470 and 455 Ma in the Quebec re-entrant (Tremblay and Pinet 2016; White et al. 2020). The hard Taconic collision preserved in the Dashwoods block occurred shortly after an earlier, Late Cambrian–Tremadocian impingement of the LBOT arc with a sediment-rich microcontinent (Dashwoods of Waldron and van Staal 2001) or isolated continental horst (Fig. 7), immediately outboard of a wide promontory in the hyperextended Baie Verte margin (van Staal et al. 2013). Evidence of this initial collision is indicated by crustal contamination of arc magmatism (Swinden et al. 1997; van Staal et al. 2007), and formation of mélanges and shear zones in the LBOT (Taconic 1 of van Staal et al. 2007). The created composite Dashwoods block and the Baie Verte margin remained separated by the Taconic seaway (Fig. 7), which was partly floored by exhumed mantle and transitional oceanic crust, but locally possibly also by highly extended continental crust, forming isolated extensional allochthons (van Staal et al. 2013).

Normal B-subduction of Iapetus lithosphere continued in the adjacent re-entrant and farther to the southwest (present coordinates) (Fig. 6). The absence of obstructing microcontinents in the re-entrants (van Staal et al. 2007) allowed SSZ ophiolite obduction (e.g. Bay of Islands ophiolite and associated Coastal Complex, Newfoundland and Thetford Mines ophiolite, Quebec) onto the narrower Humber margin during the Middle Ordovician. The continued dextral oblique convergence closed the Taconic seaway by subduction and protracted underthrusting of the thin hyperextended Baie Verte margin beneath the Dashwoods block, which culminated in an Early–Mid Ordovician hard collision and Barrovian tectonometamorphism in the upper plate Dashwoods block, including the associated BVOT. In addition, the remnants of a syn-collisional forearc basin developed above part of the BVOT and LBOT are preserved in parts of the Floian–Dapingian Snooks Arm Group and correlatives (Fig. 7; Skulski et al. 2010; van Staal et al. 2013; Castonguay et al. 2014); Snooks Arm augite-phyric diabase intruded into greenschist-facies mafic tectonites of the LBOT (Fig. 8) near Jackson's Cove, Springdale Peninsula, indicating that the LBOT and BVOT are tectonically related and both tied to Dashwoods (Fig. 7). The eastern structural boundary of the Dashwoods block (Lloyds River fault zone) accommodated Early to Mid Ordovician sinistral transpression (Lissenberg et al. 2005; Lissenberg and van Staal 2006; Zagorevski et al. 2007). Hence, the Taconic hard collision led to Mid Ordovician tectonic escape of the Dashwoods block to the southwest, towards Newfoundland.

The most proximal, correlative hard arc–Laurentia collision to northwestern Newfoundland is represented by the Grampian orogen in Ireland. The Grampian tectonites in Connemara and Tyrone resemble those in Dashwoods and the Baie

Figure 8. Undeformed and unmetamorphosed augite-phyric diabase typical of the Snooks Arm Group intruding deformed and metamorphosed Lushs Bight oceanic tract mafic rocks, close to autochthonous outcrops of the Snooks Arm Group on a peninsula immediately northwest of Jackson's Cove, Springdale peninsula, Newfoundland. Blake Hodgin for scale.

Verte Peninsula in many respects (van Staal et al. 1998). Both segments record collision with a hyperextended part of the Laurentian margin (Chew and van Staal 2014), preserve evidence of peri-Laurentian microcontinents (e.g. Waldron and van Staal 2001; Cooper et al. 2011) and have a similar Late Cambrian–Early Ordovician timing for the onset of collision, deformation and Barrovian metamorphism (Chew et al. 2010; Cooper et al. 2011; Dewey and Ryan 2016). Both areas represent a segment of the Laurentian margin with a distinct lithospheric architecture that promoted formation of sizeable syn-collisional forearc basins (e.g. South Mayo trough), but which prevented development of a notable foreland basin on the tectonically loaded margin (Dewey and Ryan 2016; Ryan and Dewey 2019). Collision between the wide hyperextended segment of the Laurentian margin in Ireland and its extension to the north of Newfoundland (Baie Verte margin) with an outboard microcontinent or isolated horst at its leading edge, and the Grampian arc and the arc preserved in the LBOT, respectively, first caused a soft collision (Ryan and Dewey 2019). Continuous convergence led to obduction of the still-active and hot arc (Dewey and Ryan 2016), including any underthrusted and underplated sedimentary rocks of the underthrusted horst and/or microcontinent, farther across the margin such that the collision progressed over time into a hard collision. This hard collision was characterized by intense deformation, Barrovian metamorphism and syn-collision magmatism formed in response to melting of the sedimentary rocks (Dewey and Ryan 2016) and/or slab break-off (van Staal et al. 2007). The Early Ordovician onset of accretion of the Grampian arc and the Dashwoods block slowed down convergence in this segment of the Grampian–Taconic orogen and caused a diachronous reversal in subduction polarity outboard of the collision zone (van Staal et al. 1998; Fig. 6). The latter formed the east-facing infant arcs of the Annieopsquotch accretionary tract in Newfoundland (Fig. 5; Lissenberg et al. 2005; Zagorevski et al. 2006) and its correlatives in Ireland (Dewey and Ryan 2016).

CONCLUSIONS

Accretion and collision of terranes to each other and to continents are basically the same process, although not when used in the sense of incorporating small bodies of sedimentary and/or volcanic rocks into an accretionary wedge by off-scraping or underplating. However, there is a distinction when used in classifying mountain belts into accretionary and collisional orogens, although most accretionary orogens will eventually terminate in continental collision (Cawood et al. 2009). Regardless, it is imperative to keep in mind that orogenic classifications are generally based on a qualitative assessment of the scale and nature of the accreted terranes and continents involved in the formation of the investigated mountain belt.

Soft collision is the stage when deformation is principally concentrated in rocks of the leading edge of the partially pulled down buoyant plate and forearc terrane of the upper plate. Several young arc–continent collisions show evidence for partial or wholesale subduction of the forearc. This process may help explain the poor preservation of forearcs in old and young mountain belts. Soft collisions generally change into hard collisions over time, except where the collision is rapidly followed by formation of a new subduction zone due to step-back or polarity reversal.

Application of the soft and hard collision terminology in comparative orogenesis can be useful, as demonstrated in western Newfoundland where soft and hard segments of the Taconic orogen were juxtaposed by significant transcurrent motions. Distinction between these two types of collision is best made on the basis whether the superstructure of the upper plate arc and retro-arc rock were subjected to contraction-related deformation and metamorphism. Where shortening-related deformation is absent or weak in the upper plate, the collision is soft or transitional; where such deformation is present, the collision is hard. Marked thickening of the arc and retro-arc part of the upper plate is thus the hallmark of a hard collision or an advancing Andean-style active margin. Strong rheological coupling of the converging plates and lower and upper crust in the downgoing continental margin promotes a hard collision. Low coupling promotes the opposite.

ACKNOWLEDGEMENTS

The first author likes to express his appreciation to Paul Hoffman and John Dewey who advanced his understanding of plate tectonics and mountain building processes in general during many discussions over the years. Jim Hibbard introduced the first author to the geology of the Baie Verte Peninsula in the early 1990s, which instigated a subsequent detailed investigation in the 2000s. Numerous fieldtrips with Paul Ryan, John Dewey and John Winchester to the Grampian orogen in the west of Ireland were instrumental in recognizing its similarities and differences to the Newfoundland Taconics. Mike Searle is thanked for showing the first author the intricacies of the Semail ophiolite obduction in Oman during a three-week fieldtrip in 1997. Participation in IGCP524 under the leadership of Dennis Brown allowed both of us to visit the various stages of the Luzon arc–South China collision in Taiwan in 2008. The first author also would like to express his gratitude to his managers (especially John McGlynn, Janet King, Murray Duke and Steve Irwin) over the 35 years he was an officer of the Geological Survey of Canada, who never ceased supporting him in his endeavours to understand formation of the Appalachian orogen and associated tectonic problems. Blake Hodgin is thanked for companionship and assistance in the field while carrying out studies in the western part of the Lushs

Bight terrane in 2018. Reviews and editing by Dave Schofield, Damian Nance, Brendan Murphy, Rob Raeside and Wouter Bleeker improved the paper.

REFERENCES

Beekman, F., Bull, J.M., Cloetingh, S., and Scrutton, R.A., 1996, Crustal fault reactivation facilitating lithospheric folding/buckling in the central Indian Ocean, *in* Buchanan, P.G., and Nieuwland, D.A., *eds*., Modern Developments in Structural Interpretation, Validation and Modelling: Geological Society, London, Special Publications, v. 99, p. 251–263, https://doi.org/10.1144/GSL.SP.1996.099.01.19.

Beltrando, M., Rubatto, D., and Manatschal, G., 2010, From passive margins to orogens: the link between ocean-continent transition zones and (ultra)high-pressure metamorphism: Geology, v. 38, p. 559–562, https://doi.org/10.1130/G30768.1.

Boutelier, D., and Chemenda, A., 2011, Physical modeling of arc-continent collision: a review of 2D, 3D, purely mechanical and thermo-mechanical experimental models, *in* Brown, D., and Ryan, P.D., *eds*., Arc-Continent Collision: Frontiers in Earth Sciences, Springer, p. 445–473, https://doi.org/10.1007/978-3-540-88558-0_16.

Brandon, M.T., Roden-Tice, M.K., and Garver, J.I., 1998, Late Cenozoic exhumation of the Cascadia accretionary wedge in the Olympic Mountains, northwest Washington State: Geological Society of America Bulletin, v. 110, p. 985–1009, https://doi.org/10.1130/0016-7606(1998)110<0985:LCEOTC>2.3.CO;2.

Brem, A.G., Lin, S., van Staal, C.R, Davis, D.W., and McNicoll, V.J., 2007, The Middle Ordovician to Early Silurian voyage of the Dashwoods microcontinent, west Newfoundland; based on new U/Pb and ^{40}Ar/^{39}Ar geochronological, and kinematic constraints: American Journal of Science, v. 307, p. 311–338, https://doi.org/10.2475/02.2007.01.

Brown, D., Wu, Y.-M., Feng, K.-F., Chao, W.-A., and Huang, H.-H., 2015, Imaging high-pressure rock exhumation in eastern Taiwan: Geology, v. 43, p. 651–654, https://doi.org/10.1130/G36810.1.

Brown, M., 2007, Metamorphic conditions in orogenic belts: a record of secular change: International Geology Review, v. 49, p. 193–234, https://doi.org/10.2747/0020-6814.49.3.193.

Brown, M., 2009, Metamorphic patterns in orogenic systems and the geological record, *in* Cawood, P.A., and Kröner, A., *eds*., Earth Accretionary Systems in Space and Time: Geological Society, London, Special Publications, v. 318, p. 37–74, https://doi.org/10.1144/SP318.2.

Burg, J-P., 2018, Geology of the onshore Makran accretionary wedge: Synthesis and tectonic interpretation: Earth Science Reviews, v. 185, p. 1210–1231, https://doi.org/10.1016/j.earscirev.2018.09.011.

Burg, J-P., and Bouilhol, P., 2019, Timeline of the South Tibet–Himalayan belt: the geochronological record of subduction, collision, and underthrusting from zircon and monazite U–Pb ages: Canadian Journal of Earth Sciences, v. 56, p. 1318–1332, https://doi.org/10.1139/cjes-2018-0174.

Byrne, T., Chan, Y.-C., Rau, R.-J., Lu, C.-Y., Lee, Y.-H., and Wang, Y.-J., 2011, The arc-continent collision in Taiwan, *in* Brown, D., and Ryan, P.D. *eds*., Arc-Continent Collision: Frontiers in Earth Sciences, Springer, p. 213–245, https://doi.org/10.1007/978-3-540-88558-0_8.

Calvert, A.J., 1996, Seismic reflection constraints on imbrication and underplating of the northern Cascadia convergent margin: Canadian Journal of Earth Sciences, v. 33, p. 1294–1307, https://doi.org/10.1139/e96-098.

Castonguay, S., Ruffet, G., Tremblay, A., and Féraud, G., 2001, Tectonometamorphic evolution of the southern Quebec Appalachians: ^{40}Ar/^{39}Ar evidence for Middle Ordovician crustal thickening and Silurian–Early Devonian exhumation of the internal Humber Zone: Geological Society of America Bulletin, v. 113, p. 144–160, https://doi.org/10.1130/0016-7606(2001)113<0144:TEOTSQ>2.0.CO;2.

Castonguay, S., Ruffet, G., and Tremblay, A., 2007, Dating polyphase deformation across low-grade metamorphic belts: An example based on ^{40}Ar/^{39}Ar muscovite age constraints from the southern Quebec Appalachians, Canada: Geological Society of America Bulletin, v. 119, p. 978–992, https://doi.org/10.1130/B26046.1.

Castonguay, S., van Staal, C.R., Joyce, N., Skulski, T., and Hibbard, J., 2014, Taconic metamorphism preserved in the Baie Verte Peninsula, Newfoundland Appalachians: Geochronological evidence for ophiolite obduction and subduction and exhumation of the leading edge of the Laurentian (Humber) margin during closure of the Taconic seaway: Geoscience Canada, v. 41, p. 459–482, https://doi.org/10.12789/geocanj.2014.41.055.

Cawood, P.A., and Suhr, G., 1992, Generation and obduction of ophiolites: constraints from the Bay of Islands Complex, western Newfoundland: Tectonics, v. 11, p. 884–897, https://doi.org/10.1029/92TC00471.

Cawood, P.A., Dunning, G.R., Lux, D., and van Gool, J.A.M., 1994, Timing of peak metamorphism and deformation along the Appalachian margin of Laurentia in Newfoundland: Silurian, not Ordovician: Geology, v. 22, p. 399–402, https://doi.org/10.1130/0091-7613(1994)022<0399:TOPMAD>2.3.CO;2.

Cawood, P.A., Kröner, A., Collins, W.J., Kusky, T.M., Mooney, W.D., and Windley, B.F., 2009, Accretionary orogens through Earth history, *in* Cawood, P.A., and Kröner, A., *eds*., Earth Accretionary Systems in Space and Time: The Geological Society, London, Special Publications, v. 318, p. 1–36, https://doi.org/10.1144/SP318.1.

Chew, D.M., and van Staal, C.R., 2014, The ocean–continent collision transition zones along the Appalachian–Caledonian margin of Laurentia: Examples of large-scale hyperextension during opening of the Iapetus Ocean: Geoscience Canada, v. 41, p. 165–185, https://doi.org/10.12789/geocanj.2014.41.040.

Chew, D.M., Daly, J.S., Magna, T., Page, L.M., Kirkland, C.L., Whitehouse, M.J., and Lam, R., 2010, Timing of ophiolite obduction in the Grampian orogen: Geological Society of America Bulletin, v. 122, p. 1787–1799, https://doi.org/10.1130/B30139.1.

Cooper, M.R., Crowley, Q.G., Hollis, S.P., Noble, S.R., Roberts, S., Chew, D., Earls, G., Herrington, R., and Merriman, R J., 2011, Age constraints and geochemistry of the Ordovician Tyrone Igneous Complex, Northern Ireland: implications for the Grampian orogeny: Journal of the Geological Society, v. 168, p. 837–850, https:// doi.org/10.1144/0016-76492010-164.

Coudurier-Curveur, A., Karakaş, Ç., Singh, S., Tapponnier, P., Carton, H., and Hananto, N., 2020, Is there a nascent plate boundary in the northern Indian Ocean?: Geophysical Research Letters, v. 47, e2020GL087362, https://doi.org/10.1029/2020GL087362.

de Wit, M.J., and Armstrong, R., 2014, Ode to field geology of Williams: Fleur de Lys nectar still fermenting on Belle Isle: Geoscience Canada, v. 41, p. 118–137, https://doi.org/10.12789/geocanj.2014.41.043.

Dewey, J.F., 1980, Episodicity, sequence and style at convergent plate boundaries, *in* Strangway, D.W., *ed.,* The Continental Crust and its Mineral Deposits: Geological Association of Canada Special Paper, v. 20, p. 317–414.

Dewey, J.F., 2005, Orogeny can be very short: Proceedings of the National Academy of Sciences, v. 102, p. 15286–15293, https://doi.org/10.1073/pnas.0505516102.

Dewey, J.F., and Mange, M., 1999, Petrography of Ordovician and Silurian sediments in the western Irish Caledonides: tracers of a short–lived Ordovician continent-arc collision orogeny and the evolution of the Laurentian Appalachian-Caledonian margin, *in* MacNiocaill, C., and Ryan, P.D., *eds*., Continental Tectonics: Geological Society, London, Special Publications, v. 164, p. 55–107, https://doi.org/10.1144/GSL.SP.1999.164.01.05.

Dewey, J.F., and Ryan, P.D., 2016, Connemara: its position and role in the Grampian orogeny: Canadian Journal of Earth Sciences, v. 53, p. 1246–1257, https://doi.org/10.1139/cjes-2015-0125.

Dorsey, R.J., 1992, Collapse of the Luzon volcanic arc during onset of arc-continent collision: evidence from a Miocene–Pliocene unconformity, eastern Taiwan: Tectonics, v. 11, p. 177–191, https://doi.org/10.1029/91TC02463.

Escher, A., and Beaumont, C., 1997, Formation, burial and exhumation of basement nappes at crustal scale: a geometric model based on the western Swiss-Italian Alps: Journal of Structural Geology, v. 19, p. 955–974, https://doi.org/10.1016/S0191-8141(97)00022-9.

Godin, L., Soucy La Roche, R., Waffle, L., and Harris, L.B., 2018, Influence of inherited Indian basement faults on the evolution of the Himalayan orogen, *in* Sharma, R., Villa, I.M., and Kumar, S., *eds*., Crustal Architecture and Evolution of the Himalaya–Karakoram–Tibet Orogen: Geological Society, London, Special Publications, v. 481, p. 251–276, https://doi.org/10.1144/SP481.4.

Groome, W.G., Thorkelson, D.J., Friedman, R.M., Mortensen, J.K, Massey, N.W.D., Marshall, D.D., and Layer, P.W., 2003, Magmatic and tectonic history of the Leech River Complex, Vancouver Island, British Columbia: evidence for ridge-trench intersection and accretion of the Crescent terrane, *in* Sisson, V.B., Roeske, S.M., and Pavlis, T.L. *eds*., Geology of a Transpressional Orogen Developed during Ridge-Trench Interaction along the North Pacific Margin: Geological Society of America Special Papers, v. 371, p. 327– 353, https://doi.org/10.1130/0-8137-2371-X.327.

Hamilton, W.B., 1988, Plate tectonics and island arcs: Geological Society of America Bulletin, v. 100, p. 1503–1527, https://doi.org/10.1130/0016-7606(1988)100<1503:PTAIA>2.3.CO;2.

Harris, R., 2011, The nature of the Banda arc-continent collision in the Timor region, *in* Brown, D., and Ryan, P.D., *eds*., Arc-Continent Collision: Frontiers in Earth Sciences, Springer, p. 163–211, https://doi.org/10.1007/978-3-540-88558-0_7.

Higgins, A.K., Elvevold, S., Escher, J.C., Frederiksen, K.S., Gilotti, J.A., Henriksen, N., Jepsen, H.F., Jones, K.A., Kalsbeek, F., Kinny, P.D., Leslie, A.G., Smith, M.P.,

Thrane, K., and Watt, G.R., 2004, The foreland-propagating thrust architecture of the East Greenland Caledonides 72°–75°N: Journal of the Geological Society, v. 161, p. 1009–1026, https://doi.org/10.1144/0016-764903-141.
Huang, C.-Y., Yuan, P.B., and Tsao, S.-J., 2006, Temporal and spatial records of active arc-continent collision in Taiwan: A synthesis: Geological Society of America Bulletin, v. 118, p. 274–288, https://doi.org/10.1130/B25527.1.
Huang, C.-Y., Chien, C.-W., Yao, B., Chang, C.-P., 2008, The Lichi Mélange: a collision mélange formation along early arcward backthrusts during forearc basin closure, Taiwan arc-continent collision, *in* Draut, A.E., Clift, P.D., and Scholl, D.W., *eds*., Formation and Applications of the Sedimentary Record in Arc Collision Zones: Geological Society of America Special Papers, v. 436, p. 127–154, https://doi.org/10.1130/2008.2436(06).
Iturralde-Vinent, M.A., García-Casco, A., Rojas-Agramonte, Y., Proenza, J.A., Murphy, J.B., and Stern, R.J., 2016, The geology of Cuba: A brief overview and synthesis: GSA Today, v. 26, p. 4–10, https://doi.org/10.1130/GSATG296A.1.
Kapp, P., DeCelles, P.G., Gehrels, G.E., Heizler, M., and Ding, L., 2007, Geological records of the Lhasa-Qiangtang and Indo-Asian collisions in the Nima area of central Tibet: Geological Society of America Bulletin, v. 119, p. 917–932, https://doi.org/10.1130/B26033.1.
Kimura, G., and Ludden, J., 1995, Peeling oceanic crust in subduction zones: Geology, v. 23, p. 217–220, https://doi.org/10.1130/0091-7613(1995)023<0217:POCISZ>2.3.CO;2.
Lin, A.T., Watts, A.B., and Hesselbo, S.P., 2003, Cenozoic stratigraphy and subsidence history of the South China Sea margin in the Taiwan region: Basin Research, v. 15, p. 453–478, https://doi.org/10.1046/j.1365-2117.2003.00215.x.
Lin, S., Brem, A.G., van Staal, C.R., Davis, D.W., McNicoll, V.J., and Pehrsson, S., 2013, The Corner Brook Lake block in the Newfoundland Appalachians: a suspect terrane along the Laurentian margin and evidence for large-scale orogeny-parallel motion: Geological Society of America Bulletin, v. 125, p. 1618–1632, https://doi.org/10.1130/B30805.1.
Lissenberg, C.J., and van Staal, C.R., 2006, Feedback between deformation and magmatism in the Lloyds River Fault Zone: An example of episodic fault reactivation in an accretionary setting, Newfoundland Appalachians: Tectonics, v. 25, TC4004, https://doi.org/10.1029/2005TC001789.
Lissenberg, C.J., Zagorevski, A., McNicoll, V.J., van Staal, C.R., and Whalen, J.B., 2005, Assembly of the Annieopsquotch accretionary tract, Newfoundland Appalachians: Age and geodynamic constraints from syn-kinematic intrusions: The Journal of Geology, v. 113, p. 553–570, https://doi.org/10.1086/431909.
Lissenberg, C.J., McNicoll, V.J., and van Staal, C.R., 2006, The origin of mafic-ultramafic bodies within the northern Dashwoods Subzone, Newfoundland Appalachians: Atlantic Geology, v. 42, p. 1–12, https://doi.org/10.4138/2152.
Liu, T.-K., Hsieh, S., Chen, Y.-G., and Chen, W.-S., 2001, Thermo-kinematic evolution of the Taiwan oblique-collision mountain belt as revealed by zircon fission track dating: Earth and Planetary Science Letters, v. 186, p. 45–56, https://doi.org/10.1016/S0012-821X(01)00232-1.
Malavieille, J., and Trullenque, G., 2009, Consequences of continental subduction on forearc basin and accretionary wedge deformation in SE Taiwan: Insights from analogue modeling: Tectonophysics, v. 466, p. 377–394, https://doi.org/10.1016/j.tecto.2007.11.016.
Mann, P., and Taira, A., 2004, Global tectonic significance of the Solomon Islands and Ontong Java Plateau convergent zone: Tectonophysics, v. 389, p. 137–190, https://doi.org/10.1016/j.tecto.2003.10.024.
Matte, P., 2006, The Southern Urals: deep subduction, soft collision and weak erosion, *in* Gee, D.G., and Stephenson, R.A., *eds*., European Lithosphere Dynamics: Geological Society, London, Memoirs, v. 32, p. 421–426, https://doi.org/10.1144/GSL.MEM.2006.032.01.25.
McIntosh, K., Nakamura, Y., Wang, T.-K., Shih, R.-C., Chen, A., and Liu, C.-S., 2005, Crustal-scale seismic profiles across Taiwan and the western Philippine Sea: Tectonophysics, v. 401, p. 23–54, https://doi.org/10.1016/j.tecto.2005.02.015.
Nelson, K.D., and Casey. J.F., 1979, Ophiolitic detritus in the Upper Ordovician flysch of Notre Dame Bay and its bearing on the tectonic evolution of western Newfoundland: Geology, v. 7, p. 27–31, https://doi.org/10.1130/0091-7613(1979)7<27:ODITUO>2.0.CO;2.
Pearce, J.A., Alabaster, T., Shelton, A.W., and Searle, M.P., 1981, The Oman ophiolite as a Cretaceous arc-basin complex: Evidence and implications: Philosophical Transactions of the Royal Society A, v. 300, p. 299–317, https://doi.org/10.1098/rsta.1981.0066.
Pinet, N., 2013, Gaspé Belt subsurface geometry in the northern Québec Appalachians as revealed by an integrated geophysical and geological study: 2—Seismic interpretation and potential field modelling results: Tectonophysics, v. 588, p. 100–117, https://doi.org/10.1016/j.tecto.2012.12.006.
Pinet, N., and Tremblay, A., 1995, Is the Taconian orogeny of southern Quebec the result of an Oman-type obduction?: Geology, v. 23, p. 121–124, https://doi.org/10.1130/0091-7613(1995)023<0121:ITTOOS>2.3.CO;2.
Platt, J.P., Leggett, J.K., Young, J., Raza, H., and Alam, S., 1985, Large-scale sediment underplating in the Makran accretionary prism, southwest Pakistan: Geology, v. 13, p. 507–511, https://doi.org/10.1130/0091-7613(1985)13<507:LSUITM>2.0.CO;2.
Price, N.J., and Audley-Charles, M.G., 1987, Tectonic collision processes after plate rupture: Tectonophysics, v. 140, p. 121–129, https://doi.org/10.1016/0040-1951(87)90224-1.
Pubellier, M., Quebral, R., Rangin, C., Deffontaines, B., Muller, C., Butterlin, J., and Manzano, J., 1991, The Mindanao collision zone: a soft collision event within a continuous Neogene strike-slip setting: Journal of Southeast Asian Earth Sciences, v. 6, p. 239–248, https://doi.org/10.1016/0743-9547(91)90070-E.
Reston, T., and Manatschal, G., 2011, Rifted margins: building blocks of later collisions, *in* Brown, D., and Ryan, P.D., *eds*., Arc-Continent Collision: Frontiers in Earth Sciences, Springer, p. 3–21, https://doi.org/10.1007/978-3-540-88558-0_1.
Roberts, D., Nordgulen, Ø., and Melezhik, V., 2007, The uppermost allochthon in the Scandinavian Caledonides: from a Laurentian ancestry through Taconian orogeny to Scandian crustal growth on Baltica, *in* Hatcher Jr., R.D., Carlson, M.P., McBride, J.H., and Martínez Catalán, J.R., *eds*., 4-D Framework of Continental Crust: Geological Society of America Memoirs, v. 200, p. 357–377, https://doi.org/10.1130/2007.1200(18).
Roberts, D., Morton, A.C., and Frei, D., 2019, A Silurian age for the metasedimentary rocks of the Ekne Group, Trøndelag, Mid-Norwegian Caledonides: and inferences for a peri-Laurentian provenance: Norwegian Journal of Geology, v. 99, p. 583–595, https://doi.org/10.17850/njg99-4-3.
Robertson, A., 1987, The transition from a passive margin to an Upper Cretaceous foreland basin related to ophiolite emplacement in the Oman Mountains: Geological Society of America Bulletin, v. 99, p. 633–653, https://doi.org/10.1130/0016-7606(1987)99<633:TTFAPM>2.0.CO;2.
Rutherford, E., Burke, K., and Lytwyn, J., 2001, Tectonic history of Sumba Island, Indonesia, since the Late Cretaceous and its rapid escape into the forearc in the Miocene: Journal of Asian Earth Sciences, v. 19, p. 453–479, https://doi.org/10.1016/S1367-9120(00)00032-8.
Ryan, P.D., and Dewey, J.F., 2019, The Ordovician Grampian orogeny, western Ireland: Obduction versus "bulldozing" during arc-continent collision: Tectonics, v. 38, p. 3462–3475, https://doi.org/10.1029/2019TC005602.
Saqab, M.M., Bourget, J., Trotter, J., and Keep, M., 2017, New constraints on the timing of flexural deformation along the northern Australian margin: implications for arc-continent collision and the development of the Timor Trough: Tectonophysics, v. 696–697, p. 14–36, https://doi.org/10.1016/j.tecto.2016.12.020.
Schmid, S.M., Pfiffner, O.A., Froitzheim, N., Schönborn, G., and Kissling, E., 1996, Geophysical-geological transect and tectonic evolution of the Swiss-Italian Alps: Tectonics, v. 15, p. 1036–1064, https://doi.org/1010.1029/96TC00433.
Searle, M., and Cox, J., 1999, Tectonic setting, origin, and obduction of the Oman ophiolite: Geological Society of America Bulletin, v. 111, p. 104–122, https://doi.org/10.1130/0016-7606(1999)111<0104:TSOAOO>2.3.CO;2.
Şengör, A.M.C., and Natal'in, B.A., 1996, Turkic type orogeny and its role in the making of the continental crust: Annual Review of Earth and Planetary Sciences, v. 24, p. 263–337, https://doi.org/10.1146/annurev.earth.24.1.263.
Şengör, A.M.C., Natal'in, B.A., Sunal, G., and van der Voo, R., 2018, The tectonics of the Altaids: Crustal growth during the construction of the continental lithosphere of Central Asia between ~750 and ~130 Ma ago: Annual Review of Earth and Planetary Sciences, v. 46, p. 439–494, https://doi.org/10.1146/annurev-earth-060313-054826.
Silver, E.A., Reed, D., McCaffrey, R., and Joyodiwiryo, Y., 1983, Back arc thrusting in the Eastern Sunda Arc, Indonesia: a consequence of arc-continent collision: Journal of Geophysical Research, v. 88, p. 7429–7448, https://doi.org/10.1029/JB088iB09p07429.
Skulski, T., Castonguay, S., McNicoll, V., van Staal, C.R., Kidd, W., Rogers, N., Morris, W., Ugalde, H., Slavinski, H., Spicer, W., Moussallam, Y., and Kerr, I., 2010, Tectonostratigraphy of the Baie Verte oceanic tract and its ophiolite cover sequence on the Baie Verte Peninsula: Current research (2010) Newfoundland and Labrador Department of Natural Resources, Geological Survey Report 10-1, p. 315–335.
Soh, W., Nakayama, K., and Kimura, T., 1998, Arc-arc collision in the Izu collision zone, central Japan, deduced from the Ashigara Basin and adjacent Tanzawa Mountains: Island Arc, v. 7, p. 330–341, https://doi.org/10.1111/j.1440-1738.1998.00193.x.
Stern, R.J., 2005, Evidence from ophiolites, blueschists and ultrahigh-pressure metamorphic terranes that the modern episode of subduction tectonics began in

Neoproterozoic time: Geology, v. 33, p. 557–560, https://doi.org/10.1130/G21365.1.

Stevens, R.K., 1970, Cambro–Ordovician flysch sedimentation and tectonics in west Newfoundland and their possible bearing on a proto-Atlantic Ocean: Geological Association of Canada, Special Paper 7, p. 165–177.

Suhr, G., and Cawood, P.A., 1993, Structural history of ophiolite obduction, Bay of Islands, Newfoundland: Geological Society of America Bulletin, v. 105, p. 399–410, https://doi.org/10.1130/0016-7606(1993)105<0399:SHOOOB>2.3.CO;2.

Supendi, P., Nugraha, A.D., Widiyantoro, S., Abdullah, C.I., Rawlinson, N., Cummins, P.R., Harris, C.W., Roosmawati, N., and Miller, M.S., 2020, Fate of forearc lithosphere at arc-continent collision zones: Evidence from local earthquake tomography of the Sunda-Banda Arc transition, Indonesia: Geophysical Research Letters, v. 47, e2019GL086472, https://doi.org/10.1029/2019GL086472.

Swinden, H.S., Jenner, G.A., and Szybinski, Z.A., 1997, Magmatic and tectonic evolution of the Cambrian–Ordovician Laurentian margin of Iapetus; geochemical and isotopic constraints from the Notre Dame Subzone, Newfoundland, *in* Sinha, A.K., Whalen, J.B., and Hogan, J.P., *eds.,* The Nature of Magmatism in the Appalachian Orogen: Geological Society of America Memoirs, v. 191, p. 337–365, https://doi.org/10.1130/0-8137-1191-6.337.

Taira, A., Mann, P., and Rahardiawan, R., 2004, Incipient subduction of the Ontong Java Plateau along the North Solomon trench: Tectonophysics, v. 389, p. 247–266, https://doi.org/10.1016/j.tecto.2004.07.052.

Tang, J.-C., and Chemenda, A.I., 2000, Numerical modelling of arc-continent collision: application to Taiwan: Tectonophysics, v. 325, p. 23–42, https://doi.org/10.1016/S0040-1951(00)00129-3.

Tremblay, A., and Pinet, N., 2016, Late Neoproterozoic to Permian evolution of the Quebec Appalachians, Canada: Earth-Science Reviews, v. 160, p. 131–170, https://doi.org/10.1016/j.earscirev.2016.06.015.

van der Velden, A.J., van Staal, C.R., and Cook, F.A., 2004, Crustal structure, fossil subduction, and the tectonic evolution of the Newfoundland Appalachians: Evidence from a reprocessed seismic reflection survey: Geological Society of America Bulletin, v. 116, p. 1485–1498, https://doi.org/10.1130/B25518.1.

van Staal, C.R., Dewey, J.F., MacNiocaill, C., and McKerrow, W.S., 1998, The Cambrian–Silurian tectonic evolution of the northern Appalachians and British Caledonides: history of a complex, west and southwest Pacific-type segment of Iapetus, *in* Blundell, D.J., and Scott, A.C., *eds*., Lyell: The Past is the Key to the Present: Geological Society, London, Special Publications, v. 143, p. 197–242, https://doi.org/10.1144/GSL.SP.1998.143.01.17.

van Staal, C.R., Whalen, J.B., McNicoll, V.J., Pehrsson, S.J., Lissenberg, C.J., Zagorevski, A., van Breemen, O., and Jenner, G.A., 2007, The Notre Dame arc and the Taconic orogeny in Newfoundland, *in* Hatcher Jr., R.D., Carlson, M.P., McBride, J.H., and Martínez Catalán, J.R., *eds*., 4-D Framework of Continental Crust: Geological Society of America Memoirs, v. 200, p. 511–552, https://doi.org/10.1130/2007.1200(26).

van Staal, C.R., Currie, K.L., Rowbotham, G., Rogers, N., and Goodfellow, W., 2008, Pressure-Temperature paths and exhumation of Late Ordovician–Early Silurian blueschists and associated metamorphic nappes of the Salinic Brunswick subduction complex, northern Appalachians: Geological Society of America Bulletin, v. 120, p. 1455–1477, https://doi.org/10.1130/B26324.1.

van Staal, C.R., Whalen, J.B., Valverde-Vaquero, P., Zagorevski, A., and Rogers, N., 2009, Pre-Carboniferous, episodic accretion-related, orogenesis along the Laurentian margin of the northern Appalachians, *in* Murphy, J.B., Keppie, J.D., and Hynes, A.J., *eds*., Ancient Orogens and Modern Analogues: Geological Society, London, Special Publications, v. 327, p. 271–316, https://doi.org/10.1144/SP327.13.

van Staal, C.R., Chew, D.M., Zagorevski, A., McNicoll, V., Hibbard, J., Skulski, T., Castonguay, S., Escayola, M.P., and Sylvester, P.J., 2013, Evidence of Late Ediacaran hyperextension of the Laurentian Iapetan margin in the Birchy Complex, Baie Verte Peninsula, northwest Newfoundland: Implications for the opening of Iapetus, formation of peri-Laurentian microcontinents and Taconic – Grampian orogenesis: Geoscience Canada, v. 40, p. 94–117, https://doi.org/10.12789/geocanj.2013.40.006.

Verhoef, J., and Roest, W.R., 1993, Reading the stripes: offshore discoveries in plate tectonics with examples from eastern Canada: Canadian Journal of Earth Sciences, v. 30, p. 261–277, https://doi.org/10.1139/e93-022.

Vogt, K., Matenco, L., and Cloetingh, S., 2017, Crustal mechanics control the geometry of mountain belts. Insights from numerical modelling: Earth and Planetary Science Letters, v. 460, p. 12–21, https://doi.org/10.1016/j.epsl.2016.11.016.

Waldron, J.W.F., and van Staal, C.R., 2001, Taconian orogeny and the accretion of the Dashwoods block: A peri-Laurentian microcontinent in the Iapetus Ocean: Geology, v. 29, p. 811–814, https://doi.org/10.1130/0091-7613(2001)029<0811:TOATAO>2.0.CO;2

Waldron, J.W.F., Henry, A.D., Bradley, J.C., and Palmer, S.E., 2003, Development of a folded thrust stack: Humber Arm Allochthon, Bay of Islands, Newfoundland Appalachians: Canadian Journal of Earth Sciences, v. 40, p. 237–253, https://doi.org/10.1139/e02-042.

Waldron, J.W.F., McNicoll, V.J., and van Staal, C.R., 2012, Laurentia-derived detritus in the Badger Group of central Newfoundland: deposition during closing of the Iapetus Ocean: Canadian Journal of Earth Sciences, v. 49, p. 207–221, https://doi.org/10.1139/e11-030.

Waldron, J.W.F., Barr, S.M., Park, A.F., White, C.E., and Hibbard, J., 2015, Late Paleozoic strike-slip faults in Maritime Canada and their role in the reconfiguration of the northern Appalachian orogen: Tectonics, v. 34, p. 1661–1684, https://doi.org/10.1002/2015TC003882.

Wang, T., Hong, D.-w., Jahn, B.-m., Tong, Y., Wang, J.-b., Han, B.-f., and Wang, X.-x., 2006, Timing, petrogenesis and setting of Paleozoic synorogenic intrusions from the Altai Mountains, northwest China: implications for the tectonic evolution of an accretionary orogeny: Journal of Geology, v. 114, p. 735–751, https://doi.org/10.1086/507617.

Wells, R., Bukry, D., Friedman, R., Pyle, D., Duncan, R., Haeussler, P., and Wooden, J., 2014, Geologic history of Siletzia, a large igneous province in the Oregon and Washington Coast Range: correlation to the geomagnetic polarity time scale and implications for a long-lived Yellowstone hotspot: Geosphere, v. 10, p. 692–719, https://doi.org/10.1130/GES01018.1.

Westbrook, G.K., 1982, The Barbados Ridge Complex: tectonics of a mature forearc system, *in* Leggett, J.K., *ed*., Trench–Forearc Geology: Sedimentation and Tectonics on Modern and Ancient Active Plate Margins: Geological Society, London, Special Publications, v. 10, p. 275–290, https://doi.org/10.1144/GSL.SP.1982.010.01.18.

White, S.E., Waldron, J.W.F., and Harris, N.B., 2020, Anticosti foreland basin offshore of western Newfoundland: concealed record of northern Appalachian orogen development: Basin Research, v. 32, p. 25–50, https ://doi.org/10.1111/bre.12364.

Willingshofer, E., Sokoutis, D., Luth, S.W., Beekman, F., and Cloetingh, S., 2013, Subduction and deformation of the continental lithosphere in response to plate and crust-mantle coupling: Geology, v. 41, p. 1239–1242, https://doi.org/10.1130/G34815.1.

Willner, A.P., Gerdes, A., Massonne, H.-J., van Staal, C.R., and Zagorevski, A., 2014, Crustal evolution of the northeast Laurentian margin and the peri-Gondwanan microcontinent Ganderia prior to and during closure of the Iapetus Ocean: detrital zircon U–Pb and Hf isotope evidence from Newfoundland: Geoscience Canada, v. 41, p. 345–364, https://doi.org/10.12789/ geocanj.2014.41.046.

Windley, B., 1992, Chapter 11 Proterozoic collisional and accretionary orogens, *in* Condie, K.C., *ed*., Proterozoic Crustal Evolution: Developments in Precambrian Geology, v. 10, p. 419–446, https://doi.org/10.1016/S0166-2635(08)70125-7.

Zagorevski, A., and van Staal, C.R., 2011, The record of Ordovician arc-arc and arc-continent collisions in the Canadian Appalachians during closure of Iapetus, *in* Brown, D., and Ryan, P.D., *eds*., Arc-Continent Collision: Frontiers in Earth Sciences, Springer, p. 341–371, https://doi.org/10.1007/978-3-540-88558-0_12.

Zagorevski, A., Rogers, N., van Staal, C.R., McNicoll, V., Lissenberg, C.J., and Valverde-Vaquero, P., 2006, Lower to Middle Ordovician evolution of peri-Laurentian arc and backarc complexes in Iapetus: constraints from the Annieopsquotch accretionary tract, central Newfoundland: Geological Society of America Bulletin, v. 118, p. 324–342**,** https://doi.org/10.1130/B25775.1.

Zagorevski, A., van Staal, C.R., and McNicoll, V.J., 2007, Distinct Taconic, Salinic and Acadian deformation along the Iapetus suture zone, Newfoundland Appalachians: Canadian Journal of Earth Sciences, v. 44, p. 1567–1585, https://doi.org/10.1139/E07-037.

Zagorevski, A, McNicoll, V.J., van Staal, C.R., Kerr, A., and Joyce, N., 2015, From large zones to small terranes to detailed reconstruction of an Early to Middle Ordovician arc-backarc system preserved along the Iapetus suture zone: A legacy of Hank Williams: Geoscience Canada, v. 42, p. 125–150, https://doi.org/10.12789/geocanj.2014.41.054.

Received April 2020
Accepted as revised June 2020