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Thermal modelling of the Laramide orogeny: testing the flat-slab subduction hypothesis

Joseph M. English [a,*], Stephen T. Johnston [a], Kelin Wang [a,b]

[a] School of Earth and Ocean Sciences, University of Victoria, P.O. Box 3055 STN CSC, Victoria, BC, Canada V8W 3P6
[b] Pacific Geoscience Centre, Geological Survey of Canada, 9860 West Saanich Road, Sidney, BC, Canada V8L 4B2

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Abstract

The Laramide orogeny is the Late Cretaceous to Palaeocene (80–55 Ma) orogenic event that gave rise to the Rocky Mountain fold and thrust belt in Canada, the Laramide block uplifts in the USA, and the Sierra Madre Oriental fold and thrust belt in Mexico. The leading model for driving Laramide orogenesis in the USA is flat-slab subduction, whereby stress coupling of a subhorizontal oceanic slab to the upper plate transmitted stresses eastwards, producing basement-cored block uplifts and arc magmatism in the foreland. The thermal models presented here indicate that arc magma generation at significant distances inboard of the trench (> 600 km) during flat-slab subduction is problematic; this conclusion is consistent with the coincidence of volcanic gaps and flat-slab subduction at modern convergent margins. Lawsonite eclogite xenoliths erupted through the Colorado Plateau in Oligocene time are inferred to originate from the subducted Farallon slab, and indicate that the Laramide flat-slab subduction zone was characterised by a cold thermal regime. Thermal modelling indicates that this regime can be produced by flat-slab subduction of old (> ~50 Myr) oceanic lithosphere at high convergence rates. In the Canadian and Mexican portions of the Laramide orogen, the coeval development of a magmatic arc within 300 km of the trench refutes the existence of flat-slab subduction in these regions. It is proposed that subduction of an oceanic plateau/aseismic ridge may have overcome the negative buoyancy inherent in old oceanic lithosphere and resulted in a spatially restricted zone of flat-slab subduction in the USA. These findings cast doubt on the flat-slab model as a primary means of driving Laramide orogenesis along its entire length, and instead point to the need for an alternative mechanism for Cordilleran-wide Laramide orogenesis.

Keywords: tectonics; flat-slab subduction; Laramide orogeny; North America; Cordillera

1. Introduction

The Laramide orogeny is the Late Cretaceous to Palaeocene (80–55 Ma) orogenic event that gave rise to the Rocky Mountain fold and thrust belt in Canada, the Laramide block uplifts in the USA, and the Sierra Madre Oriental fold and thrust belt in east-central Mexico (Fig. 1). In the

* Corresponding author. Tel.: +1-250-472-4011.
E-mail addresses: englishj@uvic.ca (J.M. English), stj@uvic.ca (S.T. Johnston), wang@pgc.nrcan.gc.ca (K. Wang).

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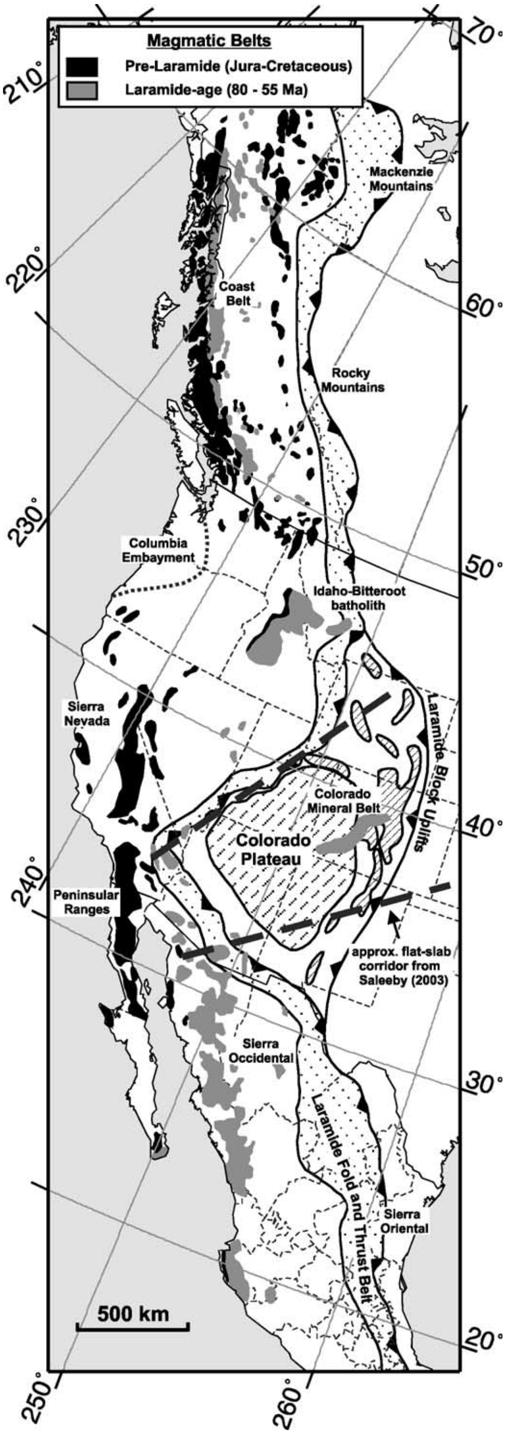

Fig. 1. Map showing areas of pre-Laramide and Laramide magmatism, the extent of the Laramide-age thin-skinned fold and thrust belt and thick-skinned block uplifts, and the approximate location of the Laramide flat-slab according to Saleeby [29]. Note that Cainozoic extension has not been restored in this figure.
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USA, deformation was coeval with significant magmatism; arc-related magmatism is inferred to have spread eastwards into a number of limited areas in the foreland: Idaho/southwestern Montana, and a narrow northeast-trending belt in Colorado known as the Colorado Mineral Belt (e.g. [1–3]; Fig. 1). The Laramide orogeny is widely believed to post-date the Jurassic and late Early Cretaceous accretion of the terranes that make up much of the North American Cordillera (e.g. [4–7]). Thus along much of its length the fold and thrust belt is thought to have developed 700–1500 km inboard of the nearest convergent plate boundary. No crustal blocks or terranes are known to have accreted to the western continental margin during this interval. A collisional origin for Laramide orogenesis has therefore been ruled out, and the favoured model is flat-slab subduction (e.g. [2,4,8]).

In the flat-slab model, the oceanic slab subducting along the western margin of the continent did not descend directly into the mantle, but remained in contact with the upper plate for a distance of >700 km inboard of the trench. As a result, the subducting slab would not have penetrated the asthenosphere beneath the Sierra Nevada, providing an explanation for why magmatism there began to wane and migrate eastwards. Stress coupling of the upper plate with the flat slab could have transmitted stresses eastwards and caused basement-cored block uplifts in the foreland [4,8]. Magmatism and deformation are inferred to have developed above the zone along which the subducting slab eventually steepened and descended into the deep mantle.

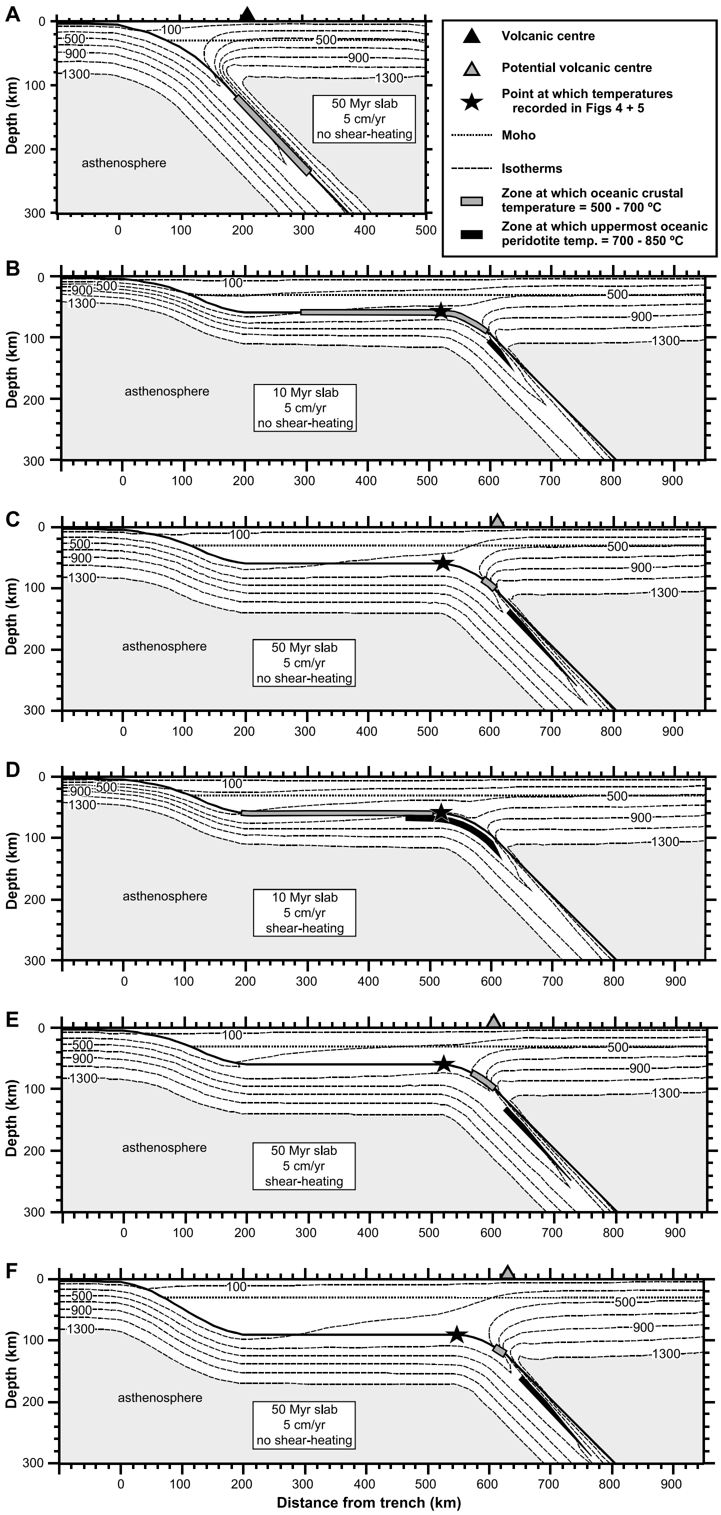
Thermal modelling was used to address two questions: (a) can a flat-slab geometry delay dehydration of the subducted slab until it reaches a distance >600 km inboard of the trench, and hence account for inboard arc magmatism (e.g. Colorado Mineral Belt; Fig. 1), and (b) what do P–T conditions determined from eclogitic xenoliths [9] reveal about the thermal structure and dynamics of Laramide flat-slab subduction? Thermal profiles were constructed across a normal, pre-Laramide subduction zone, and across two possible geometries of the flat-slab subduction model. Variations in the thermal state of the subducting slab as a result of different convergence velocities and slab ages were assessed in order to constrain the conditions under which inboard magmatism could occur. These conditions were compared with existing plate motion models (e.g. [10,11]), which provide us with estimates of rates and directions of plate convergence, and with the estimated age of oceanic crust entering the trench during Laramide time. Finally, the applicability of the flat-slab subduction hypothesis to the Canadian extension of the Laramide was considered, where Coast Belt magmatism records arc development only 250 km inboard of the trench.

2. Thermal model

The thermal regime of the hypothetical Laramide flat-slab subduction zone is investigated by constructing two-dimensional steady-state finite-element thermal models (methodology described by Hyndman and Wang [12] and Wang et al. [13]). A uniform thermal conductivity, heat capacity, heat source, and motion velocity is assigned to each element, with the value evaluated at the centre of the element. The model calculates a steady-state thermal regime for each subduction zone once the boundary conditions are specified. These thermal models include the effects of viscous corner flow in the mantle, radiogenic heating in the continental lithosphere, and shear heating along the subduction interface.

The boundary conditions of the model are: (1) at the surface, the temperature is 0°C, (2) at the left-side boundary, an oceanic geotherm of appropriate age for the incoming plate is applied based on the GDH1 plate cooling model [14], and (3) a continental geotherm with a surface heat flux of 65 mW/m^2, a temperature of 1450°C at 95 km depth and an adiabatic gradient of 0.3°C/km for depths $>$95 km down to the centre of the mantle wedge is applied [15] at the right-side boundary 1200 km from the trench. Thermal conductivities of 2.5 and 2.9 W/m/K are applied to the continental and oceanic lithosphere respectively. The thermal capacities of the crust and mantle are 2.7 and 3.3 MJ/m^3/K respectively, and radioactive decay produces 1.2 μW/m^3 in the upper crust (0–15 km depth), 0.6 μW/m^3 in the lower crust (15–30 km depth), and 0.02 μW/m^3 in the mantle. These models ignore the local effects of advective heat transport to the arc through magmatism. As investigation of the thermal and petrological states of a given flat slab is the primary objective of this study, a kinematic model with prescribed slab geometry and velocity is adequate; the dynamics of how the slab becomes flat is not considered. Following Peacock and Wang [15], and many other authors, corner flow in the mantle wedge is simulated using an analytical solution [16]; this corner flow is driven by the subducting plate. Using a fluid dynamics model with a temperature- and stress-dependent viscosity for the mantle wedge will lead to a higher temperature in the wedge, and hence also in the deeper, dipping segment of the slab, but will have little effect on the flat segment of the slab.

The three variable input parameters for the model are: the plate geometry, the age of the subducting lithosphere, and the plate convergence velocity. Steady-state models are used due to the lack of precise constraints on temporal variations of these primary input parameters. Three different slab geometries are modelled: (a) steep or normal subduction (dip ~45°) that serves as a proxy for pre-Laramide long-term (150–80 Ma; [17]; Fig. 2A) subduction beneath the Sierra Nevadan arc, (b) flat subduction where the flat-slab segment occurs at the base of a 60 km thick upper plate lithosphere (Fig. 2B–E), and (c) flat subduction where the flat-slab segment occurs at the base of a 90 km thick upper plate lithosphere (Fig. 2F). The flat slab extends a distance of 550 km inboard of the trench in order to test the possibility of arc magma generation at abnormal distances from the trench.


A
B
C
D
E
F
Volcanic centre
Potential volcanic centre
Point at which temperatures recorded in Figs 4 + 5
Moho
Isotherms
Zone at which oceanic crustal temperature = 500 - 700 ºC
Zone at which uppermost oceanic peridotite temp. = 700 - 850 ºC
50 Myr slab
5 cm/yr
no shear-heating
10 Myr slab
5 cm/yr
no shear-heating
50 Myr slab
5 cm/yr
no shear-heating
10 Myr slab
5 cm/yr
shear-heating
50 Myr slab
5 cm/yr
shear-heating
50 Myr slab
5 cm/yr
no shear-heating
asthenosphere
100
500
900
1300
Depth (km)
Distance from trench (km)

Arc magmatism occurs when water released from a dehydrating slab at depths of 60–120 km induces partial melting of the overlying mantle wedge at temperatures in excess of 1300°C (e.g. [18]). Hence, two conditions are necessary in order to produce arc magmatism: (a) the presence of an asthenospheric wedge at temperatures in excess of 1300°C, and (b) the presence of a dehydrating slab. In a flat-slab subduction setting, a transient tongue of asthenosphere can exist above the subhorizontal oceanic crust allowing magmatism to migrate inboard during the steep- to flat-slab transition [19]. It takes ~5–20 Myr for a subduction zone to reach thermal steady state [20], during which this asthenospheric tongue will cool, retreat and disappear. Hence, inboard magmatism above this asthenospheric tongue is short-lived (e.g. ~4 Myr in Sierra Pampeanas, Argentina [19]), and many modern flat-slab segments are characterised by volcanic gaps (e.g. central Chile, Peru [21]).

The *P–T* path followed by the top of the subducting oceanic crust can be plotted on a phase diagram for basalt in order to constrain where various dehydration reactions occur. At the blueschist–eclogite transition for example, hydrous minerals such as glaucophane in the oceanic crust break down to form an anhydrous assemblage of garnet and omphacite ([22]; Fig. 3). Schmidt and Poli [18] indicated that some hydrous minerals such as lawsonite and chloritoid might remain stable after the disappearance of amphibole until temperatures of ~700–750°C are attained for depths less than 150 km. In short, it appears that the subducting oceanic lithosphere becomes largely anhydrous once it has been heated above 600–700°C. If the subducting slab is heated to these temperatures before penetrating the asthenospheric wedge, little or no arc magmatism is predicted. This may be the case in modern subduction settings where volcanic gaps are associated with zones of flat-slab subduction (e.g. [19,21]). Hydrated peridotites in the subducting slab may also transport water down beneath the mantle wedge and contribute to arc magma generation (e.g. [18,23]. Phase diagrams for hydrated peridotites indicate that between ~1 and 3 GPa, serpentine minerals such as antigorite are stable until ~700–720°C [23] and ~1 wt% H_2O remains until temperatures of ~850°C are attained [18].

3. Model results

Six thermal models are displayed for a constant convergence velocity; only slab age, slab geometry and shear heating along the subduction interface are varied (Fig. 2). The first thermal model represents pre-Laramide normal subduction beneath the Sierra Nevadan arc (dip ~45°; Fig. 2A). The calculated *P–T* paths for this slab (Fig. 3) indicate that dehydration reactions such as the breakdown of chloritoid occur beneath the core of the overlying asthenospheric wedge at depths in excess of 100 km. In this scenario, partial melting within the overlying wedge would produce abundant calc-alkaline arc magmatism, analogous to modern magmatism in NE Japan [15].

For flat-slab subduction beneath a 60 km thick upper plate lithosphere, the effects of slab age and shear heating are investigated (Fig. 2B–E). A warm flat-slab subduction zone is produced by a young subducting plate (Fig. 2B). Most of the water is driven off at shallow depths and the subducting slab is largely anhydrous when it begins to descend into the asthenosphere (Fig. 3). However, a cold flat-slab subduction zone is produced by the subduction of an old, cold oceanic plate (Fig. 2C), and by high trench-normal convergence velocities. In this case, the slab remains hydrated

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Fig. 2. Thermal structure of subduction zones with a convergence velocity of 5 cm/yr. (A) Geometry of a pre-Laramide normal subduction zone. (B) 10 Myr flat slab at 60 km depth with no shear heating. (C) 50 Myr flat slab at 60 km depth with no shear heating. (D) 10 Myr flat slab at 60 km depth with shear heating. (E) 50 Myr flat slab at 60 km depth with shear heating. (F) 50 Myr flat slab at 90 km depth with no shear heating. Note that subduction of young oceanic lithosphere results in slab dehydration prior to its descent into the asthenosphere.

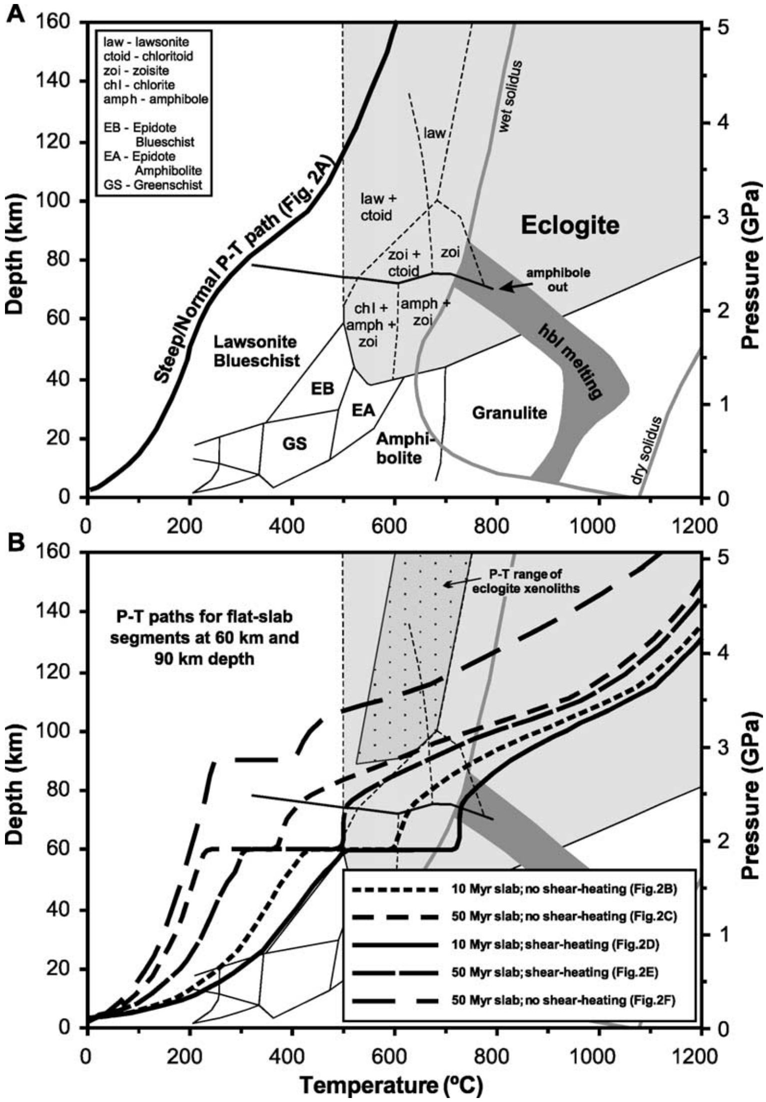

Fig. 3. P–T diagram showing the P–T paths of oceanic crust. (A) Metamorphic facies and partial melting curves for basaltic compositions from Peacock and Wang [15] and references therein, and hydrous minerals stable in the eclogite field from Schmidt and Poli [18]. Eclogite field is shown in grey. (B) P–T paths of oceanic crust for various flat-slab subduction zones shown in Fig. 2. P–T ranges of the Farallon lawsonite eclogite xenoliths from Usui et al. [9] shown in stippled pattern. Note the early-stage dehydration of the young oceanic plates.

until it begins to penetrate the asthenosphere 600 km from the trench, although dehydration occurs more rapidly and at shallower depths than in normal subduction zones (such as Fig. 2A). A shallower dehydration depth does not necessarily prevent arc volcanism. For example, feeble arc volcanism occurs in SW Japan even though thermal models indicate dehydration at shallow depths in the subduction zone [15]. We can conclude however that inboard (~600 km) arc magma generation is not predicted for warm subduction zones and is difficult at best for cold subduction zones. In the cold subduction zone models, temperatures in the mantle wedge above the zone of slab dehydration are perhaps too low to result in partial melting, but there are sufficient uncertainties in the modelling of mantle wedge dynamics that this point is inconclusive. If frictional heating along the subduction interface, and/or a non-linear mantle wedge rheology are used in these models (e.g. [24]), the mantle wedge and subducting slab will be hotter, such that slab dehydration will occur at shallower depths, and inboard arc magma generation becomes more unlikely.

If stress coupling of the upper and lower plates was the driving mechanism for inboard deformation during the Laramide orogeny, the effect of shear heating along this interface must be considered. Shear heating along the subduction interface provides an additional source of heat and results in warming of the subducting slab, thus increasing the window during which slab dehydration could occur prior to its descent into the asthenosphere (Figs. 2D,E and 3). A constant shear stress of 15 MPa is applied along the subduction interface down to the end of the flat-slab segment; realistic values may be lower for these depths and temperatures as shear stresses in the shallow portions of modern, normal subduction zones are estimated to lie in the range of 10–30 MPa [20]. In this scenario, calc-alkaline magmatism is prohibited by the premature dehydration of the slab during subduction of a young oceanic plate (Fig. 3). In addition to shear heating, thermal erosion of the base of the cold subducting oceanic lithosphere and radiogenic heat production in the oceanic crust may further push the thermal structure of the subduction zone towards a warmer end-member.

The effects of variations in the depth to the flat-slab segment are also investigated (Fig. 2F). The temperature variations along the upper surface of an oceanic plate descending to a flat-slab segment at a depth of 90 km are similar to those for the 60 km example (Fig. 3). However, the difference in pressure between these two subduction geometries may have a significant effect on the stability of various hydrous minerals. For example, amphibole is only stable in the oceanic crust at depths less than ~75–80 km (Fig. 3). Therefore, when the flat-slab segment occurs at a depth of 90 km (Fig. 2F), only hydrous minerals such as lawsonite and chloritoid will be stable in the oceanic crust (Fig. 3), and most of the slab dehydration will take place within ~200 km of the trench.

The trench-normal convergence velocity and the age of the subducting slab also have a first-order influence on the thermal structure of the subduction zone. In a model with a constant subduction geometry, the temperature of the subducting slab changes with various combinations of trench-normal convergence velocity and slab age (Fig. 4). The temperature at the top of the subducting crust is calculated at the end of the flat-slab segment before it begins to descend into the asthenosphere (stars in Fig. 2B–F). As the pressure remains constant at these fixed points, phase transitions are solely a function of temperature (Fig. 4). For young slabs and low convergence rates, the slab will have reached temperatures in excess of 600°C by the end of the flat-slab segment, and hence, rare or no arc magmatism is predicted. For slab ages greater than 50 Myr, the oceanic crust will still be relatively cold (~400°C) at the end of the flat-slab segment over a large range of trench-normal convergence velocities. In other words, inboard (>600 km) arc magmatism is not predicted to occur during flat-slab subduction of a young (<20 Myr) oceanic plate (Fig. 4A). If there is significant shear heating (15 MPa) along the subduction interface, inboard arc magmatism is problematic for subducting plates younger than ~40 Myr (Fig. 4B). In both of these scenarios, the rapid burn-up of the subducting slab after passing through a flat-slab segment may also inhibit arc magmatism, even for old (>40 Myr) slabs, as most of the dehydration occurs at much shallower levels in the mantle wedge than for a normal subduction zone (Figs. 2 and 3).

As stated above, the depth to the flat-slab segment has a primary control on the stability of hydrous minerals within the subducting plate. The water content of oceanic crust is significantly lower (<1%) when the flat-slab segment is at 90 km depth (as opposed to 60 km), and amphibole is no longer stable. In this scenario, variations in the convergence velocity and slab age are less important factors when assessing slab dehydration. Either way, warm subduction zones produced by flat-slab subduction of young oceanic lithosphere and by low convergence velocities will be characterised by premature slab dehydration and the absence of a calc-alkaline arc.

Finally, the effect of different extents of flat-slab subduction is investigated (Fig. 5). For greater trench–wedge distances, the subducting slab will have a longer time to heat up and dehydrate prior to its descent into the asthenosphere. Conversely, a decrease in the trench–wedge distance (with normal/steep subduction being the end-member) moves the subduction zone towards a cooler thermal structure. As a result, normal/steep subduction will always produce partial melting in the asthenospheric wedge and, hence, calc-alkaline arc magmatism. The longer the flat-slab segment, the less likely it is that arc magmatism will occur anywhere above the subducting slab.

On the basis of the thermal models presented here, four conclusions may be drawn: (1) warm flat-slab subduction zones produced by the subduction of young oceanic lithosphere are characterised by slab dehydration prior to its penetration of the asthenosphere, (2) a cold flat-slab subduction zone produced by the subduction of old oceanic lithosphere and by high trench-normal convergence velocities can delay dehydration of the subducting slab, although inboard (>600 km) arc magma generation remains problematic, (3) the water content of oceanic crust significantly decreases (to <1%) once the flat slab drops below 80 km depth, as amphibole and chlorite are no longer stable in the subducting oceanic crust, and (4) as the trench–wedge distance is increased, the subducting slab has a longer time to heat up and dehydrate prior to its descent into the asthenosphere.

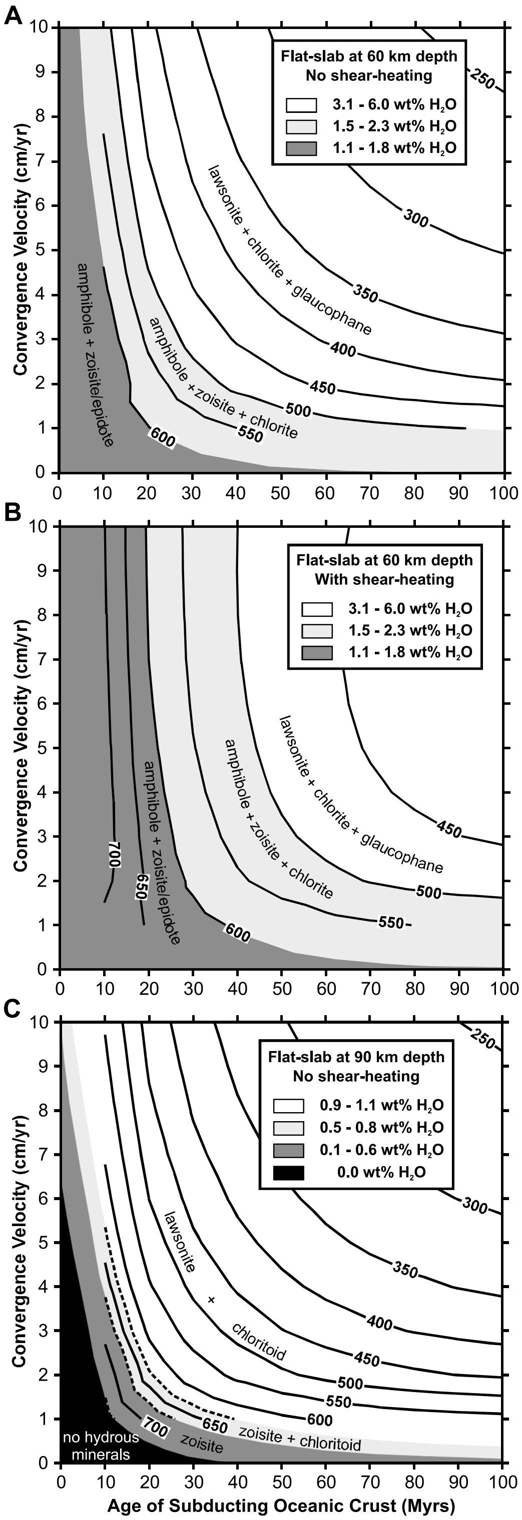

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Fig. 4. Graphs showing the change in temperature of the oceanic crust at the end of the flat-slab segment (stars in Figs. 2B–F) for various combinations of convergence velocity and slab age. (A) Flat-slab segment at 60 km depth with no shear heating. (B) Flat-slab segment at 60 km depth with shear heating. (C) Flat-slab segment at 90 km depth with no shear heating. Due to a difference in pressure, the metamorphic assemblages present in the 90 km deep flat-slab segment are different from those in the 60 km deep flat-slab segment.

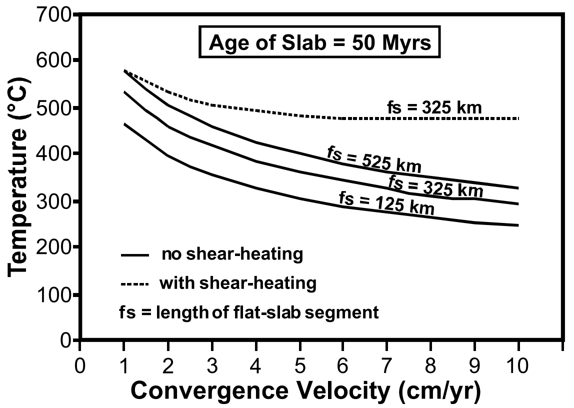

Fig. 5. Graphs showing the change in temperature of the oceanic crust at the end of the flat-slab segment for different lengths of that segment. The greater the length of the flat-slab segment, the higher the temperature of the oceanic crust at the end of that segment, and vice versa.

4. Discussion

Arc magmatism ceased in the Peninsular Ranges and Sierra Nevadan batholiths in the western USA at around 90 and 80 Ma respectively (e.g. [3]; Fig. 1); it has been suggested that this region formed a broad, refrigerated forearc during Laramide flat-slab subduction [25]. During this time, the zone of active magmatism is inferred to have swept inboard to Idaho/southwestern Montana and the Colorado Mineral Belt (e.g. [1,3]; Fig. 1) and to have eventually ceased during the Palaeocene magmatic gap [4]. Stress coupling of the lower plate to the upper plate has been proposed as a mechanism to drive Laramide deformation in the foreland. Bird [8] proposed that the subhorizontal subducting plate displaced the mantle lithosphere from beneath the USA Cordillera, and transmitted shear stress into the foreland region. However, isotopic data (e.g. [26]) and mantle xenolith studies have indicated that lithospheric mantle persisted beneath the USA Cordillera throughout Laramide time to depths of 45–60 km beneath the Sierra Nevada [27] and ~120 km beneath the Colorado Plateau [28]. Saleeby [29] incorporated these new datasets and proposed that the flat slab was segmented, that the shallow segment was approximately 500 km in width along the plate edge (Fig. 1), and that the classic Laramide basement-cored uplifts are concentrated in a northeast-trending corridor; this corridor is defined by the trajectory of this shallow segment of the Farallon slab relative to the North American plate when viewed on a pre-Neogene palinspastic map. These basement-cored uplifts have been compared with similar structures in the Sierra Pampeanas in Argentina [30], where deformation has been linked to a period of flat-slab subduction [31]. Alternatively, as these basement-cored uplifts are situated east and northeast of the Colorado Plateau (Fig. 1), it is possible that once the western side of this rigid block encountered the deformation front, stresses were transmitted through it and into the foreland [32].

As stated above, inboard Laramide-age magmatism occurred in Idaho/southwestern Montana and in the Colorado Mineral Belt. Tonalitic and quartz-dioritic arc magmatism in the Idaho–Bitterroot batholith continued until ~70 Ma (e.g. [33,34]; Fig. 1), and eastward migration was minor compared to the southwestern USA. The inboard location of the Idaho batholith arc magmatism has been explained by a palaeo-embayment in the continental margin known as the Columbia Embayment (e.g. [35]; Fig. 1), and therefore a reduction in the trench–wedge distance. This embayment may help to account for arc magmatism in Idaho if the plate convergence is trench-normal. However, given that: (a) the older portion of the Sierra Nevadan batholithic belt can be traced into the Klamath mountains in southern Oregon (e.g. [17]; Fig. 1), thereby restricting the extent of this palaeo-embayment to between central Oregon and central Washington, and (b) dextral shearing in the Sierra Nevada batholith from ~90 to 80 Ma (e.g. [36]) indicates that convergence was not trench-normal, the Columbia Embayment explanation appears to be insufficient to solely account for the inboard location of arc magmatism in Idaho during the Late Cretaceous. Given that pre-Laramide arc batholiths elsewhere in the North American Cordillera occur within ~300 km of the trench (Fig. 1), it seems plausible that the inboard location of the Idaho batholith may be an artifact produced by Laramide and post-Laramide dextral transpression. Latest Cretaceous to Palaeocene plutons in eastern Idaho and southwestern Montana are typically muscovite–biotite granites and were derived from lower crustal partial melting (e.g. [3,33]).

Magmatism in the Colorado Mineral Belt (75–60 Ma) occurred over 1000 km from the trench and has been attributed to flat-slab subduction of the Farallon plate (e.g. [3]; Fig. 1), although such an origin has been contested [37]. This northeast-trending belt of magmatism was predominantly intermediate in composition, and produced andesitic volcanic rocks, and granodiorite, monzonite and syenite hypabyssal intrusions (e.g. [3]). On the basis of the thermal models presented here, a cold subduction zone produced by the subduction of old oceanic lithosphere and by high trench-normal convergence velocities can delay dehydration of the subducting slab, although most of the dehydration occurs at much shallower levels than for a normal subduction zone (Fig. 2). Inboard arc magmatism under these conditions is not completely ruled out by the simple thermal models presented here, however, attribution of magmatism in the Colorado Mineral Belt to slab dehydration and partial melting of the mantle wedge remains problematic. It seems unrealistic that devolatilisation of the flat slab produced magmatism >1000 km from the trench in the Colorado Mineral Belt given that: (1) the high trench–wedge distance allows a greater duration for the slab to heat up, and (2) *P*–*T* constraints from eclogitic xenoliths indicate that the Farallon slab was at a depth of 90–160 km (3–5 GPa) beneath the Colorado Plateau ([9]; deeper than $\sim$120 km on the basis of mantle xenolith studies [28]) resulting in premature dehydration of amphibole and chlorite in the subducting oceanic crust.

Oligocene kimberlite-like serpentine microbreccia pipes in the Four Corners region of the Colorado Plateau contain eclogitic xenoliths that are believed to derive from the subducted Farallon plate (e.g. [9,38]). *P*–*T* constraints from these lawsonite eclogite xenoliths described by Usui et al. [9] indicate that the Farallon slab was in pressure and temperature ranges of 3–5 GPa and 500–700°C respectively (Fig. 3). This indicates that the Laramide flat-slab subduction zone was characterised by a cold thermal regime. Such a thermal regime can be produced by high trench-normal convergence velocities and subduction of an old, cold oceanic plate (Fig. 4); subduction of young (e.g. 10 Myr) oceanic lithosphere will not produce lawsonite-bearing eclogites (Fig. 3). These conditions are consistent with existing plate reconstruction models [10,11] that estimate average trench-normal convergence velocities of the Farallon and North American plates at 10–15 cm/yr during Laramide time. Engebretson et al. [10,39] estimated the age of the subducting Farallon plate to be between 150 and 50 Myr at this time, although poor constraints on the location of the Kula–Farallon spreading centre introduces a large degree of uncertainty. If there was an old ($\sim$50–100 Myr) slab subducting beneath the North American plate in Laramide time, negative buoyancy may have inhibited flat-slab subduction; oceanic crust becomes negatively buoyant after 10 Myr [40]. An older flat slab would therefore require that the North American plate actively overrode the palaeo-Pacific plates at a rate exceeding the rollback of the hinge of the dense subducting oceanic plate (e.g. [41,42]). However, modern zones of shallow/flat-slab subduction have formed in response to: (1) the subduction of buoyant aseismic ridges or young oceanic lithosphere (e.g. central Chile [21]), or (2) the curvature of the convergent margin itself (e.g. Cascadia [43]). Thus extensive flat-slab subduction of 50–100 Myr regular oceanic lithosphere seems unlikely, and is not supported by modern analogues. This problem may be overcome if a buoyant oceanic plateau/aseismic ridge was subducting beneath the western USA during Laramide time (e.g. [28,44,45]).

Laramide-age deformation extended outside the USA, southwards into the Sierra Madre Oriental of east-central Mexico (e.g. [46,47]), and northwards into the Rocky, Northern Rocky and Mackenzie Mountains of Canada (e.g. [48,49]; Fig. 1); this deformational belt is believed to have developed approximately 1000 km inboard of the nearest convergent margin along much of its length. The extent of the Laramide orogeny indicates that this inboard deformation occurred irrespective of which oceanic plate (i.e. Kula or

Farallon) was subducting beneath western North America. In Canada, the locus of arc magmatism in the Coast Belt migrated eastwards by ~100 km during Laramide time (e.g. [50,51]; Fig. 1), although it remained within 300 km of the western convergent margin. This eastward migration of arc magmatism may be attributable to a shallowing of slab dip, increased convergence velocities, or tectonic erosion of the forearc. However, one certain point is that the subducting oceanic plate descended into the asthenosphere beneath the Coast Belt and did not extend eastwards as a flat slab at the base of upper plate lithosphere as has been proposed further south in the USA. A similar conclusion may be drawn for the Mexican portion of the Laramide orogen, where arc magmatism continued in the Sierra Occidental (e.g. [52]) while deformation occurred ~400 km to the east in the Sierra Oriental ([47,53]; Fig. 1). Therefore, flat-slab subduction cannot explain the localisation and inboard nature of the Laramide-age fold and thrust belt along its entire length.

Another mechanism for driving far-field strain in the foreland region is the 'orogenic float' concept proposed by Oldow et al. [54]. In this model, faults in the foreland are linked to a collision zone at the plate boundary by a major deep crustal detachment; this concept has been used to relate current deformation in the Mackenzie Mountains to collision of the Yakutat block in southeastern Alaska [55]. However, no crustal blocks are known to have accreted to the western margin of the Cordillera during Laramide time. The localisation of deformation in the foreland of the Canadian Cordillera may be explained by Cordilleran backthrusting (intracontinental subduction), during which thrust faulting is antithetic with respect to subduction at the plate margin (e.g. [48]). Alternatively, Laramide-age dextral transpression [56] may in some way be linked to wholesale northward translation of much of the Canadian and Alaskan Cordillera [57], as is suggested by palaeomagnetic studies (e.g. [58–60]). Either way, Laramide-age deformation in the North American Cordillera requires a mechanism capable of causing orogenesis along the entire western margin of the continent.

5. Conclusions

The thermal models presented here indicate that: (1) warm flat-slab subduction zones produced by the subduction of young oceanic lithosphere are characterised by slab dehydration prior to penetration of the asthenosphere, (2) cold flat-slab subduction zones produced by the subduction of old oceanic lithosphere and high trench-normal convergence velocities can delay dehydration of the subducting slab, although inboard (>600 km) arc magma generation remains problematic, (3) the water content of oceanic crust significantly decreases (to <1%) once the flat slab drops below 80 km depth as amphibole and chlorite are no longer stable in the subducting oceanic crust, and (4) as the trench–wedge distance is increased, the subducting slab has a longer time to heat up and dehydrate prior to its descent into the asthenosphere.

Hence, these thermal models indicate that arc magma generation at significant distances inboard from the trench (>600 km; >1000 km in the case of the Colorado Mineral Belt) during flat-slab subduction is problematic; this conclusion is consistent with the coincidence of volcanic gaps and flat-slab subduction at modern convergent margins. Lawsonite eclogite xenoliths erupted through the Colorado Plateau in Oligocene time are inferred to originate from the subducted Farallon slab, and indicate that the Laramide flat-slab subduction zone was characterised by a cold thermal regime. Thermal modelling indicates that this regime can be produced by flat-slab subduction of old (> ~50 Myr) oceanic lithosphere at high trench-normal convergence rates. In the Canadian and Mexican portions of the Laramide, the coeval development of a magmatic arc within 300 km of the trench refutes the existence of flat-slab subduction in these regions. It is proposed that subduction of an oceanic plateau/aseismic ridge may have overcome the negative buoyancy inherent in old oceanic lithosphere and resulted in a spatially restricted zone of flat-slab subduction in the USA. These findings cast doubt on the flat-slab model as a primary means of driving Laramide orogenesis along its entire length, and instead point to the need for an alternative mechanism for Cordilleran-wide Laramide orogenesis.

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