The hit-and-run model for Cretaceous-Paleogene tectonism along the western margin of Laurentia

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ABSTRACT

The North American Cordillera experienced major contractional deformation during the Cretaceous-Paleogene, which is commonly attributed to normal subduction transitioning to shallow-slab subduction. We provide details of an alternative hit-and-run model: The Insular Superterrane obliquely collided with the North American margin from 100-85 Ma (the "hit"), followed by northward translation during continued oblique convergence with North America from 85-55 Ma (the "run"). This model assumes that the paleomagnetic evidence from the accreted terranes of the northern North American Cordillera, indicating up to thousands of kilometers of northward movement primarily between ~85-55 Ma, is correct. The hit-and-run model also incorporates new advances: 1) A 105-100 Ma worldwide plate reorganization; and 2) Multiple subducted slabs characterize subduction systems of the North American Cordillera since ~120 Ma. Finally, we explicitly address along-strike variations, such as the role of the pre-existing rifted Precambrian margin and Permian-Triassic truncation of North America, on margin-parallel movement along western North America.

The 100-85 Ma "hit" phase of the orogeny is characterized by dextral transpressional deformation that occurs simultaneously in the magmatic arcs of Idaho, Northern Nevada, eastern California, and the Peninsular Range of southern California and northern Mexico. The hit phase also records incipient plateau formation, foreland block uplifts in the northern Rocky Mountains, and significant foreland sedimentation in adjacent North America. The transition from "hit" to "run" is hypothesized to occur because of the clockwise rotation of a Precambrian promontory in Washington State that was blocking northward translation: This rotation was accommodated by sinistral motion along the Lewis and Clark deformation zone. The 85-55 Ma "run" phase resulted in dextral strike-slip faulting of coastal blocks and significant contractional deformation in adjacent North America. The hit-and-run model is consistent with first-order geological

and geophysical constraints from the Cordillera, and the proposed type of oblique orogeny requires a three-dimensional, time-dependent view of the deformation along an irregular and evolving continental margin.

INTRODUCTION

Dickinson and Snyder (1978) originally proposed the shallow slab model to explain Cretaceous-Paleogene deformation in the western United States. It was an innovative attempt to understand the tectonism on the western margin of Laurentia. The authors evaluated a contractional magmatic arc, a continental collision, and a transcurrent faulting setting for the Laramide orogeny, but rejected these models. The main argument was the cessation of coastal magmatism from a steeply dipping slab below North America. This argument followed from the pattern of magmatism in the southwestern United States, interpreted as evidence for shallowing then re-steepening of a shallow slab (Coney and Reynolds, 1977). Further, Dickinson and Snyder (1978) argued that subduction continued until the Paleogene as determined by sedimentation in the Franciscan complex of California. Using these constraints, they utilized a model of flat-slab subduction, based on the then-emerging work on the subduction system from the Andes of South America (Megard and Phillip, 1976). They noted the existence of active block-uplift type structures and widespread earthquakes that are currently active in one of the flat-slab segments of the Andes, and noted the similarity to the structural style of the Laramide block uplifts to the block uplifts in that segment of the Andes (also Jordan and Allmendinger, 1986).

The concept of flat slab subduction is now widely accepted by the geoscience community. It is used as the topic for sessions at international meetings, used in article titles (e.g., Chapman et al., 2020), and incorporated into a variety of textbooks. It has undergone two major modifications as new data have accumulated. First, there is now a recognition of a plateau (herein called the Sevier orogenic plateau) in the region east of the extinct magmatic arc but west of the fold and thrust belt. Because this orogenic plateau was inferred to occur mostly in Nevada and it was inferred to formed in a shallow subduction system with similarities to the Altiplano of the Andes, it was called the "Nevadaplano" (e.g., DeCelles, 2004; Long, 2012). Second, the interpretation of a deep (a minimum of 110-130 km) eclogitic root underneath the Cretaceous Sierra Nevada batholith indicated that a shallow slab could not have existed below central California (e.g., Ducea and Saleeby, 1996, 1998). Saleeby (2003) therefore considered that the shallow slab only occurred below the Mojave portion of California, and not below the central Sierra Nevada. This model was consistent with a major ~100 Ma deformational event in the Mojave region (e.g. Barth et al., 2004). Different numerical models have been made to mechanically explain how shallow slab subduction would result in far-foreland uplifts (e.g., Bird, 1984; Liu et al., 2010; Axen et al., 2018).

There are, however, a variety of new datasets obtained from the North American Cordillera that are generally not consistent with shallow slab subduction. These include: 1) A consistent paleomagnetic data set from the western margin of North America that suggests large-scale translation of accreted terranes currently in the Canadian Cordillera (e.g., Irving et al., 1996; Housen and Beck, 1999; Enkin, 2006); 2) Detrital zircons as a method of determining tectonic provenance which place the outboard terranes significantly south of their present location at ~100 Ma (e.g., Housen and Beck, 1999; Garver and Davidson, 2015; Matthews et al., 2017; Sauer et al., 2019); 3) An understanding of transpressional deformation and a documentation of dextral transpressional features throughout the Cordillera (e.g., Fossen and Tikoff, 1993; Andronicos et al., 1999; McClelland et al., 2000; Giorgis et al., 2017; Krueger and Yoshinobu, 2018); and 4) Tomographic images of the mantle below North America indicating the presence of multiple slabs (Sigloch and Mihalynuk, 2013; 2017). As a result, there has been a proliferation of tectonic models, many of which require plate configurations that are inconsistent with the existence of shallow slab subduction under the western United States and adjacent Mexico (e.g., Maxson and Tikoff, 1996; Moores, 2002; Johnston, 2008; Sigloch and Mihalynuk, 2013; 2017; Hildebrand, 2015; Clennett et al., 2020; Hildebrand and Whalen, 2021a,b).

In this contribution, we re-examine, update, and more fully articulate the hit-and-run model of Maxson and Tikoff (1996). Our approach here is very straightforward: We accept that the paleomagnetic data are correct, and propose the hit-and-run model that accommodates these data in addition to other geological and geophysical constraints. We propose that there was a major “hit” on the western edge of the North American

Cordillera that lasted from 100-85 Ma. This hit phase is manifest from Idaho to central Mexico, and from the margin to the foreland. The location of this deformation is consistent with the paleomagnetically determined placement of the Insular terrane ~3000 km south of its current location. The “run” phase occurs from ~85-55 Ma, during the major northward translation of the Insular terrane. We interpret major Late Cretaceous-Paleogene geological structures in the North American Cordillera as a result of these “hit” and “run” phases. The hit-and-run model can be compared and contrasted to the prevailing idea of shallow slab subduction of a Farallon plate – and other emergent models (Sigloch and Mihalynuk, 2013; 2017; Hildebrand, 2015; Clennett et al., 2020; Hildebrand and Whalen, 2021a,b) – as the cause of middle mid-Cretaceous-Paleogene tectonism in western North America. Note that we do not categorically reject the existence of shallow slab subduction, given its documentation as currently occurring in South America (e.g., Ramos and Folguera, 2009) and Alaska (e.g., Martin-Short et al., 2016). We do, however, reject it as a causal mechanism for 100-55 Ma tectonism of the western margin of North America.

THE INSULAR SUPERTERRANE OF THE CANADIAN CORDILLERA

The hit-and-run model describes the collision, accretion, and northward translation of the Insular Superterrane, which caused deformation in western North America from 105-55 Ma. The Insular Superterrane is effectively equivalent to “Baja BC” of Irving (1985) or Wrangellia composite terrane. Two additional amalgamated superterranes – Intermontane and Guerrero – are involved in the hit-and run model and are discussed below.

The term Insular Superterrane includes the southern Alaskan Peninsular terrane, the Alexander terrane in southeast Alaska and northern British Columbia, and Wrangellia in Alaska, southern British Columbia, and northern Washington (Fig. 1; see Coney et al., 1980; Dickinson, 2004). Along with these large crustal blocks, the Insular Superterrane includes at least a portion of the metamorphic and plutonic rocks of the Coast Mountains batholith (e.g., Rusmore et al., 2013; Woodsworth et al., 2020).

The eastern margin of the Insular Superterrane is both complex and variable along strike. In central British Columbia, the eastern margin is obscured by metamorphism and plutonism in the Central Gneiss Complex of the Coast Mountains batholith (summarized in Woodsworth et al. 2020) and by Paleogene transpression along the Coast shear zone (e.g., Andronicos et al., 1999). In Alaska and northern British Columbia, the eastern margin coincides with the Gravina-Nutzotin-Kahiltna Basin (McClelland et al., 1992; Trop, 2008; Ricketts, 2019).

In southern British Columbia and Washington, the eastern margin of the Insular Superterrane is marked by an assemblage of smaller terranes that include the Cadwallader, Methow, and Bridge River terranes. Multiple investigations have linked these terranes and the Jurassic-Cretaceous sedimentary strata that overlie them either to the Insular Superterrane (e.g., Wynne et al., 1995; Enkin, 2006), the Intermontane Superterrane (e.g., Haggart et al., 2011), or to both. The lattermost model is achieved by postulating that that Cretaceous strata underlain by these terranes constitute an overlap sequence (e.g., Garver, 1992; Ricketts, 2019).

These smaller terranes comprise oceanic crustal and accretionary complexes, volcanic arc fragments, and early to mid-Mesozoic sedimentary sequences. Generally, these smaller terranes are overlain by distinct and internally coherent Jurassic-Cretaceous strata of the Tyaughton-Methow basin. Notably, both the Tyaughton-Methow and Gravina-Nutzotin-Kahiltna basins are truncated on their eastern/northern margin by a major dextral strike-slip fault. Additional mid- to Late Cretaceous depocenters of the Insular Superterrane – the Georgia (Nanaimo and Comox sub-basins) and Queen Charlotte basins – developed between the Coast Mountains batholith and rocks of Wrangellia. Each of these basins acted as significant mid-Cretaceous depocenters, and several have been interpreted as recording mid-Cretaceous accretion of the Insular Superterrane to North America (e.g., Garver, 1992; Maxson, 1996; Trop, 2008; Ricketts, 2019).

Within the scope of this paper, we are not able to resolve or even to fully review the observations and interpretations that have led to establishing discrepant superterrane affinities for the basins and smaller terranes that exist between the Insular and Intermontane Superterrane. We acknowledge, however, the disparities between robust paleomagnetic data that separate the superterranes by >1000 km (detailed in the next section) and the geological observations, correlations, and interpretations that juxtapose and link them by Early Cretaceous time. Consequently, we utilize the paleomagnetic signatures, rather than geologic interpretation of terrane linkages, as the basis of correlation. While unconventional, we note that this is a data-driven, rather than interpretation-driven, approach. Accordingly, we assign the Cadwallader, Methow, and Bridge River terranes to the Insular terrane; they are basement terranes that are structurally linked to strata whose paleomagnetic signature corresponds those of other Insular Superterrane sites (Garver 1992; Wynne et al, 1995; Enkin et al., 2002).

We especially note the difficulty posed by observation and interpretation of geologic relations at Churn Creek in south central British Columbia (Enkin et al., 2003; Haskins et al., 2003; Riesterer et al., 2003; Enkin, 2006). At Churn Creek, stratified mid-Cretaceous volcanic rocks (Spences Bridge equivalent) with paleomagnetic signatures typical of the Intermontane Terrane (~1000 km of northward displacement) are interpreted to be in stratigraphic contact with coeval sedimentary and volcanic rocks (Powell-Creek/Silverquick equivalent) for which paleomagnetic data require much larger offsets (~2500-3000 km) characteristic of Insular Terrane (see discussion).

Collision of the Insular Superterrane with North American is inferred to have occurred ~105-100 Ma. Major mid-Cretaceous contractional belts occur throughout the Insular Superterrane (Crawford et al., 1987; Rubin et al., 1990; Rusmore and Woodsworth, 1991; 1994). First, in the southern portion of the Insular Superterrane, in northern Washington and in southwestern BC, the North Cascades - San Juan thrust system was active from 100-84 Ma (Brandon et al., 1988; Brown et al., 2007; Brown, 2012). Second, the Coast Belt Thrust System was active at ~100 Ma (Journeay and Friedman, 1993; Umhoefer and Miller, 1996). Third, the eastern Waddington thrust belt was active in the mid- to Late Cretaceous (Rusmore and Woodsworth, 1991; 1994). These thrust systems include both west-dipping and east-dipping structures. Umhoefer and Miller (1996) note that southwest vergent thrusting both pre-dates and outlasts northeast vergent thrusting in the southern Insular Superterrane.

The central Insular Superterrane of northern British Columbia, in contrast with regions to the south and northwest, shows the absence of: 1) Smaller amalgamated terranes; 2) Cretaceous accretion-related basins; and 3) Brittle structures. The central Insular Superterrane, however, shares a history of mid-Cretaceous crustal shortening (e.g., Woodsworth et al., 2020) followed by significant Paleogene transpression in the Coast shear zone (Andronicos et al., 1999). Crustal thickening and shortening – accommodated by thrust faulting – was roughly coeval with the North Cascades-San Juan thrust system to the south (Woodsworth et al. 2020), i.e., circa 100-90 Ma. Transpression coincided with dextral Late Cretaceous-Paleogene motion to the south on the Fraser-Straight Creek-Yalakom fault system and to the northwest on the Chatham Straight, Denali, and associated faults (e.g., Colpron et al., 2007).

A debate in the Canadian and Alaska panhandle involves the timing of collision of the Insular and Intermontane Superterranes. There are Jurassic and younger sedimentary rocks that are deposited on various parts of the Insular and Intermontane Superterranes, but we know of no unambiguous data that the terranes were linked before ~105-100 Ma (also see Busby et al., 2022). In some sense, however, the debate is not relevant to our model: By 100 Ma, the paleomagnetic data place the Insular Superterrane significantly south of both currently adjacent North America and Intermontane Superterrane. Importantly, there is good evidence for a major collision along most of the North American margin and previously accreted terranes at ~105-100 Ma.

INTERMONTANE, GUERRERO, and ALISITOS TERRANES

The Intermontane Superterrane of the Canadian Cordillera also plays an important part of the 100-55 Ma tectonic history along the western margin of North America. The Intermontane Superterrane consists of two magmatic arcs (Stikinia, Quesnellia), an intervening subduction complex/basin (Cache Creek terrane), and additional smaller terranes including the Yukon-Tanana and Slide Mountain terranes (Fig. 1). Accretion of the Intermontane Superterrane to North America is thought to have occurred in Jurassic time (e.g., Nixon et al., 2019) or earlier (e.g., Beranek and Mortensen, 2011).

The Intermontane Superterrane is exposed mostly north of the US-Canadian border; however, two significant pieces of the Intermontane Superterrane are present in the northern U.S. Cordillera. The Blue Mountain terranes of easternmost Oregon and western Idaho also consist of two island arc terranes (Wallowa, Olds Ferry) separated by an argillite-matrix mélange (Baker) (Ave Lallement, 1995; Vallier, 1995; Schwartz et al., 2011). The similarity indicates that the Blue Mountain terranes correlate to the

Intermontane Superterrane. The second possible piece is the Black Rock terrane of northwest Nevada. S. Wyld (pers. comm., 2021) notes that its stratigraphy and deformational history likely correspond to that of the Quesnellia terrane in the Canadian Cordillera, and suggests that these crustal blocks were initially contiguous. This correlation is consistent with the model of Mihalynuk and Diakow (2020).

Two major terranes currently located in Mexico are also relevant to our discussion of terrane collisions: the Alisitos and Guerrero terranes (Fig. 1). The Alisitos terrane acts as a magmatic arc in the Early Cretaceous, separated from mainland Mexico by a backarc basin. Rifting along a southern California-Arizona-Sonora boundary started in the Late Jurassic, is associated with the Bisbee basin, and is likely part of the same extensional episode associated with back arc of the Alisitos magmatic arc (Busby et al., 2006). The Guerrero Terrane is sutured to the western margin of Laurentia along the Arperos suture, by closure of the Arperos basin. Busby (2022) considers that the Alisitos and Guerrero terranes are part of an amalgamated superterrane, which has not been displaced northward significantly after ~90 Ma, on the basis of their association with mainland Mexico.

The San Martir "thrust" juxtaposes granites coming through the oceanic Alisitos terrane and granites intruding through the Caborca block, a fragment of continental North America that was offset in a sinistral sense from California during the Permian-Triassic (e.g., Walker, 1988). As a result, the $^{87}Sr/^{86}Sr_i = 0.706$ isopleth is found within the Peninsular Range batholith and lies along the San Martir "thrust".

There is some ambiguity about the timing of the Arperos suture. It is hypothesized that the Arperos suture occurred in the Early Cretaceous (Early Aptian), with subsequent deposition above the suture zone (Martini et al., 2014, 2016; C. Busby, pers. comm., 2021). Subsequently, it was reactivated at ~100 Ma. Alternatively, the Arperos suture formed at ~100 Ma (Hildebrand and Whalen, 2021a). Regardless, collision between the Alisitos arc and mainland Mexico was complete by ~95 Ma, with the San Martir "thrust" delineating the boundary (e.g., Johnson et al., 1999; Schmidt and Paterson, 2002). The zone is cross-cut by ~95-90 Ma La Posta granites that constrain the timing of deformation.

PALEOMAGNETIC DATA

For this work, we rely on the reference frame provided by paleomagnetism, following the Geocentric Axial Dipole (GAD) model for time averaged field geometry that is commonly used in tectonic reconstructions. For this time period (100 Ma to 50 Ma), there is a very well established and robust record of paleomagnetic results from cratonic portions of North America that provide for accurate paleogeographic reconstructions of the North American margin. These results are compared to paleomagnetic results from terranes that have interacted with the western margin of North America during this time. For additional, and more detailed, discussions of these data, please see Irving et al. (1996), Dickinson and Butler (1998), Housen and Beck (1999), Enkin (2006), and Kent and Irving (2010).

Reference Frame

The paleogeography of North America, as established by paleomagnetic studies, has been relatively well understood since the early 1970s (e.g., Beck and Noson, 1972). Subsequent work has produced a more robust set of data from the North America craton, which has essentially confirmed these earlier results. Before reviewing them in detail, we first provide some criteria which will be used to select and analyze these data.

Previous workers have taken two approaches for these compilations. The first approach is to rely only on paleomagnetic studies from the North American craton (Mankinen, 1978; Van der Voo, 1988; Van Fossen and Kent, 1992; Beck and Housen, 2003). The second approach is to use paleomagnetic studies from other tectonic plates, as rotated into North America coordinates using Euler poles (and in some cases plate circuits based on several Euler poles) (e.g., Enkin, 2006; Torsvik et al., 2012). Both approaches have advantages and drawbacks. By restricting data to a single plate/craton, the availability, quality, and age distribution of paleomagnetic results can be limited, which will introduce uncertainty in spatial and temporal resolution of paleogeographic reconstructions made using these data. By using data imported from other plates via rotations, the availability and resolution of data can be improved, but this comes at the price of uncertainties introduced by errors or uncertainties in the plate reconstructions used to determine the Euler poles, and in assumptions made regarding the motion of a hot-spot reference frame.

Another analytical choice, which can be applied to either set of data, is how to use the paleomagnetic data to construct an Apparent Polar Wander Path (APWP). The APWP is then used for paleogeographic reconstructions, and can also be used to determine motion of that plate within the GAD framework (May et al., 1986; Beck and Housen, 2003; Kent et al., 2015). The simplest APWP model is a pole-to-pole path, constructed by connecting paleomagnetic poles from rocks that span a limited period of time (5-10 m.y.). This model is attractive in that no further assumptions are required. Other APWP models involve combinations of "moving windows" for poles with a distribution of ages. These models are attractive in that some variation caused by inadequate sampling of time (not satisfying the GAD model to average secular variation) and/or other errors can be minimized by averaging. Such paths also smooth abrupt changes in the shape of the APWP that could be produced by rapid changes in the direction or rate of plate motion. There are also different methods for moving-window averages, including simple geometric moving window means, fitting the pole paths using cubic splines, and other options. Finally, some of the global, averaged APWP models have also incorporated assumptions and corrections for other effects, such as motion of the hot-spot framework. The hot-spot framework influences plate circuits and can be manifest as True Polar Wander (TPW) in the APWP. These corrections (e.g., Torsvik et al., 2008) can offset the APWP and subsequent paleogeographic reconstructions, as compared to those using data from a single plate.

For this analysis, we use only paleomagnetic data from North America to reconstruct its paleogeography. As we discuss below, these data lend themselves to the simpler pole-to-pole type of APWP construction (see also Wynne et al., 1992; Dickinson and Butler, 1998), so this is also the approach that we follow. The interpretations that follow are also robust to this approach. An additional advantage of this simpler approach is that the results are directly comparable to the paleomagnetic results available for the various terranes from the North America Cordillera. The paleomagnetic data from the terranes, in most cases, lack the same temporal resolution that is available from the North America craton. Further, the APWP analyses – such as importing data from other plates

– are not applicable to the data from terranes. Comparison of data and paleogeographic information (paleolatitude) from individual terranes with paleomagnetic paleogeography of the North America craton for restricted time periods may introduce bias due to the differences in APWP construction.

North America Paleomagnetic framework

For this compilation, we use paleomagnetic studies from cratonal, or minimally disturbed areas, of North America. Existing tabulations of these data include Beck and Noson (1972), Mankinen (1978), Smirnov and Tarduno (2000), Beck and Housen (2003), Housen et al. (2003), Enkin (2006), and Kent and Irving (2010). For many of these compilations, including pole tables in global models (e.g., Torsvik et al., 2012), large studies of a region are averaged together, and reported with an average age most commonly taken from the original paleomagnetic literature, but not updated with newer geochronology. For the compilation here, we use the approach taken in Housen et al. (2003) and Housen (2021), who examined each paleomagnetic study, identified specific rock units (or spatially adjacent units) that have enough site mean data to average together, provide updated ages for each units, and report a unit/locality average pole with revised age. Further details and analyses of the North American dataset using this methodology are reported elsewhere (Housen, 2021).

An example of this approach are the results from the Arkansas Alkalic province, studied by Globerman and Irving (1988). In their paper, individual site poles Virtual Geomagnetic Poles (VGPs) were calculated from 40 individual sites from intrusive rocks located along a W to E trend from Prairie Creek to Granite Mountain, Arkansas, are reported. While Globerman and Irving (1988) separately documented the results from each area sampled, the results are reported as a single average pole with an assigned age of 100 Ma in paleomagnetic databases (e.g., Torsvik et al., 2012) and compilations (Enkin, 2006). A review of published ages of these intrusive rocks (Eby and Vasconcelos, 2009) indicates they have $^{40}Ar/^{39}Ar$ and fission track dates that range from 106 Ma to 88 Ma. Because these collective rock units span 20 Ma of time, averaging their paleomagnetic results together may not be ideal. Thus, for this study, the paleomagnetic results of Globerman and Irving (1988), informed by the ages of those rock units in Eby and Vasconcelos (2009), are grouped as Potash Sulfur Springs (7 sites, 101 +/- 1.7 Ma), Magnet Cove (8 sites, 96 +/- 1.2 Ma), and Granite Mountain (5 sites, 88 +/- 1.0 Ma). Following this approach, paleomagnetic and geochronology data from rocks of undisturbed portions of North America from 110 to 55 Ma were compiled to provide a framework for the paleogeography of North America for this range of time.

An analysis of the compiled North American paleomagnetic poles indicates that, for purposes of paleogeography and geodynamic analysis, motion of North America during Cretaceous time can be grouped into two time intervals. Within each interval of time, comparison of pole positions finds relatively little change in location. This data suggest that for each interval, motion of North America relative to the spin axis was not large. Similar conclusions have been made by Diehl et al. (1983), Gunderson and Sherriff (1991), Wynne et al. (1992), Dickinson and Butler (1998), and Beck and Housen (2003).

130 to 85 Ma: Cretaceous still stand summary

Compilations of paleomagnetic data from Cretaceous rocks of stable North America (Mankinen, 1978; Van Fossen and Kent, 1992; Besse and Courtillot, 2002; Beck and Housen, 2003; Enkin, 2006; Torsvik et al., 2008) all show relatively small changes in pole position for most of Cretaceous time. Despite over 40 years of study, there remain questions regarding the nature and duration of this APWP still-stand, particularly regarding the onset and termination of this feature, and its geodynamic significance.

Reanalysis of North America paleomagnetic data with updated geochronology for many of the igneous units is used to define a total of 27 locality means, with ages spanning from 130 to 85 Ma (Housen, 2021). Mean poles calculated for 10 Ma age ranges (centered on 130, 120, 110, 100, and 90 Ma) are separated by less than 10 degrees (Fig. 2); the APW path connecting these mean poles can be described as defining a very small loop, or as a single cluster. This short path, or lack of APW, indicates that motion of North America did not have any appreciable latitudinal component relative to the spin axis, and motion was mainly or entirely toroidal during that time, with the Euler pole for North America motion in an absolute (global) sense coinciding with the mean pole for the still-stand (71.8 N, 192.7 E, A_{95}=2.4, N=27). The main points, for the purpose of this paper, are that: 1) The western margin of North America was at high latitudes compared to the present day; and 2) From 130 to 85 Ma, there was no appreciable change in the latitudinal position of this margin. Geodynamically, motion of North America is confined to being E-W, likely at slow rates (proportional to rates of opening of the north Atlantic basin). The lack of latitudinal change of North America also provides a well-defined reference for comparison with paleomagnetic results from terranes that now make up the western portion of North America. While we have used only data derived from North American rock units, this conclusion is essentially the same as reached by other compilations (Enkin, 2006; Torsvik et al., 2008) that use globally derived data.

85 to 65 Ma

For the latter part of Cretaceous time, the available paleomagnetic poles for North America are relatively sparse, and there are some differences in interpretation of results from this period. The best quality results, in terms of well-determined ages, paleohorizontal control, and use of volcanic rocks, are from the Adel Mountains (Gunderson and Sherriff, 1991) and Elkhorn Volcanics (Diehl, 1991). Updated geochronology (Harlan et al., 2005; Horton, 2016) for these units provide ages of 76-73 Ma and 84-83 Ma, respectively. For the latest portion of Cretaceous time, a set of 9 sites in the Moccasin, Judith, and Little Rocky Mountains (Diehl et al., 1983) have ages from 67-65 Ma, and so will be used to represent the latest Cretaceous. The pole positions from all three of these studies are well-grouped (Fig. 2) and can be averaged together as a well-defined 84-65 Ma pole for North America (82.6 N, 184.1 E, A_{95} = 3.5, N=3). Similar approaches, using just the Adel Mountains and Elkhorn volcanics as an average North America pole, were taken by Dickinson and Butler (1998) and by Beck and Housen (2003).

Other compilations use North America poles from locations that also may have been rotated (Hagstrum et al., 1994), and/or include global data (Enkin, 2006; Somoza, 2011) for the Late Cretaceous. These results have pole positions falling at higher latitudes, which are very similar to those from the Cretaceous still-stand. These models continue the APWP still-stand described above to Eocene time (Enkin, 2006; Somoza, 2011; Torsvik et al., 2008). This has the effect of placing North America at paleolatitudes that are higher (by 5º) than our preferred model until ~55 Ma. The implication for the paleogeography discussed here is mainly a larger difference in paleolatitude of terranes compared to their present locations along the western North American margin, so that displacements for this time period would be larger.

Accreted Terranes

Below we characterize paleomagnetic results from Cordilleran terranes of the western parts of Canada and the United States. The most important factors to consider are the age control of the sampled units, the extent to which the study has constrained the age of magnetization to be primary (dating from the time at which the particular rocks were formed), and constraints on paleohorizontal that are critical for a robust determination of the unit's paleolatitude and history of rotation. The constraints on paleohorizontal and corrections for inclination error (where needed) directly address earlier, more *ad hoc* criticisms of the paleomagnetic data (e.g., Dickinson and Butler, 1998). Reviews and discussions of these data include Beck (1988), Irving and Wynne (1991), Irving et al. (1996), Cowan et al. (1997), and Enkin (2006). For this discussion, the results will be organized according to larger tectonic (terrane) units.

Intermontane Superterrane

For the Intermontane Superterrane, several quality paleomagnetic studies exist (Figs. 3, 4). These include results from the 105 Ma Spences Bridge volcanics (Irving et al., 1995), the 104-101 Ma volcanics of the Churn Creek area (Haskin et al., 2003), and the 70 Ma Carmacks volcanics (Marquis and Globerman, 1988, Wynne et al., 1998, Enkin et al., 2006a). We also include the results from Rusmore et al. (2013) from 110-85 Ma plutonic rocks from Knight Inlet, which they associated with the Intermontane Superterrane. Other terranes that maybe be correlative, to the south, include the Blue Mountain terranes of Oregon and Idaho (Fig. 1), with available paleomagnetic results from 135-110 Ma plutons (Wilson and Cox, 1980; Housen, 2018), and 100-90 Ma sedimentary rocks of the Ochoco basin (Housen and Dorsey, 2005; Callebert et al., 2017). We organize these results by age for this summary.

The paleomagnetic studies of the Spences Bridge and Churn Creek volcanics represent the best paleomagnetic constraints on the paleogeography of the Intermontane Superterrane on rocks older than 85 Ma. The Spences Bridge (SB) results (Irving et al., 1995) are from volcanic flows, using flow structures as paleohorizontal. These results pass a paleomagnetic tilt test, and are of uniform normal polarity as would be expected for magnetizations of this time period. Similarly, results from the volcanics of Churn Creek (CC) are well-defined, pass both a paleomagnetic tilt test and a conglomerate test, and have normal polarity (Haskin et al., 2003). Both units are dated with either U-Pb or $^{40}Ar/^{39}Ar$ geochronology, with ages ranging from 105 to 101 Ma. The volcanics of Churn Creek (CC) record a shallower paleomagnetic inclination, consistent with significantly larger northward offset, relative to the Spences Bridge volcanics. These disparate paleomagnetic signatures are addressed in the discussion.

Rusmore et al. (2013) report paleomagnetic results from Cretaceous plutonic rocks near the Insular/Intermontane boundary in Knight Inlet, BC (KI). The paleomagnetic results from these plutonic rocks are well defined. Constraints on tilt are provided by thermobarometry, and detailed determination of uplift ages from $^{40}Ar/^{39}Ar$ thermochronology were used by Rusmore et al. (2013) to constrain the age of these magnetizations to be 110 to 85 Ma.

The plutonic rocks of the Blue Mountain terranes of Oregon and Idaho range in age from 135 to 110 Ma and paleomagnetic studies by Wilson and Cox (1980) and Housen (2018) reported well-defined magnetizations (Fig. 1). While direct constraints on paleohorizontal for these plutons is not available, both studies concluded that large-scale tilt of the Blue Mountain terranes is not likely (see discussion in Housen, 2018). Sediments of the Ochoco Basin, which overlap portions of the Blue Mountain terranes, were found to have well-defined magnetizations that pass the paleomagnetic fold, baked-contact, and conglomerate tests, demonstrating that the magnetizations of these Albian-Cenomanian sedimentary rocks were acquired upon deposition (Housen and Dorsey, 2005, Callebert et al., 2017). As part of these studies, the effects of inclination-shallowing were evaluated, and corrected for, finding 5 degrees of shallowing using fabric-based methods (Callebert et al., 2017).

The 70 Ma Carmacks Group (CG) volcanics have paleomagnetic results from Marquis and Globerman (1988), Wynne et al. (1998), and Enkin et al. (2006a). All studies have reported well-defined, primarily reverse-polarity magnetizations that pass paleomagnetic tilt tests. The reverse polarity and existing geochronology would suggest these rocks were magnetized during Chron C31r (71.72 – 69.60 Ma; Malinverno et al., 2020). The newer data and compilation of Enkin et al. (2006a) show that all 41 paleomagnetic sites combine to provide a paleolatitude of 55° N, and a translation of 1400 +/- 400 km relative to North America).

From these studies, a consistent estimate of the paleogeography of the Intermontane Superterrane is found (Intermontane Table 1).

Insular Superterrane

For the Insular Superterrane, several paleomagnetic studies provide very good constraints on its paleolatitude (Figs. 3, 4). These include analyses of the volcanics and associated sediments at Mt. Tatlow (Powell Creek/Silverquick; Wynne et al., 1995), correlative units from Churn Creek (Enkin et al., 2003) and other areas (Enkin et al., 2006b), Mt Stuart batholith (Housen et al., 2003), Duke Island ultramafics (Bogue and Grommé, 2004), sediments and volcanics from the Methow basin (Enkin et al., 2002), clastic sediments of the Nanaimo Group (Kim and Kodama, 2004; Krijgsman and Tauxe, 2006) and volcanics and volcaniclastics of MacColl Ridge (Stamatakos et al., 2001).

The most robust set of data are from the paleomagnetic studies of volcanic flows and interbedded clastic sedimentary rocks of the Powell Creek/Silverquick Formations, sampled in five locations: Mt. Tatlow-MT (Wynne et al., 1995), Churn Creek-CH (Enkin et al., 2003), Battlement-Amazon-BA (Enkin et al., 2006b), Tete Angela-TA (Enkin et al., 2006b), and Jamison Creek-JC (Enkin et al., 2006b). These rocks range in age from Late Albian to Santonian, as indicated by combinations of U-Pb, ^{40}Ar/^{39}Ar, and fossil pollen assemblages. The strata sampled for the paleomagnetic studies is assigned an age range of ~95-86 Ma (Wynne et al., 1995; Enkin et al., 2003), with the Jamison Creek location likely representing younger (~77 Ma) strata (Enkin et al., 2006b). These units have excellent paleohorizontal control, pass the paleomagnetic tilt-test, and collectively include results from 80 sites (5-12 samples per site). The mean inclinations from sites of volcanic rocks are identical to those from clastic sedimentary rocks, so issues with possible inclination error are negligible. Paleolatitudes of these units range from 35° to 47° N. Comparisons between these paleolatitudes and those expected from their NA location (using the 100-85 Ma pole for North America) indicates translations that range from 3000 to 1000 km, with the lesser translation (and higher paleolatitude) from the younger Jamison Creek location.

The paleomagnetic study of the Mt. Stuart batholith (Beck and Noson, 1972) provided the first such comparison for the larger Insular Superterrane. Subsequent work (e.g., Housen et al., 2003) improved the resolution, constrained the age of magnetization (91-88 Ma) using thermochronology, and corrected for modest tilt (Ague and Brandon, 1992). These updated results indicate a paleolatitude of 31° N, and using the comparison to NA, a translation of 3000 km is obtained.

The layered ultramafic rocks of the Duke Island complex (Bogue and Grommé, 2004) also provide useful paleomagnetic results. The paleomagnetic directions are well defined, but the significance and use of cumulate layering in these rocks as an approximation of paleohorizontal has been debated (see Bogue et al., 1995; Butler et al., 2001; Bogue and Grommé, 2004). This places some additional uncertainty in the interpretation of these results. We include the analysis of Bogue and Grommé, (2004), which indicated a paleolatitude of 44° N and a translation of 2300 km.

Similarly, paleomagnetic studies of Late Cretaceous volcanics of the Methow Basin (Bazard et al., 1990; Enkin et al., 2000) have yielded well-defined magnetizations, but these have a syn-magnetization paleomagnetic tilt test, suggesting remagnetization. The age of this magnetization was constrained to be between 88 and 80 Ma. The partially tilt-corrected result of Enkin et al. (2000) provides a paleolatitude of 43° N, and a translation estimate of 1100 km. Although these rocks are remagnetized, and so their paleohorizontal control is less certain, we include this result as there are also data, using the abundant leaf fossil flora from the Methow Basin, which provide an independent and quantitative estimate for the paleolatitude of these strata for late Albian (100 Ma) time (Miller et al., 2006). This study determined a paleotemperature estimate from analysis of leaf morphology using the CLAMP method, applied to fossils preserved in strata found on the North American craton, and within the strata of the Methow Basin. The derived, latitudinally controlled temperature gradient was then used to estimate the expected paleolatitude of the Methow Basin (38° N), and an estimate of northward translation (2200 km).

Other studies from the Insular Superterrane include work on younger units of Late Cretaceous age. Results from volcanic rocks and volcanoclastic sedimentary rocks of MacColl Ridge (Stamatakos et al., 2001) from SE Alaska have well-defined, reverse polarity magnetizations that pass the paleomagnetic tilt test. These rocks were likely magnetized during Chron 34r (84-80 Ma) and have a paleolatitude of 52.5° N, with a translation of 1600 km, using the Late Cretaceous reference for North America as discussed above.

The turbidites of the Nanaimo Group, which range in age from ~ 90 to 66 Ma have been well-studied (e.g., Ward et al., 1997; Enkin et al., 2002; Kim and Kodama, 2004), and are attractive in that the age range for these strata span the majority of time proposed for the translation (the "run") of the Insular Superterrane during the latest portion of the Cretaceous. The magnetizations of these rocks are poorly defined, but primary magnetizations are demonstrated by paleomagnetic tilt and reversals tests. These strata are also rich in clay minerals, which would suggest inclination error may be present. For our compilation, we use the corrected results from Kim and Kodama (2004) as preferred estimates of paleolatitude and of translation. Additionally, Kodama and Ward (2001) compared fossil bivalve occurrences along western North America, reconstructing the habitat zone of Rudistid bivalves, for Late Cretaceous time. Using this latitude-controlled zone, and the lack of Rudistid bivalves found in strata of the Nanaimo Group, they argued that the paleolatitude of these rocks (and by extension the portion of the Insular Superterrane the Nanaimo Group was deposited on) must have been deposited to the north of 46° N at ~75 Ma. Pearon and Hebda (2006) also report CLAMP-based temperature estimates from fossil leaf flora in terrestrial units of the Nanaimo Group, and conclude that the paleolatitude of the basin was at 45°N at ~75 Ma.

Paleomagnetic data and estimates for translation of the Insular Superterrane are provided in Table 2.

Collectively, the paleomagnetic data from North America serve as a very well-defined paleogeographic reference for the abundant set of paleomagnetic results from the units that make up the Intermontane and Insular Superterranes (Fig. 5). The paleomagnetic data from the terranes were selected to include studies from rocks with well-defined ages, well-defined magnetizations, and good paleohorizontal control. For sedimentary units, the effects of inclination shallowing are considered and corrected for as needed. Taken together, several consistent observations can be made. These data, and their comparisons with revised reference poles for North America, indicate that the Intermontane and Insular Superterranes were both located significantly to the south of their present locations throughout most of Cretaceous time (Fig. 5). The Intermontane and Insular Superterranes have different amounts and histories of displacement: 1) The Intermontane Superterrane experiencing post-100 Ma displacements of ~700 to 1400 km; and 2) The Insular Superterrane experiencing post-100 Ma displacements that are larger (2000-3000 km). This pattern suggests a separate Late Cretaceous tectonic history for these two terranes, as argued previously by Irving et al. (1996) and Cowan et al. (1997).

Our analysis also finds that significantly less displacement of the Insular Superterrane is recorded by units that are younger than 80 Ma (Fig. 5). Consequently, the paleomagnetic data records the transition from the lower paleolatitudes recorded by 90 Ma and older rocks, to progressively higher paleolatitudes recorded by 80 Ma and younger rocks. Thus there is evidence for the "run" phase of the hit-and-run model described below.

WORLDWIDE PLATE REORGANIZATION AT 105-100 MA

There is evidence for a worldwide plate organization at 105-100 Ma (Matthews et al., 2012). The cessation of activity along a 7000 km long subduction zone beneath eastern Gondwana is the probable cause for this change in plate motion. This subduction zone was located under eastern Australia/Zealandia, New Zealand, and west Antarctica; effectively, it defined the southern edge of the Pacific basin. The cessation of this subduction system and the transition to extension is well documented geologically in both New Zealand and Antarctica (e.g., Jordan et al., 2020). There are questions as to the ultimate cause of this subduction cessation and the amount of time it takes to effect a plate reorganization. Major changes in plate motion changes do occur: A well-documented example of plate motion change occured at 55-50 Ma within the Pacific

Basin (e.g., Morgan, 1971; Matthews et al., 2015). Although there are proposed worldwide tectonic effects of the 100 Ma plate reorganization (Matthews et al., 2012; Seton et al., 2012), we focus exclusively on the effects on the Pacific basin and particularly North America. These results are largely confirmed by more recent models (Matthews et al., 2016; Müller et al., 2019).

The critical aspect of the plate reorganization is that the subduction system that ceased occurred at the south end of the Pacific basin (Matthews et al., 2012). Because slab pull is thought to be the primary driver of plate motion (e.g., Conrad and Lithgow-Bertolloni, 2004), the cessation of subduction at the southern end of the Pacific basin end the southerly "pull". In contrast, subduction of the Izanagi plate in the north part of the Pacific basin continued at this time, which would continue to move plates to the northward. The effect on the western edge of North America would be the activation of dextral shear zones initiating at 100 Ma. In a prescient article, Oldow et al. (1984) documented a change from dominantly margin-parallel left-lateral shear zones along the western margin before 100 Ma, to exclusively margin-parallel right-lateral shear zones after 100 Ma.

Seton et al. (2012) created a model for worldwide plate motions between 200 Ma and present. This model follows earlier approaches – similar to those by Engebretson et al. (1985), Debiche et al. (1987), and Doubrovine and Tarduno (2008) – that relied heavily on seafloor spreading models and were applied to understand the tectonic development of the western margin of Laurentia. Data from Seton et al. (2012) provide evidence for a plate motion reorganization at 103-100 Ma. Specifically, they predicted a dominantly right-lateral transcurrent motion on the margin of North America at ~100-83 Ma. Seton et al. (2012) note that this result is inconsistent with geological interpretations that invoke subduction under North America at this time.

The Seton et al. (2012) model suggested that after 100 Ma, the western margin of North America was mostly a strike-slip – rather than a subduction – margin. This model also assumed that the Farallon plate was directly adjacent to North America (as does Müller et al., 2019). This assumption might be incorrect, as intervening plates between the Farallon and North America could alter the relative plate motion on the western edge of Laurentia (e.g., Haeussler et al., 2003; Clennett et al., 2020). Rather, as discussed below, the Insular Superterrane was likely adjacent to much of the western edge of North America starting at ~100 Ma, as restored according to paleomagnetic constraints discussed in the previous section. Regardless, these plate motion models (e.g., Matthews et al., 2012; Seton et al., 2012) make two specific predictions: 1) There was a major plate reorganization at ~105-100 Ma; and 2) The western margin of North American had a significant right-lateral component of motion after ~100 Ma.

Further, because of the well-documented paleomagnetic still-stand for North America, there was no significant latitudinal change in margin position at this time. Consequently, deformation on North America can be largely or entirely attributed to the motion of the offshore plates. In this framework, we discuss the corroborating evidence for right-lateral translation along the western margin of Laurentia provided by paleomagnetic analyses.

THE IRREGULAR WESTERN MARGIN OF NORTH AMERICA (LAURENTIA)

Although the paleomagnetic data constrain the north-south position of the terranes and the plate models constrain plate motion, neither approach directly informs how the terranes interacted with the western margin of North America. Most models for tectonic development specifically assume a two-dimensional model that can be shown in a cross section (e.g., shallow slab subduction; Dickinson and Snyder, 1978). Even models that assume significant margin-parallel motion do not *explicitly* address the pre-existing morphology of the margin (e.g., hit-and-run model of Maxson and Tikoff, 1996; moderate translation model of Umhoefer and Blakely, 2006). This contribution recognizes that there were important pre-existing structures that significantly modified the tectonic response to transcurrent movement. The main features are: 1) The rift-transform margin of the late Precambrian breakup of Laurentia; 2) Permian-Triassic left-lateral truncation of the North American margin in southern California; and 3) The Lewis and Clark deformation zone ("Lewis and Clark line") that was distinct from the rift-transform segmentation caused by late Precambrian rifting. In cases where the inboard Intermontane superterrane was located between the colliding Insular block and North America (e.g., northernmost Nevada and northward), the response is more complex.

The western margin of Laurentia was likely segmented as a result of Neoproterozoic rifting and subsequent strike-slip faulting (Fig. 6). The Precambrian rifted margin of western Laurentia consisted of ~330-oriented rift segments and ~060-oriented transform faults (Lund, 2008). This geometry suggests formation by NE-SW directed extension. We note aan alternative interpretation that suggests NW-SE directed extension (e.g., Christie-Blick and Levy, 1989; Speed, 1994). In a separate contribution in this volume, Tikoff et al. (2022) argue that the geometry proposed by Lund (2008) is correct and that an undocumented promontory (Palouse) must have existed in Washington State (Fig. 6). The Palouse promontory is a major feature in the tectonic model presented below. Geologists have previously recognized the significant effect of these Precambrian boundaries on younger tectonism. For example, Oldow et al. (1994) noted the effect of the Mina deflection of Nevada – a Precambrian transform fault – on deformation in the Walker Lane belt.

Precambrian rifting resulted in a major continental promontory in California. It is generally accepted that this margin was truncated in Permian-Triassic time by a major left-lateral strike-slip fault (e.g., Walker, 1988; Snow, 1992; Stevens and Stone, 2005). This left-lateral fault is hypothesized to bend into a WNW-ESE orientation starting in southern California and continuing into Mexico, known as the California-Coahuila transform (Fig. 6; Saleeby and Busby, 1992; Dickinson, 2008). A block of continental material – known as the Caborca block – was translated from the California margin into northern Mexico (Sonora) (Walker, 1988; Dickinson and Lawton, 2001). We acknowledge that some interpretations call on Jurassic movement for this fault (the Mojave-Sonora megashear of Anderson and Silver, 2005).

The third pre-existing structure is the Lewis and Clark deformation zone of Montana, Idaho, and easternmost Washington (Fig. 7). This structure appears to have initiated at ~1.5 Ga, as a rift-related structure during deposition within the Belt-Purcell basin (Lydon, 2000). Its current ~110 orientation is distinct from the 330 and 060 trends attributed to Precambrian rifting (e.g., Lund, 2008). King (1969) noted that this structure demarcates the northernmost extent of the basement-cored block uplifts, and demarcates the boundary between the central and northern Cordillera.

The western margin of continental North America can be located using the $^{87}Sr/^{86}Sr_i$ = 0.706 isopleth (hereafter the Sr_i = 0.706 line) (e.g., Armstrong, 1977; Kistler and Peterman, 1973; Fleck and Criss, 1985; Kistler, 1990). This isotopic tracer works because of the abundance of granitic rocks throughout the North American Cordillera. For example, the steped geometry of the Precambrian rifted margin determined by Lund (2008) is directly reflected by the orientation of Sr_i = 0.706 line (e.g., Tosdal et al., 2000). These pre-existing features significantly affected the response of deformation on North America, with respect to the collision of the Insular Superterrane.

THE HIT-AND-RUN MODEL: OVERVIEW

The hit-and-run model explains two distinct phases of deformation recorded by ages and kinematics of deformation zones. The hit phase occurred from 105-85 Ma and the run phase occurred from 85-55 Ma. Continued strike-slip movement after 55 Ma is hypothesized for terranes outboard of the Insular Superterrane, suggesting even larger amounts of dextral offset (e.g., Plumley et al., 1983; Garver and Davidson, 2015). The "hit" refers to the collision of the Insular Superterrane with North America, which we interpret as having occurred at latitudes from central Idaho in the north to central Mexico in the south. As we discuss below, this was not a collision driven by orthogonal motion. Rather, the juxtaposition of the Insular Superterrane and western North America was mostly by highly oblique, possibly nearly strike-slip, motion.

We provide three figures for the hit phase of mountain building: 1) A paleogeological map with subsequent deformation (e.g., Basin and Range extension, offset along the San Andreas fault system) restored (Fig. 8a); 2) A table that divides the Cordilleran margin into NS segments, approximately scaled to their length (Fig. 9a); and 3) A schematic map of the 110-65 Ma tectonic evolution (Fig. 10). In Figures 8-10, note that the "Mojave" segment refers to the region south of the Garlock fault and north of the Peninsular ranges ("Baja" segement), which is significantly larger than the current Mojave region when Miocene-present dextral displacement is removed.

Deformation also occurred in the Canadian Cordillera, although care is required because these terranes might have been located significantly further south as constrained by paleomagnetic data. Monger et al. (1982) interpreted the ~100 Ma event to result from the collision of the Insular Superterrane with North America, which is a laterally extensive event (Rubin et al., 1990). This information indicates that the Insular Superterrane collided with the Intermontane terrane at some location along the North American margin. More recently, Pană (2021) documents a strong mid-Cretaceous (111-96 Ma) pulse of deformation in the Canadian hinterland. This mid-Cretaceous deformation is attributed to dextral transpression, partly on the basis of detailed studies of granitoid intrusions in the northern Canadian Rockies (e.g., McMechan, 2000).

The question, however, is whether there is evidence for contractional deformation in material that is clearly tied to the Canadian interior (craton), rather than occurring in terranes that could be located significantly further south. For example, in the Canadian fold-and-thrust belt, which can be linked to the craton, contractional deformation is relatively limited at ~100 Ma (e.g., Pană and van der Pluijm, 2015). Rather, there is abundant evidence of significant deformation in the southern Canadian fold-and-thrust belts in the Early Cretaceous, but deformation locally ceases prior to ~105 Ma (e.g., McDonough and Simony, 1988; Larson et al., 2006; Larson and Price, 2006; Evenchick et al., 2007). Likewise, in mainland Alaska away from the Insular terrane, there is no evidence for a 100 Ma collision (Busby et al., 2022). Rather, 100 Ma in northern and western Alaska is marked by the cessation of major crustal shortening (Moore and Box, 2016). In short, it is not likely that the Insular Superterrane collided in place. Rather, compelling geologic evidence suggests that it collided from Idaho to central Mexico, where paleomagnetic data would reconstruct it at ~100 Ma.

There are three major effects of the Insular Superterrane collision at 100-85 Ma – with the latitude constrained by paleomagnetic data – on the tectonics of North America. First, there is a nearly simultaneous dextral transpressional deformation in all of the magmatic arcs from Idaho to central Mexico (Fig. 11). Second, there are zones localized uplift on the southern edge of western Laurentia's promontories (Figs. 6, 11, 12). This effect is most apparent in central Idaho and southern California. Third, there is pronounced movement on the fold-and-thrust belts and thickening in the orogenic hinterland. Below we discuss geological features on North America and/or previously accreted terranes, starting at the plate margin and moving toward the foreland, including: 1) Strike-slip faulting along the continental margin; 2) Hinterland shortening and plateau formation; 3) Clockwise rotation of crustal blocks, accommodated by left-lateral faulting; 4) Contractional deformation in the fold-and-thrust belts; and 5) Basement-cored block uplifts south of the Lewis and Clark line in Idaho-Montana.

THE 100-85 MA HIT PHASE

The Idaho segment as an exemplar of oblique terrane collision

The Idaho segment has never been fully integrated into the tectonic history of the Cordillera, because it does not fit neatly into either of the better-studied Canadian or California segments of the Cordillera. The Late Cretaceous-Paleogene tectonic history of the Canadian segment is dominated by accreted terranes and includes significant right-lateral, strike-slip faulting. The California segment is typically considered in terms of subduction. To emphasize this point, the Idaho segment lies too far south for the recent compilation from the northern Cordillera of Pavlis et al. (2019) and Monger and Gibson (2019) and too far north from the central Cordillera emphasized by Yonkee and Weil (2015) and DeCelles and Graham (2015).

The Idaho segment is critical, however, because deformation resulted from collision of the Insular Superterrane: There is coherence of both the location and timing of deformation. Wyld et al. (2006) restored the offset on known dextral, strike-slip faults in Washington and British Columbia to provide a 100 Ma model for the location of terranes. The southern margin of the Insular Superterrane restores to northernmost coastal California, outboard of all known occurrences of the western Idaho shear zone (Benford et al., 2010; Schmidt et al., 2017). The Wyld et al. (2006) reconstruction is nearly identical to the reconstruction of Butler et al. (2001), which minimizes the possible paleomagnetically derived offset of both the Insular and Intermontane Superterranes. In more mobilistic versions of ~100 Ma reconstructions of the Cordillera – Alta-BC (e.g., Umhoefer and Blakey, 2006) or Mojave-BC (e.g., Sauer et al., 2019) – the northern Insular Superterrane is located offshore Idaho. If the known N-S extent of the Insular Superterrane is utilized, the northern portions of the Insular Superterrane are also offshore Idaho in the most mobilistic versions of Baja-BC (Cowan et al., 1997). Thus, regardless of whether one accepts the paleomagnetic data or not, the Idaho segment records the Insular Superterrane collision at 100 Ma.

The western Idaho shear zone is a major structure active in the northern U.S. Cordillera at 100-85 Ma. The western Idaho shear zone restores to a pre-Miocene orientation of N-S, vertical foliation and vertical lineations (Tikoff et al., 2001). The kinematics of the shear zones are dextral transpressional, as constrained by numerical modeling (Giorgis and Tikoff, 2004), field studies (Braudy et al., 2017), and microstructural analysis (Michels et al., 2015). The magnitude of dextral offset on the western Idaho shear zone is estimated at ~400 km (Tikoff et al., 2017).

Deformation of the western Idaho shear zone extends to southwest Idaho, although deformation fabrics are significantly less well developed there (Benford et al., 2010). Deformation fabrics continue to the north, where the NS-oriented transpressional fabric of the WISZ is in continuity with the reverse-motion of the Ahsahka shear zone (Giorgis et al., 2017; Schmidt et al., 2017). The fabrics continue westward along the EW-oriented continental boundary delineated by the $Sr_i = 0.706$ isopleth. Fabrics are extremely well developed near Orofino, Idaho, at the transition from the NS- to EW-oriented boundary (e.g., Strayer et al., 1989).

The timing of deformation in Idaho is nearly identical to the inferred collision of the Insular Superterrane. The ~100 Ma event in southern Canada and the Alaska panhandle is widely accepted to be caused by collision of the Insular Superterrane with North America (Monger et al., 1982; Rubin et al., 1990). This is the approximate section of the Insular terrane that would be adjacent to the Idaho margin at 100 Ma. Further, the timing of the western Idaho shear zone is well constrained. Braudy et al. (2017) interpret that the shear zone was not active at 103 Ma, but was active by ~99 Ma based on Lu-Hf dates on garnets. Giorgis et al. (2008) indicate that the deformation ceased by 90 Ma, at least in that section of the western Idaho shear zone on which they focused, based on the presence of an undeformed pegmatitic dike of that age. Recent U-Pb zircon and titanite geochronology investigations near McCall, Idaho, suggest that deformation started at 99-96 Ma and continued until ~85 Ma (Harrigan et al., 2019; 2021). Similar timing is inferred for other right-lateral shear zones east of the western Idaho shear zone in Idaho (Ma et al., 2017).

The Blue Mountain terranes collision (Salmon River suture zone) vs. the Insular Superterrane collision (western Idaho shear zeon)

Understanding the tectonic history in Idaho has long been hampered by the fact that there are two tectonic structures that are spatially identical but temporally distinct (e.g., McClelland et al., 2000). The Salmon River suture zone refers to the juxtaposition of the Blue Mountain terranes (e.g., Ave Lallement, 1995; Vallier, 1995) – correlated to the Intermontane Superterrane – to North America. There are some locations where the suture zone is argued to be preserved along the Idaho margin (Woodrat thrust zone; R. Lewis, pers. comm., 2019) and sections where the Blue Mountain terranes were juxtaposed with North American crust as interpreted from geophysical (Stanciu et al., 2016; Davenport et al., 2017) or geochemical (Braudy et al., 2017) data. The initial suturing event could have occurred by 155 Ma or earlier (e.g., Schwartz et al., 2010; 2011; LaMaskin et al., 2011), although final accretion of the Blue Mountain terranes to North America might have occurred as late as ~135-125 Ma (e.g., Getty et al., 1993; Montz and Kruckenberg, 2017).

In contrast, the western Idaho shear zone is attributed to the collision of the Insular Superterrane to the western margin of the Blue Mountain terranes (Giorgis et al., 2008; Tikoff et al., 2022). The collision of the Blue Mountains could not be the cause for the western Idaho shear zone or any of the other right-lateral faults in the Idaho batholith region (e.g., Ma et al., 2017), as the Blue Mountains were already amalgamated to North American and were being intruded by arc magmas (Gaschnig et al., 2017). We do not know what type of deformation occurred at the boundary between the Insular and Intermontane terrane located further west from the western Idaho shear zone. The reason is that this suture was modified by later ~2000 km differential terrane movement, which is the difference between the ~3000 km movement of the Insular Superterrane and the ~1000 km movement of the Intermontane Superterrane after 100 Ma (e.g., Irving et al., 1996). Further, to the west of the western Idaho shear zone, the western portion of the accreted terranes are largely covered by younger volcanic rocks and sediments.

The Idaho segment records two unique aspects related to the initial Insular Superterrane collision (Figs. 7, 8, 10): 1) Transpressional kinematics within the magmatic arc system; and 2) Block uplifts in the foreland. The transpressional deformation with the magmatic arc systems occurs in all magmatic arcs on North American south of Idaho at ~100 Ma (e.g., NW Nevada, Sierra Nevada, Peninsular Range). If terrane collision is the cause of the ~100 Ma transpressional magmatic arc deformation, then the Insular Superterrane likely occurred everywhere south of Idaho, consistent with the paleomagnetic results. Second, block uplifts in the foreland are known to occur in every collisional orogen (e.g., Rodgers, 1987). However, under the commonly accepted model (Yonkee and Weil, 2015; Carrapa et al., 2019 for southwest Montana), block uplifts are attributed solely to shallow slab subduction, although recent studies point out the problems with this interpretation (e.g., Garber et al., 2020).

The deformation-related exhumation of block uplifts east of the Idaho segment at ca. 100 Ma by shallow slab subduction is problematic for multiple reasons. First, flat slab subduction is assumed to start after cessation of magmatism in the magmatic arcs, after 85 Ma (Dickinson and Snyder, 1978). Second, from either a fixist (e.g., Butler et al., 2001) or mobilist perspective, the Insular belt – with its own subduction system – is located to the west of Idaho. There is simply no slab – shallow or otherwise – left to subduct under the Idaho segment of the North American Cordillera. Third, the most widely accepted model for shallow slab subduction has it occurring only under the Mojave region (e.g., Saleeby, 2003). Thus, the Insular collision is likely responsible for the collisional deformation observed in the northern U.S. Cordillera at 100-85 Ma.

As shown diagrammatically in Figure 11, we cannot fully resolve the facing direction (or slab dip directions) for the subduction zones. We use the consensus opinion for E-dipping subduction below the North American margin in the Early Cretaceous, based on the geological constraints from Idaho, central California, and northern Mexico. The less constrained problem is whether there was an E-dipping or W-dipping subduction zone below the Insular terrane (Fig. 11). In the E-dipping subduction zone model, the Insular was on the same tectonic plate as the Mezcalera ocean. In the W-dipping subduction zone model, the Mezcalera plate subducted below both the North American margin to the east and the Insular terrane in the west. This double-subducting geometry is observed in the Sea of Molucca, and was inferred for other terrane collisions in the Cordillera (e.g., Schweickert and Cowan, 1975).

Magmatic arcs: Transpressional deformation in the the western Idaho shear zone

Magmatism occurred prior to, during, and after WISZ deformation (Manduca et al., 1993; Giorgis et al., 2008; Gaschnig et al., 2010; 2011). As defined by Idaho workers, the mylonitic rocks of the western Idaho shear zone are the gneissic border (Taubeneck, 1971) but not part of the Idaho batholith proper. Those mylonitic rocks, however, are all orthogneisses and are part of a pre-existing Early Cretaceous magmatic arc that existing in Idaho (Gaschnig et al., 2017). This Early Cretaceous magmatic arc was tectonically telescoped by the significant contractional deformation associated with the western Idaho shear zone (Giorgis et al., 2005). The earliest phase of Idaho batholith magmatism is the suture zone suite of Gaschnig et al. (2010), which involves ~92-85 Ma hornblende-bearing tonalites and granodiorites that are weakly deformed in the WISZ. The Atlanta lobe of the Idaho batholith, which constitutes the majority of the batholith, contains mostly two-mica granites and exhibits U-Pb zircon ages of 83-70 Ma (Gaschnig et al., 2010). The Atlanta lobe has been interpreted to result from crustal melting (Gaschnig et al., 2011).

The question remains as to why the deformation is so localized along the western Idaho shear zone, which occurs significantly (>200 km) eastward from the inferred suture zone between Insular and Intermontane collision. We postulate that the answer is the presence of a magmatic arc in localizing strike-slip deformation. Strike-slip faulting is common – although often segmented – along the axis of magmatic arcs in areas of oblique plate convergence (Fitch, 1972; Sieh and Natawidjaja, 2000 for Sumatra; Garibaldi et al., 2016 for El Salvador). Many authors have speculated that the tabular, vertical zone of magmatism associated with an arc would cause a lithospheric-scale weakness for strike-slip motion (e.g., Beck, 1986; St. Blanquat et al., 1998). If non-orthogonal terrane collisions occur, one would likewise expect the magmatic arcs to accommodate the transcurrent motion until the rheologically weak magmas “freeze” into granites.

It is important to note that a magmatic arc cannot immediately cease magmatism after a collisional event, because the pre-existing slab must still sink into the mantle. This argument explains the continued magmatism during deformation in the western

Idaho shear zone. Further, Hildebrand and Whalen (2017; 2021b) used geochemical discrimination plots to determine whether magmatism resulted from arc magmatism or slab detachment (Whalen and Hildebrand, 2019): This approach has been evaluated in different settings (Hildebrand and Whalen, 2017; Hildebrand et al., 2018). The results from Idaho show a clear and consistent pattern that conforms to the regional tectonic setting. Granitic rocks intruded prior to 100 Ma, which are strongly deformed by the western Idaho shear zone, show arc affinities. In contrast, rocks that post-date the major phase of western Idaho shear zone deformation (e.g., suture zone suite of Gaschnig et al., 2010) dominantly plot in the slab detachment field. As documented by Hildebrand and Whalen (2021a), this same temporal pattern for a switch from arc to slab breakoff magmatism at ~100 Ma holds for the Sierra Nevada and Peninsular Range batholiths.

Magmatic arcs south of Idaho: Dextral transpression

Northwestern Nevada

Evidence for mid-Cretaceous transpressional deformation is present in northwestern Nevada, along the northward continuation of the Sierra Nevada batholith (Van Buer and Miller, 2010) (Fig. 7). Evidence for Cretaceous arc magmatism in Nevada is preserved in isolated plutons and batholiths scattered from south to north across the region (Van Buer and Miller, 2010). In the Black Rock region, Wyld and Wright (2001) inferred dextral motion in the Western Nevada shear zone. The shear zone is not exposed and therefore the timing is poorly constrained.

The Sahwave and Nightingale Range provide direct evidence for strike-slip offset (Trevino et al., 2021). The ca. 106 Ma Powerline intrusive complex shows evidence of mid- to low-temperature solid-state deformation and the development of the NS striking vertical foliation and subvertical lineation. Dextral shear indicators (horizontal movement direction) perpendicular to stretching lineation (vertical) suggest that the unit experienced dextral transpressional shearing. The deformation geometry of this unit is reminiscent of the pure-shear dominated transpression recorded in the western Idaho shear zone (e.g., McClelland et al., 2000; Giorgis et al., 2017). The internal fabrics of the Power Line intrusive complex (field-measured and magnetic foliations) are concordant to wall rock foliation. This concordance may indicate extensive post-emplacement deformation cross-cutting the pluton/country rock contact.

The ca. 96-88 Ma plutons of the Sahwave batholith preserve internal fabrics reminiscent of the Sierra Crest shear zone system (Trevino et al., 2021). Discrete, synmagmatic dextral offsets are locally observed along the eastern margin of the Sahwave Range within the youngest intrusive unit, indicating that dextral shearing continued to ~85 Ma in northwestern Nevada. We note that this timing is similar to that of the late-stage, subsolidus dextral shear zones in the eastern Sierra Nevada batholith (e.g., Tikoff and St. Blanquat, 1997).

Sierra Nevada batholith, California

Several independent lines of evidence for transpressional deformation are found along the axis of the Sierra Nevada batholith: 1) Inferred right-lateral offset of the Snow Lake relative to the Mojave region (e.g., Lahren et al., 1990); 2) Dextral shear zones initiating at ~100 Ma in the Sierra Nevada batholith(e.g., Krueger and Yoshinobu, 2018); and 3) Right-lateral offset of Sr_i = 0.706 isopleth (e.g., Kistler, 1990) (Fig. 13). Together, these features indication approximately 400 km of right-lateral offset.

The hypothesized Mojave-Snow Lake fault was proposed to accommodate ~400 km of right-lateral slip occured along the axis of the Sierra Nevada batholith (Lahren et al., 1990). This fault was inferred based on correlation of sedimentary rocks in the Snow Lake Pendant to rocks in the Mojave desert, although there has never been direct evidence for the existence of this fault.

Krueger and Yoshinobu (2018) documented a major dextral transpressional deformation within the Sing Peak shear zone at ~100 Ma in the Sierra Nevada batholith. The Sing Peak shear zone was mostly obliterated by the major 95-85 Ma magmatism along the axis of the Sierra Nevada. Ongoing work indicates that multiple other shear zones (Kaiser Peak, Courtright) were active at 100 Ma, and show local evidence for dextral transpressional deformation. Direct evidence for strike-slip deformation along the axis of active magmatism occurs in the Sierra Crest shear zone system (e.g., Tikoff and Greene, 1997) and the slightly older Bench Canyon shear zone (McNulty, 1995). A series of right-lateral shear zones occur along the crest of the Sierra Nevada, with deformation found in the large intrusive suites (Tuolumne, Mono Pass, Mt Whitney) (e.g., Tikoff and St. Blanquat, 1997; Tikoff et al., 2004; Cao et al., 2015). Some of the youngest plutons of these intrusive suites were emplaced syntectonically (e.g., Tikoff and Teyssier, 1992).

Another line of evidence for ~100 Ma dextral shearing comes from Sr isotope values on granitic rocks within the Sierra Nevada batholith (Kistler, 1990: Fig. 13). Kistler (1990) document a series of NNW-trending interbatholith breaks and interpreted these as a series of right-lateral offsets of the Sr_i = 0.706 isopleth. The trend of these interbatholith breaks loosely correspond to the trend of shear zones in the Sierra Nevada batholiths, although the shear zones are often intruded by younger magmatic bodies. The magnitude of right-lateral offset can be estimated if the northern edge of these blocks restore to the position of the Mina deflection (e.g., Oldow et al., 1994), interpreted as a transform fault inherited from late Precambrian rifting (Lund, 2008). These offsets were superimposed on an earlier, NNW-oriented Permian-Triassic truncation of the boundary by a sinistral strike-slip fault, consistent with geochemical studies (Lackey et al., 2012).

Combining all the data, there was likely dextral transpressional deformation from 100 to 83 Ma, after which the Sierra Nevada magmatic arc ceased. Further, the offsets of interbatholith breaks of Kistler (1990) add up to approximately 400 km of dextral displacement (Fig. 13), consistent with estimates along the Mojave-Snow Lake fault. Both the timing and the displacement are similar to dextral transpressional deformation in Idaho, suggesting a kinematic link. The dextral shearing in the Sierra Nevada magmatic arc would have offset everything to its west (outboard of the Late Cretaceous axis of magmatism), including the Early Cretaceous plutons of Sierra Nevada arc, the Great Valley sequence, Franciscan Complex, and the Klamath mountains (Figs. 1, 13).

It is also worth noting that paleomagnetic studies from the Cretaceous Sierra Nevada batholith suggest that there has been little, or no, displacement with respect to their present location relative to North America. Paleomagnetic studies of the Late Cretaceous granites of the central Sierra Nevada batholith have well-defined magnetizations, which yield a mean paleopole that is identical to the 130-85 Ma North America pole (Frei et al., 1984; Hillhouse and Grommé, 2011). Relatively minor (a few 100 km) displacement, or minor rotation, is permitted within the errors associated with the paleomagnetic directions from the Sierra Nevada, the North American reference pole, and with possible minor tilt of these plutonic rocks.

Peninsular Range batholith and the San Martir "thrust"

In the southern U.S. Cordillera and adjacent Mexico, we note the presence of a major shear zone located in the middle of the Peninsular Range batholith. This structure is called the San Martir "thrust". This amphibolite-faces shear zone separates a western magmatic arc (Alisitos) from an eastern magmatic arc. Deformation is constrained to have occurred between ~102 and 85 Ma, as the zone is intruded by La Posta granites (e.g., Walawender et al., 1990; Schmidt et al., 2013; Duque-Trujillo et al., 2015). This thrust corresponds to a steep gradient of the Sr_i = 0.706 isopleth, with the higher values and more continental signature on the east side. In part, this gradient exists because the continental Caborca block is located on the east side of the San Martir "thrust".

We hypothesize that that the San Martir "thrust" records a major component of strike-slip motion. First, the shear zone has a flower-structure type geometry, suggestive of transpressional deformation (Schmidt and Paterson, 2002). Second, steep gradients of the Sr_i = 0.706 isopleth occur within both the western Idaho shear zone and on shear zones within the Sierra Nevada batholith, all of which are interpreted as right-lateral transpressional shear zones. Third, the timing is consistent with the strike-slip tectonism in the other arcs. Finally, there are vertical tonalite sills in this setting, similar to those in the western Idaho shear zone. For the purposes of the hit-and-run model, it is not significant how much of a strike-slip component occurred in the San Martir "thrust". The important aspect is that there was a major change from a subduction system to a collisional setting at ~105-100 Ma (Hildebrand and Whalen, 2021a).

In general, the magmatism in the Peninsular Range batholith (with the San Martir "thrust") is very similar to that adjacent to the western Idaho shear zone. In both cases: 1) An Early Cretaceous magmatic arc is found on the oceanic side of a major shear zone (e.g., Schmidt et al., 2013); and 2) That Early Cretaceous magmatic arc must have been located near the continental margin, because of the presence of Precambrian detrital zircons (e.g., Busby, 2004 for the Alisitos arc; Gaschnig et al., 2017 for Idaho). The foliation in both shear zones in both locations dip steeply (~75° E). In the WISZ, however, the fabric has clearly been rotated on a regional basis, as observed by shallowly westward dipping basalt flows that overlay that structure (e.g., Tikoff et al., 2001). Thus, the western Idaho shear zone restores to a sub-vertical orientation. Paleomagnetic studies on one of the cross-cutting La Posta plutons, the mid-Cretaceous (102 Ma) El Potrero pluton, indicate that it rotated up to 35° about a horizontal axis (Cabello et al., 2006). Since this rotation must also affect the San Martir "thrust", it rotates the "thrust" fabrics to a steep orientation. One significant difference between these two areas is that the Peninsular Range batholith appears to have undergone a major Early Cretaceous extensional event with deposition of major clastic rocks with distinct provenance (e.g., Martini et al., 2014; 2016). In contrast, the Idaho region underwent Early Cretaceous contraction recorded by the Salmon River suture zone.

Hinterland: Promotories and focused contractional deformation

There are two major promontories of basement rocks in the western United States: One in Idaho and one in southern California. Both record significant 100 Ma deformation. The concept is that a ragged edge of a continent would produce promontories that would hinder margin-parallel movement. Such corners have been identified worldwide as areas of strong deformation (e.g., Hoffman, 2020). The ongoing Yakutat collision in the corner of Alaska provides a modern analog for this type of process (e.g. Plafker et al., 1994; Pavlis et al., 2004; Redfield et al., 2007; Worthington et al., 2012).

Idaho

The western margin of Laurentia was segmented as a result of Neoproterozoic rifting (Fig. 6), resulting in ~330-oriented rifted segments and ~060-oriented transform faults (Lund, 2008). A companion paper in this volume (Tikoff et al., 2022) reports on the 30° clockwise rotation of a Blue Mountains-Adjacent Laurentia block after 85 Ma, accommodated by the Lewis and Clark deformation zone (see below). It follows that the western Idaho and Ahsahka shear zones formed in a different orientation than their current orientation (Fig. 12). The original orientation can be restored through a 30° counter-clockwise rotation. Thus, the NS portion of the WISZ was originally oriented at

330, parallel to the other rift segments of western Laurentia margin. Likewise, the EW trending portion of the continental margin was originally oriented 060, parallel to other transform segments. Thus, the 90° bend in the continental margin near Orofino Idaho is attributed to inheritance of a Precambrian rift-transform boundary (Lund et al., 2008; Tikoff et al., 2022).

In this model, a continental promontory existed in central Washington (Palouse promontory), and an embayment existed in eastern Oregon (McCall embayment) (Fig. 6). Terranes moving northward after 100 Ma would encounter the Palouse promontory of the Laurentian margin (Figs. 6, 11). Because of the 330 (rift) - 060 (transform) orientation, accreted terranes moving northward (right-lateral sense) against the continental margin would have been caught in "corners" presented by promontories.

The Cretaceous promontory corner in Idaho explains the intensity of deformation at Orofino, Idaho, because it acted as a transpressional syntaxis (Strayer et al., 1987; Giorgis et al., 2017; Schmidt et al., 2017; Tikoff et al., 2022). The deformation zone that resulted in this "corner" is known as the Ahsahka shear zone, which is structurally continuous with the western Idaho shear zone (Schmidt et al., 2017). The Ahsahka shear zone is a zone of dominantly reverse-sense kinematics, which distinguishes it from the dextral transpressional kinematics of the WISZ (Schmidt et al., 2017). The sense of vergence is top to the SW and the magnitude of shortening is significant (Strayer et al., 1989), indicating that the already-accreted Blue Mountain terranes were underthrust below North America. Additional major contractional structures, such as the Coolwater culmination, occur in the bend of the shear zone (Lund et al., 2008).

Another significant aspect of recognizing transpressional syntaxes is that we can use published studies to determine the relative motion of the colliding terranes. Giorgis et al. (2017), using the kinematic vorticity analysis, argue for a ~45-60° angle of oblique convergence in the NS-section of the WISZ. This analysis assumes no strike-slip partitioning; any partitioning will reduce that angle. It has been determined that the continental margin here has been rotated 30° counterclockwise from the current orientation (Tikoff et al., 2022). As such, the azimuth of the movement of the Blue Mountain Terranes relative to North America must also rotate, which then restores to

015-030. That is, the western Idaho shear zone formed from dominantly northward movement of outboard terranes.

Southern California

The continental promontory in southern California (Fig. 6) formed loosely along a WNW-ESE trend of a structure variably named the California-Coahuila transform (Dickinson, 2000), Mojave-Sonora megashear (Anderson and Silver, 2005), or Texas Lineament (King, 1969). Rocks of the central and southern Sierra Nevada form on the westernmost margin of pre-100 Ma North America. The continental margin, however, bends eastward south of the Sierra Nevada mountain. Left-lateral motion along the North American margin occurred in the Permo-Triassic (e.g., Walker, 1988), although additional movement may have occurred in the Jurassic (e.g., Anderson and Silver, 1979). Extensional deformation occurred along this WNW-ESE trend during Jurassic timw, leading to the development of the Bisbee basin of Arizona. The existence of a Jurassic arc that extends along southern California, southern Arizona, and northern Sonora (e.g., Bassett and Busby, 2005) – continuous with the Jurassic Sierra Nevada arc – indicates that the boundary of continental North America locally had a WNW-ESE trend. This orientation is a deviation from the rift-transform pattern that occurs farther north and would form a barrier to northward terrane movement.

The major contractional deformation in this region occurs on the WNW-ESE Maria fold-and-thrust belt (e.g., Reynolds et al., 1986; Tosdal, 1990, Boettcher and Mosher, 1998; Boettcher et al., 2002). SW shortening is recorded by basement-involved thrust faults and fold nappes, which occurred synchronously with greenschist-amphibolite facies metamorphism. Within the nappes, significant ductile thinning of the stratigraphy occurred (Hamilton, 1982). Deposition of the McCoy Formation is linked to movement on this thrust belt. In general, deposition started in mid-Cretaceous time and continued to the Late Cretaceous time, although the basal part of the McCoy Formation was deposited in Jurassic time (e.g., Barth et al., 2004). Deposition of the McCoy Formation – related to contraction – appears to have initiated as deformation associated with the Bisbee Group – related to extension – appears to have ended (Jacques-Ayala, 2003; Barth et al., 2004). Deformation is constrained to be mid-Cretaceous, prior to cross-cutting plutonism (Boettcher et al., 2002) and regional cooling (Knapp and Heizler, 1990).

There is a clear difference in orientation between the WNW-trending Maria fold-and-thrust belt and the NNW-trending Sevier fold-and-thrust belt in southern Utah. Three models were proposed to explain this difference: 1) The lack of a sedimentary assemblage in which thin-skinned deformation could be accommodated (e.g., Burchfiel and Davis, 1975); 2) Thin-skinned deformation was associated with thickening in the coastal batholiths (e.g., Smith, 1981); and 3) Variations in orientation of the southern California margin, in which thrust movement in the Maria fold-and-thrust belt was linked to right-lateral strike-slip shearing to the north (Sierra Nevada) and the south (Peninsular Range batholith) (Boettcher, 1996). We hypothesize that deformation occurred because of the ~100 Ma oblique collision of the Insular Superterrane, in a model otherwise following that of Boettcher (1996). It appears unlikely that the Maria fold-and-thrust belt formed due to crustal shortening along a magmatic arc, because the WNW-trending Maria fold-and-thrust is at an oblique angle to the NNW-trending arc. Rather, we infer that the Maria fold-and-thrust developed in response to closure of the Jurassic extensional structures along the western edge of North America.

Another effect of the ~100 Ma oblique collision was underthrusting beneath the southern "tail" of the Sierra Nevada (e.g., Chapman et al., 2012). While this underthrusting is inferred to result from eastward subduction (Chapman et al., 2020), there are significant problems with this interpretation (Hildebrand and Whalen, 2021a). First, both paleomagnetic data (Kanter and Williams, 1982) and tectonic reconstructions indicate that the Sierra Nevada tail has rotated ~40 clockwise since ~80 Ma (Fig. 13). Second, the geological maps indicate that continental North America is underthrust below the western Sierra Nevada batholith (see Hildebrand and Whalen, 2021a). This geometry is incompatible with eastward subduction of oceanic material from the Pacific basin, regardless of a steep vs. shallow dip of the subduction zone. It is, however, consistent with either westward subduction (Hildebrand and Whalen, 2021a) or northward translation of crustal blocks (this contribution).

Foreland: Fold-and-thrust belts

There is an abundant and rich literature on the Sevier fold-and-thrust belt in the Canadian, U.S., and Mexican sections of the North American Cordillera, as summarized in reviews by Evenchick et al. (2007), Yonkee and Weil (2015), and Fitz-Diaz et al. (2017), respectively. We highlight only first-order trends and how they support the hit-and-run model.

Deformation in the Canadian fold-and-thrust belt is, for the most part, younger than its along-strike counterparts in the U.S.. Pană and van der Pluijm (2015) documented the timing of movement within the Canadian thrust belt, using radiometric dating on illite from within fault gouge. The majority of contractional deformation initiated at about 76 Ma, consistent with other regional compilations (e.g., Evenchick et al., 2007). Deformation within the thrust belt continued to ~52 Ma, with the youngest shortening occurring later than in the U.S. segment.

The Sevier fold-and-thrust belt in the western U.S. records a long history of contractional deformation, initiating in Late Jurassic time. A contractional deformation event occurred at 125 Ma, at least in the central Cordillera, as evidenced by movement along the Willard thrust sheet of central Utah (e.g., Yonkee et al., 2019). This deformation is consistent with contractional deformation in northwestern Nevada (e.g., Wyld and Wright, 2001) and western Idaho, possibly related to accretion of the Blue Mountain terranes to the western margin of North America (Getty et al., 1993; Montz and Kruckenberg, 2017).

Contractional deformation in the U.S. portion of the Sevier fold-and-thrust belt appears to have accelerated around 100 Ma. Low-temperature thermochronology indicates a major phase of orogenic exhumation at 100-96 Ma in the Pavant Valley and Nebo thrust sheets of the Provo salient (Pujols et al., 2020). Deformation from farther south in Utah indicate movement on multiple thrust faults at ~100 Ma, interpreted as a mid-Cretaceous shortening event (Quick et al., 2020). Studies on sedimentation suggest that hinterland uplift starts in the mid-Cretaceous, potentially prior to throughgoing movement on the Sevier fold-and-thrust belt (e.g., Heller et al., 1986; Heller and Paola, 1989). Contractional deformation as recorded by foreland sedimentation continued through the Late Cretaceous and Paleogene, in a punctuated manner likely related to behaviour described by the critical wedge model (DeCelles and Mitra, 1995).

The Sevier fold-and-thrust belt appears to disappear near Las Vegas, Nevada, although it changes orientation to become the Maria fold-and-thrust belt (discussed above). Wells (2016) noted the presence of a short-lived tectonic event that occurred from 100-90 Ma near Las Vegas, Nevada (also see Hildebrand and Whalen, 2021a,b).

The fold and thrust belt in Mexico steps eastward through time, but the earliest activation occurs in the Late Cenomanian (~96 Ma) (Fitz-Diaz et al., 2017). This westernmost deformation occurs in the Mesa Central area of central Mexico. The timing is approximately coincident with the first phase of La Posta plutonism and cessation of deformation along the San Martir "thrust" (e.g., Walawender et al., 1990).

Foreland: Block uplifts

Block uplifts in the far foreland, also known as Laramide uplifts, are typically attributed to shallow slab subduction. Understanding the timing of these features was initially based on the first appearance of sediments related to uplifts, which lead to the interpretation that uplifts initiated at ~78 Ma (e.g., Dickinson et al., 1988). In fact, block uplifts locally started earlier than 85 Ma. Merewether and Cobban (1986) document ~12 uplifts that formed at 96-88 Ma throughout the foreland of Montana, Wyoming, and northern Colorado. Their study is based on marine fossils data, as the area was mostly covered by the Cretaceous Interior seaway at this time. Steidtmann and Middleton (1991) note that, based on fault chronology, the Wind River uplift might have initiated at 100 Ma with rapid uplift starting at 90 Ma.

More recent geochronology efforts support the interpretation of earlier (i.e., mid-Cretaceous) uplift of these zones. Carrapa et al. (2019) used low-temperature thermochronology to show that uplifts (Highland and Tobacco Root Mountains; Beartooth, Gravelly, Madison, and Ruby Ranges) in southwest Montana started exhuming at ~100 Ma. Garber et al. (2020) also infer ongoing uplift in SW Montana by 88 Ma. Finally, U-Pb dates on calcite veins in northern Wyoming indicate that layer-parallel shortening in the Laramide foreland by ~90 Ma (Beaudoin et al., 2018).

As noted by multiple authors, this mid-Cretaceous initiation of block uplifts is not consistent with a shallow slab model. Steidtmann and Middleton (1991) explicitly state that if the early block uplift deformation was continuous in time with later block uplifts, attributing Laramide crustal shortening to shallow slabs subduction may not be appropriate. Garber et al. (2020) also noted that the shallow slab model has difficulties in the northern part of the Cordillera. Carrapa et al. (2019) noted that exhumation is consistent with the timing of deformation in the western Idaho shear zone. If the western Idaho shear zone is caused by Insular collision, it follows that block uplifts could also be caused by this event.

THE 85-55 MA RUN PHASE

The “run” phase of the orogeny occurred from 85-55 Ma. The “run” phase might be better considered a “run-and-lean” or “run-and-squeeze” phase , as it is associated with continued contractional deformation in the hinterland and foreland of adjacent North America. We provide also three references for the run phase of mountain building: 1) A paleogeological map with subsequent deformation removed (Fig. 8b); 2) A table that separates the Cordilleran margin into coastal segments, approximately scaled to their length (Fig. 9b); and 3) A schematic map of the 110-65 Ma tectonic evolution (Fig. 10). We first address why there was a switch from a “hit” to a “run” phase of the orogeny, which we interpret to record activation of the Lewis and Clark deformation zone. Then, we discuss from the geological structures that formed during this time interval, starting at the continental edge and moving toward the foreland.

Idaho catch-and-release

There is a curious problem related to Cretaceous-Paleogene terrane motion on the western edge of the North American Cordillera. The Insular Superterrane appears to have collided somewhere on the North American margin at 100 Ma, but the northward movement does not appear to have initiated until 85 Ma (e.g., Wynne et al., 1995). We return to Idaho again to address this question. The end of the “hit” phase at 85 Ma is coincident with two significant events in Idaho: 1) Cessation of movement on the WISZ (e.g., Giorgis et al., 2008; Harrigan et al., 2019); and 2) Initiation of the sinistral Lewis and Clark deformation zone (e.g., Sears and Hendrix, 2004).

We propose that northward translation of the Insular Superterrane into Canada was only possible once a Precambrian (Palouse) promontory of North America located in the Pacific Northwest of the United States moved (rotated) eastward (Fig. 6). As discussed above, Tikoff et al. (2022) argue that the Blue Mountain terranes and the adjacent portions of Laurentia (hence the Blue Mountain-Adjacent Laurentia block) were part of this rotation. The paleomagnetic evidence for this rotation includes: 1) ~30° clockwise rotation from ~90 Ma granites along the continental margin in Idaho (Tikoff et al., 2022); and 2) ~40° of clockwise rotation of sedimentary deposits of the Blue Mountain terranes between 85 and 45 Ma (Housen and Dorsey, 2005; Housen, 2018). Tikoff et al. (2022) propose that the Blue Mountains-Adjacent Laurentia block pivoted on a point in northern Nevada and that clockwise rotation was accommodated by sinistral movement on the Lewis and Clark deformation zone.

If this model is correct, the northern end of the Insular Superterrane was "caught" by the Paulouse continental promontory, but then "released" by sinistral movement on the Lewis and Clark deformation zone and the associated 30° clockwise rotation of the Blue Mountains-Adjacent Laurentia block (Fig. 12; Tikoff et al., 2022). Both the western Idaho shear zone and the rotation of the central Idaho blocks are a result of the interaction of Insular Superterrane with the North America margin and the intervening Blue Mountain / Intermontane terrane. The difference is how the displacement associated with the oblique convergent plate motion is partitioned in the "hit" versus the "run" phase. During the "hit" phase, the vorticity is localized into the simple shear cmponent of transpressional deformation within the magmatic arc (e.g., western Idaho shear zone). During the "run" phase, that northward motion causes the clockwise rotational component of crustal blocks. Most of the discrete strike-slip displacement, however, must have localized on the western boundary of the Insular and/or Intermontane Superterranes, to account for the difference in paleomagnetic signals of the two Superterranes.

The recognition of the role of this rotation may help resolve some long-standing puzzles in the Cordillera. One such puzzle is why the Idaho segment – including the Idaho batholith – is so far recessed relative to the plate margin in California (Fig. 1). The proposed answer is that it while it initiated as a Precambrian embayment, it has been moved eastward and rotated clockwise by post-85 Ma deformation (see Tikoff et al., 2022). This same rotation partially explains the presence of the Columbia embayment

(Fig. 7), because continental North America once extended farther west in the Pacific Northwest. The remainder of Columbia embayment formation could result from the northward translation of Intermontane Superterrane, moving terranes originally located in eastern Oregon into southern British Columbia (Wernicke and Klepacki, 1988; Wyld et al., 2006).

The second puzzle pertains to the genesis of the Idaho batholith, which is distinctly younger than the Sierra Nevada and Peninsular Range batholiths (Gaschnig et al., 2017). As defined by workers in Idaho, the granitic rocks affected by the western Idaho shear zone are not part of the Idaho batholith. Rather, the Idaho batholith is composed of dominantly the two-mica granites of the Atlanta and Bitteroot lobes (Gaschnig et al., 2010). The two-mica granites likely result from crustal melting, and the Idaho batholith is part of an anatectic zone in the North American Cordillera (Figs. 1, 14; Gaschnig et al., 2011; Chapman et al., 2021). This record of concentrated crustal melting – particularly in the Bitteroot lobe located at the north end of the rotating central Idaho block – requires major contraction. The amount of exhumation associated with this localized contraction may also be responsible for the widespread distribution of of detrital zircons from Idaho throughout the Cordillera in the Late Cretaceous (e.g., Dumitru et al., 2016).

A change in plate motion in the Pacific basin is proposed to occur at 85 Ma (Matthews et al., 2016). This plate motion change resulted from when the Manihiki, Hikurangi, parts of Catequil, and parts of the Chazca plate became part of the Pacific plate. The direct effect on the North American margin is not clear, as there are likely intervening plates between the Farallon plate and the North American margin (e.g., Insular Superterrane, Resurrection plate). However, a switch to a dominantly strike-slip regime at 85 Ma along the North American margin could explain the rapid northward movement of the Insular Superterrane. Thus, the switch from the “hit” to the “run” phase may result from a geometric effect (the Palouse promontory whose clockwise rotation allows for dextral strike-slip motion of the terranes), plate motion changes in the Pacific basin, or a combination of these two effects.

The western margin of North America and terranes east of the Insular Superterrane: Dextral, strike-slip deformation

If the Insular and Intermontane Superterranes were located farther south at ~100 Ma, there should be some evidence for their presence along the plate boundary. The difficulty is that there are, by definition, no piercing points. Despite these issues, evidence for strike-slip faulting and rotation along the western margin of North American that has been observed and documented for the last several decades. Throughout the Cordillera, paleomagnetic datasets document significant vertical axis rotation, much of which is clockwise, (e.g., Beck, 1980; Irving et al., 1996), in addition to northward motion of accreted terranes.

In the Canadian Cordillera, there is direct evidence for strike-slip tectonism along the margins of the Superterranes. Multiple workers have constrained the amount and timing of dextral motion on strike-slip faults after 100 Ma. These results were utilized by Wyld et al. (2006) to reconstruct the fault-based reconstructions of the southern Canadian Cordillera. The important point is that all of these strike-slip estimates represent minimum offsets.

Strike-slip faulting also occurred in the Late Cretaceous along the California margin. Workers from the United States Geological Survey determined that there was 100s of km of dextral offset in the Late Cretaceous and Paleogene that occurred in the Franciscan complex (McLaughlin et al., 1988; Jayko and Blake, 1993). This work followed from earlier work suggesting a proto-San Andreas fault in western California (e.g., Suppe, 1970; Nilsen, 1978). Bourgeois and Dott (1985) documented sedimentation in the Gold Beach terrane, suggesting a wrench environment during portions of the Late Cretaceous. Paleomagnetic data suggest that the Gold Beach terrane was located ~1000 km south at the time (Liner, 2005), near the latitude of southern California, and has rotated clockwise ~90°.

Magmatic arcs: Cessation

There is clear evidence that magmatism in the Sierra Nevada and Peninsular Range batholiths ceased at ~85 Ma. The same is true for arc magmatism in the Idaho region, although the emplacement of two-mica granites of the Idaho batholith –

interpreted as reflecting crustal melting – continues until ~60 Ma (Gaschnig et al., 2010). Hildebrand and Whalen (2017) interpreted that all post ~100 Ma granites in the Idaho, NW Nevada, Sierra Nevada, and Peninsular Range magmatic arcs reflect slab breakoff magmatism, rather than related to typical arc magma genesis.

Coney and Reynolds (1977) interepreted the inward sweep of magmatism in the southwest U.S., from the coastal batholiths to the continental interior, as a result of shallow slab subduction. A similar pattern of magmatism was recently described for the Paleogene deformation in Mexico (Fitz-Diaz et al., 2017). If so, this would be important evidence to support shallow slab subduction, as magmatism would occur in a forward sweeping pattern following the propagation of the shallow slab and then a backsweeping during retrogression of the slab.

We argue that a "sweep" does not characterize the pattern of magmatism. Rather, abundant magmatism occured in the coastal magmatic arc region until ~85 Ma. After this time, magmatism moved into the continental interior and particularly into the two-mica belt (e.g., Miller and Bradfish, 1980). There is, however, no clear "sweeping" pattern from west to east, as can be seen from the IEDA database (A. Glazner, pers. comm., 2020). Rather, when coastal magmatism ceased, magmatism occurs everywhere throughout the hinterland region. This interpretation is visible in the graphs of Coney and Reynolds (1977) and Fitz-Diaz et al. (2017).

We note that the lack of a coherent eastward sweeping pattern was also consistent with a shallow slab model, if the main role of the shallow slab was to provide an endload on the western margin of North America rather than generating magmas by hydration melting (e.g., Axen et al., 2018).

Hinterland: Northwestern Nevada and Klamath conundrums

The strike-slip component of this orogeny allowed efficient northward movement of the Insular and Intermontane terranes. This movement, however, left behind some tectonic detritus along the western margin of North America, particularly in the locations of basement promontories. Reconstruction of the Intermontane Superterrane to its original latitude of accretion, based on both paleomagnetic data (Irving et al., 1996) and reconstruction of post-mid Cretaceous dextral faulting (Wyld et al., 2006), positions the southern Intermontane superterrane at the latitude of the Columbia Embayment (~45-47° N latitude) (Fig. 6). Whereas the majority of the Intermontane superterrane was moved northward on known dextral fault systems, remnants remained at lower latitudes. These remnants are the Blue Mountain terranes of eastern Oregon and western Idaho (e.g., Gaschnig et al., 2017) and the Black Rock terrane of northwestern Nevada (S. Wyld, pers. comm., 2021) (Fig. 7).

The hit-and-run model explains these remnants in the following way. The Blue Mountain terranes are essentially caught in the right-angle Orofino syntaxis during the clockwise rotation that initiates at ~85 Ma (Fig. 11). This tectonic history is consistent with the paleomagnetic clockwise rotation of these terranes (Wilson and Cox, 1980, Housen and Dorsey, 2005; Housen, 2018; Tikoff et al., 2022).

The preservation of Black Rock terrane of northwest Nevada (Fig. 7) is more complex. The evidence from the Sierra Nevada mountains/batholith suggests ~400 km of strike-slip motion along the axis of the magmatic arc. This interpretation is based on ~400 km of northward translation of the Snow Lake block from the Mojave (e.g., Lahren et al., 1990) and the dextral offset of the $Sr_i = 0.706$ line in the batholith (Kistler, 1990). This movement would result in a ~400 km displacement of the western side of the Sierra Nevada batholith relative to the eastern side of the Sierra Nevada batholith. It would also require this same northward movement of the Klamath and Great Valley blocks, as well as all terranes – including the Intermontane Superterrane - located north of them. Thus, the right-lateral slip along the axis of arc magmatism effectively “moves in front” of Black Rock terrane. When the remainder of the Intermontane Superterranes moved northward on an intra-Intermontane fault (e.g., Cowan et al., 1997), the Black Rock and Blue Mountain terranes are left behind. Note that this model differs in detail, but is conceptually compatible with the “escape” model of Wernicke and Klepacki (1988).

Our reconstruction also has some unexpected consequences (Fig. 13). First, the Klamath Mountains are currently ~700 km northward from their location prior to ~100 Ma. About 400 km of the movement was accommodated by strike-slip along the Sierra Nevadan arc. The other ~300 km resulted from Miocene and younger deformation along the eastern California shear zone (e.g., Snow, 1992). As such, the Intermontane

Superterrane – which paleomagnetic evidence suggests moved ~1100 km since 105 Ma (Irving et al., 1996) – could sit entirely north of the Klamath Mountains.

Hinterland: The Sevier Plateau and Anatectic Melting

Sevier and Laramide-related shortening thickened the crust in the orogenic hinterland and created a high-elevation plateau, called the Nevadaplano in the central U.S. Cordillera (DeCelles, 2004), the Arizonaplano in the southern U.S. and northern Mexican Cordillera (Chapman et al., 2021). The same belt extends into Idaho and southernmost British Columbia. We refer to this entire thickened hinterland as the Sevier Plateau. Maximum crustal thickness estimates across the Sevier Plateau range from 50 to 65 km in the U.S. and Mexican Cordillera (Coney and Harms, 1984; Chapman et al., 2015) to as high as 80 km in southeastern British Columbia (Hinchey and Carr, 2006). Much of the structural and geochemical evidence for hinterland crustal thickening is preserved in the central Cordillera metamorphic core complexes. Thermobarometry of exhumed mid-crustal rocks indicate localized but significant Cretaceous crustal thickening, including the Snake Range core complex in east-central Nevada (e.g., Lewis et al., 1999; Cooper et al., 2010), the Ruby–East Humboldt core complex in northeast Nevada (e.g., Hodges and Walker, 1992; McGrew et al., 2000; Hallett and Spear, 2014), and in the footwall of the Windermere thrust in northeast Nevada (Camilleri and Chamberlain, 1997). By the Late Cretaceous to early Paleogene, near the end of crustal thickening, the Sevier Plateau is interpreted to have been a high-elevation orogenic plateau (e.g., Coney and Harms, 1984; DeCelles, 2004) with the regions of thickest crust associated with the metamorphic core complexes (Coney and Harms, 1984; Bendick and Baldwin, 2009; Konstantinou and Miller, 2015; Gottardi et al., 2020).

The central Cordilleran metamorphic core complexes of the Sevier Plateau are also associated with a belt of peraluminous, muscovite-bearing granite intrusions that are generally considered to have formed by crustal melting (anatexis) (Miller and Bradfish, 1980; Farmer and DePaolo, 1983; Haxel et al., 1984; Miller and Barton, 1990; Patino-Douce et al., 1990; Wright and Wooden, 1991; Chapman et al., 2015), termed the North American Cordilleran anatectic belt (Chapman et al., 2021). The intrusive units of the Cordilleran anatectic belt were typically emplaced as thick sheets, laccoliths, and dike/sill complexes that extend in a 3,000 km region across the Sevier Plateau. Geochemistry data from Cordilleran anatectic belt intrusions yield partial melting temperatures of 675–775 °C, indicative of water-absent muscovite dehydration melting and/or water-deficient melting as the primary melt reactions and are generally inconsistent with water-excess melting and high-temperature (biotite to amphibole) dehydration melting. The lack of water involvement suggests that this belt is not subduction related. Figure 14 shows the timing of the melting of the belt in terms of latitude. The magmatism starts earliest in a zone from northern Nevada to central Idaho (e.g., Idaho batholith). This trend suggests that these areas experienced significant contraction earlier than elsewhere in the Cordillera.

The hit-and-run model has explanatory power for the timing and location of this magmatism. At any single location, partial melting appears to have been a protracted process (≥10 m.y.) and evidence for re-melting and remobilization of magmas is common. Given this time lag, it is worth noting that the initiation of peralumimous magmatism at 80 Ma is consistent with a ~100 Ma collision. The Cordilleran anatectic belt also extends well beyond the corridor – to both the north and the south - assumed for flat-slab subduction; however, its location is nearly identical to the inferred collision zone ("hit") of the Insular Superterrane. There is only one deviation from this pattern: southern British Columbia was likely not affected by the Insular collision and contains evidence of major crustal thickening (Hinchey and Carr, 2006). Figure 14 shows that the Cordilleran anatectic belt is distinctly younger in the area north of the Lewis and Clark deformation zone. In fact, shortening in this location is likely due to the 30° clockwise rotation of the Blue Mountain – Adjacent Laurentia, which only occurred after sinistral movement commenced on the Lewis and Clark deformation zone (e.g., Sears and Hendrix, 2004). This scenario would have created a very localized zone of crustal thickening in southern British Columbia and one that is distinctly younger from thickening to the south: Both of these predictions are supported by the data.

Foreland: Fold-and-thrust belts

Deformation in the fold-and-thrust belts remained active throughout the Cordillera during the run phase of deformation. Deformation in southern British

Columbia initiates at ~80 Ma (Pană and van der Pluijm, 2015), consistent with the northward motion of the Insular Superterrane. In all sections of the Cordillera, deformation appears to migrate eastward in time. In Mexico, domainal contraction started at ~95 Ma and continued until ~65 Ma; far foreland deformation in Mexico continues until ~50 Ma (e.g., Fitz-Dias et al., 2017). Contractional deformation also occurs in the hinterland during the Late Cretaceous. It has been postulated that low-magnitude (a few 10s of km) upper crustal shortening of Cretaceous age was accommodated in the Central Nevada thrust belt (Taylor et al., 2000; Long, 2012; Long et al., 2014) and by regional-scale, open folding across much of eastern Nevada (Long, 2015). Deformation in fold-and-thrust belts during the Late Cretaceous-Paleogene is expected in any of the tectonic models, and thus does not distinguish between them.

Foreland: Block uplifts

Starting in the middle Cretaceous and continuing into the Paleogene, deformation occured far into the continental interior (e.g., Tikoff and Maxson, 2001). This deformation is best expressed as Laramide-style block uplifts in Wyoming and in the Colorado Plateau region, often taking the form of arches (e.g., Erslev, 1991). These Laramide-style block uplifts were attributed to shallow subduction, in analogy to the Sierra Pampeanas block uplifts, which occur in one of the two shallow slab segments currently active along the west coast of South America (e.g., Jordan and Almendinger, 1986). However, this pattern of deformation is not unique to the Laramide orogeny. Both ancient and modern collisional belts exhibit far-foreland deformation that are similar to the foreland, Laramide-style uplifts in the western U.S. (e.g., Rodgers, 1987).

There are reasons, however, to favor collision over subduction for genesis of the Late Cretaceous-Paleogene block uplifts. First, as described in the "hit" phase, the block uplifts start prior to the proposed inception of shallow-slab subduction. Second, the block uplifts have a wider distribution than the proposed shallow slab segment, ranging from Texas to Montana (e.g., Tikoff and Maxson, 2001). Third, similar low-amplitude folding also occurs throughout the high plains of the U.S., often buried by post-orogenic sedimentation. In the mid-continent region, geologists recognized low-amplitude folds, which were recognized as examples of "Plains-style" folding (e.g., Merriam, 1963). The earliest of these folds, such as the San Marcos arch in Texas, formed at ~95 Ma, coincident with the beginning of Insular Superterrane collision.

We also note that the most inboard and youngest of the block uplifts occur in South Dakota and Montana, possibly reactivating basement structures with transpressional kinematics (e.g., Bader, 2018). These features are inboard of the left-lateral Lewis and Clark deformation zone, which we interpret to have formed because of terrane collision-induced, clockwise rotation of the Blue Mountain and Adjacent Laurentia block (e.g., Tikoff et al., 2022). Hence, at least in the northern Rocky Mountains, one can make a case for a link between terrane translation and block uplift formation during "the run" phase of tectonism.

DISCUSSION

Antecedent models

This contribution is an expanded and updated version of the hit-and-run model of Maxson and Tikoff (1996). In the most fundamental sense, it is based on the work from the paleomagnetic community that originated the "Baja-BC" concept (Beck and Noson, 1972, Irving, 1985; Beck, 1992; Irving et al., 1996). The proposed model, however, is also part of series of articles that attempts to understand the interaction of the accreted terranes to orogeny on North America. The transpressional terrane model of Oldow et al. (1989) was an early attempt to characterize the obliquely convergent nature of the accretionary margins of the North American Cordillera (also Beck, 1983). This model was a critical breakthrough in imagining the tectonic development of the North American Cordillera. Moores (2002) also proposed that terrane collision was the source of the Laramide orogeny. The hit-and-run model also shares a mobilistic viewpoint with the Ribbon Continent model of Johnston (2008), although there are significant differences in the interpretation of terrane collision (e.g., westward vs. eastward subduction in the Early Cretaceous; whether the Insular and Intermontane Superterranes move together or separately). P. Umhoefer and colleagues have tried various models to match the paleomagnetic data and the geological constraints (e.g., Umhoefer, 1987; Umhoefer and Blakey, 2006). Finally, Cowan et al. (1997) popularized the Baja-BC debate and proposed crucial tests for the hypothesis.

The 100-85 Ma "oblique orogeny"

There is evidence for contractional and/or transpressional deformation throughout the North America Cordillera starting at 100 Ma. The 100-85 Ma portion of the orogeny is unlike traditional mountain belts because is not contiguous. We use the term "oblique orogeny" is to distinguish it from the more traditional orogenic belts with nearly orthogonal convergent motion. The non-contiguous nature of the orogen is further exacerbated by the irregularity of the continental margin within the Cordillera. As denoted by the boundary of the $Sr_i = 0.706$ line, there are zones of contraction, transpression, strike-slip, and even local extensional deformation. In the case of the 100-55 Ma North American Cordillera, the strike-slip/transpressional motion appear to be particularly localized into mélange belts and active magmatic arcs, because both form zones of lithospheric-scale, margin-parallel weakness.

The proposed deformation is also similar to the 30 Ma-present model for the tectonic development of the western U.S. of Atwater (1970): Both envision the entire western margin of North America as a right-lateral shear zone. In the 30 Ma-present case, there are zones of margin-parallel right-lateral slip (e.g., San Andreas and eastern California fault systems), extension (Basin and Range), and local contraction (e.g., Yakima fold-and-thrust belt) in the U.S. Cordillera. The same is true of the hit-and-run model, which contains major zones of margin-parallel right-lateral slip (e.g., transpressional shearing in the magmatic arcs, major faults of the Canadian Cordillera such as the Tintina and Fraser-Straight Creek), contraction (Sevier fold-and-thrust belt; Sevier hinterland plateau), and local extension (e.g., Columbia embayment). The differences between the Atwater (1970) model and the proposed model include: 1) The existence of an oblique collider (Insular Superterrane); 2) The resultant overall contractional component rather than extensional component of deformation, leading to overall transpressional deformation; 3) The increased importance of magmatic arcs in accommodating the initial phases of the transpressional deformation; and 4) The role of the irregular margin of Precambrian North America.

The California margin

In this section, we address how the hit-and-run model is consistent with the preservation of the California triad (Franciscan-Great Valley-Sierra Nevada) despite the collision of the Insular Superterrane. During Late Jurassic-Early Cretaceous time, there is simultaneous development of blueschist-facies metamorphism in the Fransiscan complex, sedimentary deposition in the Great Valley forearc, and arc magmatism in the Sierra Nevada batholith. These parts make up the so-called “California triad”, and together make a compelling case for east-dipping subduction below the California margin through the Early Cretaceous (e.g., Hamilton, 1969; Dickinson, 1976; Schweickert and Cowan, 1975; Engebretson et al., 1985; Ingersoll and Schweickert, 1986). We do note, however, that some models have called this interpretation of east-dipping subduction into question (e.g., Johnston, 2008; Hildebrand, 2013; Clennett et al., 2020; Hildebrand and Whalen, 2021a,b). In what follows, we will provide a highly speculative reinterpretation of California tectonics. This approach is required because almost all tectonic models for this area have assumed Farallon subduction under this margin since Jurassic time. In our model, the “California triad” subduction system starts to falter at ~100 Ma and breaks down completely at ~85 Ma.

Starting with the Sierra Nevada magmatic arc portion of the triad, there is evidence for a switch in both deformation patterns and magmatic geochemistry starting at 100 Ma. As discussed earlier, there is evidence for pure shear dominated transpressional deformation in the magmatic arc starting at 100 Ma (e.g., Krueger and Yoshinobu, 2018). Further, Hildebrand and Whalen (2017) document a change from arc magma granites to slab-breakoff granites at ~100 Ma. Regardless, arc magmatism ceases at ~85 Ma (e.g., Stern et al. 1981; Chen and Moore 1982; Coleman and Glazner 1997).

The Great Valley sequence also exhibits a major change in sedimentation at ~85 Ma (Orme and Graham, 2018). Deposition in the Great Valley sequence starts at ~130 Ma and appears continuous until at least the Eocene. However, deposition patterns indicate a maximum sedimentation along the western margin at the initiation of the “run” phase. After 85 Ma, the depocenter moves to the southern margin of the basin. This depocenter shift is consistent with the rotation of the Sierra Nevada tail (see below) and northward movement of Salinian block, all associated with the northward movement of the Insular Superterrane (the “run” phase).

The assumption in coastal California is that the Franciscan complex accretes only by subduction processes (e.g., Wakabayashi, 1992; 2015). This interpretation is in spite of the fact that there cannot be shallow slab subduction underneath under central California, because of the presence of a ~120 km deep root underneath the Sierra Nevada arc during the Late Cretaceous-Paleogene (e.g., Ducea and Saleeby, 1996, 1998). The only geometry that allows eastward-dipping subducting slab underneath coastal California is one in which the slab dips steeply closest to the trench, and then shallows after it reaches >120 km depth. To our knowledge, this slab geometry is not consistent with any known observation of slab geometry or slab dynamics in the upper 150 km of the Earth's surface. In contrast, Sigloch and Mihalynuk (2013; 2017) suggest that the Farallon slab first encounters the North American margin at ~60 Ma, which is consistent with the hit-and-run model.

We propose that the Franciscan complex stopped being a subduction complex at ~85 Ma and was instead a broad transpressional zone associated with northward movement of the Insular Superterrane. First, the maximum depositional ages of Franciscan metasedimentary rock samples indicate that accretion was continuous from ca. 123–80 Ma (Apen et al., 2021). Breaks in the continuity of the deposition indicate periods of non-accretion, and indicate a change in P-T conditions. Second, blueschist facies metamorphism – which started at ~180 Ma (Mulcahy et al., 2018) – appears to end at ~85-80 Ma. Third, central Franciscan belt contains blocks of the Cenomanian-Coniacian Laytonville limestone. Paleomagnetic analyses on these rocks indicate that they were deposited at southerly latitudes (Alvarez et al., 1980; Tarduno et al. 1990), and that they became incorporated into the Franciscan belt by ~50 Ma. These results require rapid and large-scale northward movement from ~90-50 Ma, consistent with – or even greater than – the inferred northward motion of the Insular Superterrane. Fourth, Ernst (2015) notes that there is a difference in detrital zircons along strike in the Franciscan complex, which he suggests indicates ~1600 km of dextral strike-slip movement. Finally, the exhumation of the blueschists in coastal California could result from the collision of the Insular Superterrane. This exhumation mechanism is the same as blueschists in other orogenic belts, where they are commonly associated with a suture zone. The above represents a significant re-interpretation from more accepted models on continuous subduction in the Franciscan complex; consequently, we specifically acknowledge a counterargument to the presence of the Insular Superterrane being offshore central California given by Wakabayashi (2015).

How could the Great Valley and Franciscan complex be preserved despite the presence of a collider? One explanation is the clockwise rotation of the southern "tail" of the Sierra Nevada batholith. The Sierran "tail" (e.g., Tehachapi Mountains) rotated ~40° clockwise since approximately 80 Ma (Kanter and Williams, 1982) (Fig. 13). Clockwise, vertical axis rotation is consistent with the hit-and-run model. After ~85 Ma, during the run phase, the Insular Superterrane would have rotated this tail as part of its northward motion. If so, the Sierran tail would have extended the North American buttress westward, which would have protected the western portions of the Great Valley and Franciscan complexes. As noted above, this rotation likely resulted in uplift and increased deposition in the southern Great Valley (Orme and Graham, 2018) starting at ~85 Ma.

The hit-and-run model suggests dextral strike-slip accretion of the Franciscan complex and we speculate that the Klamath Mountains act as an impediment to northward motion of accretionary slivers of material. The geology of the Klamath Mountains is very similar to that of the northern Sierra Nevada until the Late Jurassic when the Klamath Mountains likely moved westward prior to the Early Cretaceous (e.g., Ernst, 2015), as they do not contain a Cretaceous magmatic arc. In a forearc position, the Klamath Mountains would have formed a barrier to the northward movement of forearc and accretional complexes that were between the Insular Superterrane and the Great Valley complex. This may explain why there are three distinctive belts (Eastern Belt, Central Belt, Coastal Belt) in terms of both lithology and metamorphic grade, that generally decrease in age toward the west (e.g., Irwin, 1960). There is evidence for strike-slip in coastal California (e.g., Jayko and Blake, 1993), and it is permissible that the outer Franciscan belts were moved by outboard terrane movement, particularly the mélange-rich Central belt. Thus, the forearc basins and accretionary prisms – many of which are missing to the south of central California – may have become imbricated by strike-slip faulting along the California margin.

The Pelona and Orocopia schists of southern California

The Pelona and Orocopia schists of southern California are used as evidence for shallow slab subduction during the Late Cretaceous in southern California. These schists have recently become a possible tie point for the Insular Superterrane being offshore southern California at 65 Ma (e.g., Matthews et al., 2017 for the Nanaimo Group). Sauer et al. (2019) shows that the detrital population for the Orocopia and Pelona schists in southern California is nearly identical to the Swakane schist of the North Cascades. This coincidence led the authors to suggest a "Baja-Mojave" connection. However, because the sedimentary protoliths for the schists are 65 Ma, it only constrains the southern part of the Insular Superterrane (North Cascades) to be adjacent to southern California in the middle of the "run" phase. Thus, the Paleocene "Mojave-BC" connection is copacetic with both the Cretaceous "Baja-BC" connection and the paleomagnetic results from the Insular Superterrane overall. Further, it is also worth noting that the detrital signature of the Orocopia-Pelona schists and the Swakane schist are nearly identical to detrital zircons in coastal Alaska (Garver and Davidson, 2015). Therefore, these terranes on the west side of the Insular Superterrane, continued northward after the effective docking of most of the Insular Superterrane to North America at 55 Ma.

The Churn Creek Problem

The paleomagnetic results from Churn Creek, British Columbia (Haskin et al., 2003, Enkin et al., 2003 and 2006b) are the outlier in the clear separation of a far-travelled Insular Superterrane and less-travelled Intermontane Superterrane. The resolution of these controversy depends upon interpretation of the stratigraphy at Churn Creek as conformable (Riesterer et al., 2001; Haskin et al. 2003; Enkin et al., 2003) or not. Starting with the former, there is a proposed correlation linking Insular and Intermontane Superterranes prior to 105 Ma, which is the age of magnetization for the Spences Bridge and Churn Creek equivalent volcanic rocks. If so, the "big Baja BC" would consist of both Insular and Intermontane Superterranes, which is consistent with the ribbon continent model of Johnston (2008; also Hildebrand, 2013). Note, however, to satisfy the paleomagnetic constraints, the Intermontane Superterrane (± the Insular Superterrane) would have to be located ~1000 km south of their current orientation at

~100 Ma, move ~2000 km south very rapidly south until ~95 Ma, and then move ~3000 km north before ~55 Ma (see Mahoney et al., 2021). While permissive, the rapid (38 ± 16 cm/yr; Enkin, 2006) southward motion of "big Baja BC" during 105-90 Ma is not realistic.

An alternative hypothesis is the presence of thrust faults separating the Insular rocks from the Intermontane rocks at the Churn Creek location. The Churn Creek "section" does contain covered intervals and areas of fine-grained material interpreted as shales; the alternative model is that these covered intervals are the location of thrust faults containing fault gouge. The Churn Creek site sits adjacent to the Fraser fault to the east and the Yalakom fault to the west, both which accommodates significant right-lateral strike-slip motion (e.g., Wyld et al., 2006). Along large-offset, strike-slip faults, there would be significant interleaving of rocks with different tectonic histories (e.g., Busby et al., 2022). Thrust faults, associated with a flower structure within a strike-slip zone, is one possibility to explain the relations. Resolution of this issue will require additional study.

The Nanaimo Group

Our model for evolution of the western margin of North America is based foremost on paleomagnetic evidence for long transport of Cordilleran terranes. We acknowledge challenges to the idea of large-scale transport of the Insular terrane derived from interpretations of sediment provenance, including of the Late Cretaceous Nanaimo Group (e.g., Mahoney et al., 1999; 2021; Isava et al., 2021). Nanaimo Group strata were deposited on Wrangellia-North Cascades (San Juan Islands) basement units between ~90 Ma and 60 Ma. As Cowan et al. (1997) suggested, these strata would record the history of translation of the Insular terrane. Therefore, certain indicators of sediment provenance — that can be tied to diagnostic sources from the adjacent North American margin — could form a crucial test of the Baja-BC hypothesis.

This crucial test spawned several efforts to use sediment provenance, particularly the age(s) of detrital zircons from the Nanaimo Group and associated clastic units. Mahoney et al. (1999) reported that a total of five (5) detrital grains from the Nanaimo

Group have ages > 2.5 Ga, and thus concluded that the presence of those zircons refutes the Baja BC model. Housen and Beck (1999) used the tabulation of detrital zircon ages from Mahoney et al. (1999) to examine these distributions in more detail. They found that the distribution of ages of the more abundant Proterozoic detrital zircons could be well-explained by sources in the SW portion of North America. Newer detrital zircon data, including Hf isotopes from the zircon grains, have led to conflicting interpretations of sediment source and of paleogeographic reconstructions for the Nanaimo Group. Matthews et al. (2017) and Sauer et al. (2019) conclude that the detrital zircons found within the Nanaimo Group are most consistent with SW North American sources, and are consistent with the paleomagnetic estimates of the Late Cretaceous paleolatitudes for the Insular terrane. Mahoney et al. (2021) report similar data, with additional results from quartzite clasts, and interpret that these results rule out SW North American sources. Rather, they suggest provanence linkages between the Nanaimo Group and sources in Idaho (also see Isava et al., 2021). The linkage to Idaho sources was interpreted to indicate a maximum of 100s of kms of northward motion of the Insular superterrane. Even if the link to Idaho sediment sources is correct, the paleolatitude interpretation is problematic given the widespread distribution (Alaska to southern California, in current distribution) of Idaho-derived sediment in the North American Cordillera in the Late Cretaceous (Dumitru et al., 2016).

The fundamental issue is the non-equivalence of paleomagnetism and detrital zircon data in determining paleolatitude. The paleomagnetic data provide a direct record of paleolatitude. Ward et al. (1997) estimated a paleolatitude of 25° N from Nanaimo Group strata, but did not perform a robust correction for possible inclination error. Kim and Kodama (2004), sampling many of the same strata used by Ward et al. (1997), evaluated and corrected for inclination error using magnetic fabric methods. These authors reported a paleolatitude of 41° N, thus providing a much lower estimate of latitudinal displacement.

Detrital zircon ages and their geochemical signatures provide data about sediment provenance, not paleolatitude. Any interpretation of paleolatitude from detrital zircon data requires the use of an interpretational framework, which is effectively a model. As addressed in the discussion, data are inherently less uncertain than models. Thus, the paleomagnetic *data* are an inherently a more reliable determination of paleolatitude. In contrast, detrital zircon analyses require *models* of paleogeography, source region age distributions, the timing of exhumation of source regions, and proximal sediment dispersal patterns to interpret paleolatitude. The significant uncertainty of these models is the cause of the major disagreements in interpretation — see Mahoney et al. (1999) vs. Housen and Beck (1999); Matthews et al. (2017) and Sauer et al. (2019) vs. Mahoney et al. (2021) — despite the basic agreement of all of the data. The approach of Sauer et al. (2019) — a direct comparison of the sediment source in two basins — provides a more robust approach because it: 1) Is more closely tied to the provenance data; and 2) Requires fewer and stronger assumptions. Thus, for us, there is inherently low uncertainty that the Swakane schist of the North Cascades shared the same sediment supply as the Orocopia and Pelona schists of southern California (Sauer et al., 2019), regardless of the sediment source or the geometries of paleo-drainages at that time.

The Shatsky-rise conjugate hypothesis

The collision of the Shatsky (sometimes Shatsky-Hess) conjugate – a thick oceanic plateau generated in the Early Cretaceous on the Pacific-Farallon plate boundary in the Pacific basin – is sometimes invoked as a causal mechanism for Laramide deformation (e.g., Livaccari et al., 1981; Barth and Schneiderman, 1996; Liu et al., 2010; Axen et al., 2018). The basic argument is that the Laramide deformation looks like a collisional orogen, yet there is no collider. Hence, the idea of a thick oceanic collider, that could be later subducted, is often utilized. Saleeby (2003) notes that the "Southern California only" shallow slab subduction model is consistent with the presence an oceanic plateau at that location, but not dependent on it.

There are multiple and significant problems with this Shatsky conjugate. The single largest problem is that it simply may not exist: It has always been a hypothesis rather than a proven entity. Torsvik et al. (2019) provide a recent review of the Shatsky and Hess rises. First, they note that the Shatsky rise seems to have formed at the Pacific-Farallon-Izanagi triple junction. Second, they note that a series of eastward "ridge jumps" – movement of the spreading center between Pacific (west) and Farallon (east) – resulted in almost all of the plume-related volcanism associated with the Shatsky Rise being transferred to the Pacific plate. If this interpretation is correct, the "conjugate" Shatsky Rise on the Farallon plate is a chimera. In fact, the other large igneous provinces in the southwestern Pacific (e.g., Ontong Java, Manihiki, Hikurangi) joined the Pacific plate after their formation (e.g., Matthews et al., 2016), and thus lack conjugate margins. Third, if the Insular Superterrane was outboard of North America, the Shatsky rise would never have encountered North America.

The shallow slab model: A critique

The shallow slab model is the prevailing paradigm for the Late Cretaceous-Paleogene deformation in the western U.S Cordillera. It does explain the shutoff of coastal magmatism. It also provides a mechanism for the origin of block uplifts in the foreland by analogy with the Andean Sierra Pampeanas (e.g., Jordan and Allmendinger, 1986). However, the timing of block uplifts is problematic, as they demonstrably start prior to an inferred initiation of shallow slab subduction in northwest Wyoming and southwest Montana (e.g., Steidtmann and Middleton, 1991; Carrapa et al., 2019; Garber et al., 2020). While some authors consider that shallow slab subduction might have started earlier (~100 Ma) in this section of the orogen, that interpretation is inconsistent with the presence of the Insular terrane outboard of the Idaho section of the northern U.S. Rocky Mountains at this time. Even if one does not accept the paleomagnetic data, the fault reconstructions of Wyld et al. (2006) rule out this possibility, because the Insular Superterrane was located offshore this section of the continental margin of North America.

The shallow slab model does not explain a growing trend of data associated with the North American Cordillera. The particularly problematic dataset has always been the paleomagnetic data from the North American Cordillera, which puts accreted terranes outboard of California during the time of proposed shallow subduction. The position of the Insular Superterrane at ~75 Ma was recently supported by detrital zircon analyses comparing: 1) the Orocopia and Pelona schists of southern California to the Swakane gneiss of the North Cascades (Sauer et al., 2019); and 2) The same southern California schists to the Nanaimo Basin of the Insular Superterrane (Matthews et al., 2017). The striking similarities of the patterns suggest that the Insular Superterrane occupied a significantly farther south position (e.g., Mojave-BC) at ~70 Ma, completely consistent with the paleomagnetic data from that time (Figs. 4-5). The paleomagnetic data, however, suggest that the Insular Superterrane was significantly south of that location at 100 Ma (e.g., Baja-BC; Figs. 4-5).

If the southern edge of the Insular Superterrane was located on the western part of the North American plate margin in southern California at 75 Ma, it suggests there is no connection between the Farallon plate and Late Cretaceous-Paleogene tectonism. We note that this interpretation is broadly consistent with the tomographic work of Sigloch and Mihalynuk (2013; 2017), who suggest that the Farallon slab does not encounter the North American margin until ~60 Ma.

The shallow slab model has difficulties remedying the timing and extent of features attributed to it. The zone of crustal anatexis/two-mica granites extends far outside the inferred location of the shallow slab (Chapman et al., 2021). The shallow slab, however, is unlikely to be the cause of such crustal melting. Further, the crustal melting starts at ~80 Ma, which requires thickening to initiate at least 10-15 m.y. earlier (e.g., Chapman et al., 2021). Thus, some thickening must initiate at ~95 Ma in northwestern Nevada and central Idaho. Is worth noting that ~100 Ma is a time of significant shortening in the Sevier fold-and-thrust belt (e.g., DeCelles and Mitra, 1995; DeCelles et al., 1995; Pujols et al., 2020; Quick et al., 2020). This timing is again too early for the inferred initiation of shallow slab subduction.

Finally, there is a philosophical argument against shallow slab subduction causing major orogenic events. If flat slab subduction was capable of causing the magnitude of orogenesis observed in the western U.S., with deformation continuing into the mid-continent region (e.g., Tikoff and Maxson, 1996), all continents should be full of block uplifts of various ages. That is, given the long duration of geological time, every part of every continent has likely had shallow subduction underneath it at some time. However, almost every other mountain belt – and especially ones that involve deformation in the far foreland – are demonstrably the result of collision. It is only in the Andes that shallow slab subduction is definitely connected to block uplifts (Jordan and Allmendinger, 1986). However, even in this case, it is critical to realize that some of the Sierra Pampeanas block uplifts record low-temperature thermochronology dates that are no younger than 80

Ma (Löbens et al., 2011), suggesting that much of the differential uplift occurred earlier that recent shallow slab subduction. Further, many modern slope breaks may occur on Late-Paleozoic to Paleogene paleosurfaces (e.g., Carignano et al., 1999). Thus, particularly since the Sierra Pampeanas formed significantly closer to the current subduction margin relative to the Laramide block uplifts of the western U.S., they might be a poor analog for the far-foreland block uplifts.

The shallow slab model was an insightful model based on the data available when that paper was written. Dickinson and Snyder (1978) rejected each of the three possible mechanisms for mountain building: a continental collision, a contractional magmatic arc, and a transcurrent faulting setting. Interestingly, the hit-and-run model is the *combination* of all three of these rejected mechanisms occurring simultaneously, along an irregular continental margin. Paleomagnetic analyses have demonstrated that a collider – the Insular Superterrane – was outboard of the entire Laramide belt of the western U.S. when it was formed. Geological evidence indicates that the Insular Superterrane had an active magmatic arc, and hence it was its own contractional arc setting. Finally, paleomagnetic evidence requires the presence of major, dextral transcurrent faults, which are locally expressed as transpressional shear zones.

Data and models

Some readers might consider that we are taking the paleomagnetic data as "truth" and that we consider that the geological data "are missing the big picture". This is incorrect. We are, however, prioritizing the paleomagnetic *data* over geologically based *models*, but not over the geological (or geophysical) *data* (see section above on The Nanaimo Group). For this reason, we think it is necessary to critically address the role of data and models.

Both data and models are uncertain. Data uncertainty reflects variability either in the Earth structure/process or in the data collection methods. Models may be uncertain for many reasons, including: 1) There is little relevant data; 2) The data that support the model is uncertain; 3) Some data are inconsistent with the model; and/or 4) The geological processes that structured the data have not yet been characterized. As geologists, we are well versed in the use of multiple working hypotheses (e.g., Gilbert, 1886), in which the same data could be used to support different models. While the use of the multiple working hypotheses method is designed to reduce cognitive bias, it also effectively demonstrates that models are inherently more uncertain than the data that they are based on. That is, multiple models can be used to explain the same data. Yet, the professional community in geology is focussed more on models than on data. This same preference occurs in non-scientists in a range of decision-making contexts (Kuhn, 2001), and therefore appears – as does cognitive bias – to be an inherent part of human cognition.

This emphasis on models in science likely explains why community-accepted models are so difficult to remove. For instance, there is the well-known quote: “the great tragedy of Science - the slaying of a beautiful hypothesis by an ugly fact,” or one of its variants (commonly attributed to T.H. Huxley). One rarely hears the same sentiment positively expressed from the empirical viewpoint: The triumph of science is the destruction of an oversimplification, if not an outright fabrication, by a steadfast fact. Such, to us, characterizes the paleomagnetic data in the debate about Cretaceous western margin of the North American Cordillera. Paleomagnetism is the best single type of data to evaluate long-range transport of terranes along a ~NS-oriented margin. There are uncertainties associated with the paleomagnetic datasets from the North American Cordillera, but the overall signal is strong, robust, and consistent. Moreover, some areas of the North American Cordillera (e.g. Sierra Nevada; Frei et al., 1984; Frei, 1986) record paleomagnetic data that indicate that they are mostly in-place relative to cratonic North America, at exactly the same time as data from outboard terranes suggest large-scale movement. In summary, despite the fact that every paleomagnetic study has weaknesses, there is no aspect of this dataset that would force a paleomagnetist to reject the interpretation of large displacements without some form of special pleading. The paleomagnetic community has made this clear for over 50 years (e.g., Beck and Noson, 1972; Beck et al., 1981; Beck, 1986, 1992; Wynne et al., 1995; Irving et al., 1996; Beck and Housen, 2003; Enkin, 2006): It is time for us to listen.

There are at least four alternative models for the tectonic development of western North American from ~100 – 55 Ma: 1) Shallow slab subduction (Dickinson and Snyder, 1978; modification by Saleeby, 2003); 2) Hit-and-run (Maxson and Tikoff, 1996; this contribution); 3) Westward subduction/ribbon continents (Johnston, 2008; Hildebrand and Whalen, 2021a, b); and 4) Slab walls (Sigloch and Mihalynuk, 2013, 2017; Clennett et al., 2020). The value of alternative models is that they provide a way to revisit established theories. The history of science shows that it is very difficult to abandon a community-accepted model, and provides the most likely path to do so: "The decision to reject one paradigm is always simultaneously the decision to accept another, and the judgement leading to that decision involves the *comparison of both paradigms with nature and with each other*" (Ch. 8; 1st paragraph; p. 78 in Kuhn, 2012 -italics added). A comparison of models considering uncertainty in both data and models is a part of paradigm change. Moving forward, considering data and model uncertainty separately might reduce the need for a paradigm shift, because: 1) A strict division beween two possible models is not necessary; and 2) The community would be less likely to prematurely commit to one model and have it become entrenched.

To our knowledge, there has never been any attempt to evaluate the uncertainty of the shallow slab model given the paleomagnetic data. There are at least two studies that suggest that the shallow slab model is inconsistent with the paleomagnetic data (Maxson and Tikoff, 1996; Butler, 2006). The implication is that despite the uncertainty in the paleomagnetic data, the shallow slab model does not fit the data and that fact should increase the uncertainty in the shallow slab model. Furthermore, to accept the shallow slab model but ignore non-conforming data or an entire class of data (e.g., paleomagnetism) is demonstrably unproductive. One such example of this unproductive approach was wholesale rejection of geological data by the geophysical community, which resulted in their rejection of continental drift (Oreskes, 1998).

The proposed hit-and-run model is uncertain. The hit-and-run model, however: 1) Honors the high-quality paleomagnetic data from the Cordillera (e.g., Enkin, 2006); 2) Accepts the tomographic results that suggests the presence of multiple subducted slabs (e.g., Sigloch and Mihalynuk, 2013; 2017), 3) Incorporates components of the 100 Ma orogeny recognized by Hildebrand and Whalen (2021a,b); 4) Addresses the three-dimensional deformational patterns by explicitly recognizing the role of prior deformation events (principally late Precambrian rifting); and 5) Links tectonism in the coastal, hinterland, foreland, and far foreland regions. To the best of our ability, we have emphasized the inclusion of high quality, low uncertainty data. We are not negating any prior data, but – as with any new idea – we are asking for a more careful analysis of the inferences and interpretations (e.g., models) that arise from them.

Our articulation of a hit-and-run model is almost certainly flawed. At best, the model is incorrect about the details; at worst, it will be shown to be incompatible with critical observations. Success, however, is not about being correct. Rather, success is about establishing with clarity the uncertainty about the data *and* the uncertainty about the models, and to have data that are incompatible with the current paradigm fairly evaluated. Progress is most likely if we can utilize all the different datasets and consider multiple models for how to explain them.

CONCLUSIONS

Since its original articulation (Maxson and Tikoff, 1996), the hit-and-run model is further supported and articulated based on two simple premises: 1) The paleomagnetic data from the North American Cordillera – including the Insular and Intermontane Superterranes – are correct; and 2) The oblique collision of the Insular Superterrane at southern latitudes at ~100 Ma caused the mid-Cretaceous through Paleogene deformation in western North America. The latter point is consistent with a worldwide change in plate motion that is likely responsible for the right-lateral oblique collision of the Insular Superterrane along the irregular western margin of North America (Matthews et al., 2012; Seton et al., 2012). Tomographic results suggest that there are multiple subducted slabs under North America, which are not consistent with a single east-dipping Farallon slab for the last 200 m.y. (e.g., Sigloch and Mihalynuk, 2013; 2017). Some detrital zircon studies support the contention of large-scale, northward transport of accreted terranes (e.g., Sauer et al., 2019). The strength of the hit-and-run model is that it clearly demonstrates the role of terrane collision where and when it unambiguously occurred: The Idaho segment of the North American Cordillera at ~100 Ma. This region experienced major transpressional deformation within the magmatic arc, significant foreland sedimentation, and block uplifts in the foreland between 100-85 Ma. Other parts of the southern part of the western margin of North America – specifically the magmatic arcs in northwest Nevada, the Sierra Nevada batholith, and the Peninsular Ranges batholith – experienced similar transpressional deformation at ~100-85 Ma. Promontories along the western margin of North America formed geometric buttresses that attenuated northward movement of terranes, including the Mojave region of southern California, also experienced major contractional deformation at this time. As such, this contribution explicitly recognizes the effects of pre-existing features in the North American cratonic margin, and their effect on subsequent tectonism.

The activation of the Lewis and Clark deformation zone at 85 Ma – which removes a Precambrian (Palouse) promontory that was stopping northward terrane motion – is proposed as the causal mechanism that separates the "hit" from the "run" phase of deformation. The rotation occurred after cessation of the western Idaho shear zone. Both the Insular and Intermontane Superterranes moved to the north, by different amounts, from 85-55 Ma. During this "run" phase, the tectonic development of the North American Cordillera is extremely three-dimensional: The entire margin is essentially a dextral "megashear" zone with attendant translations, rotations, and transpressional shearing. We name this style of deformation an oblique orogeny, and it is comparable to the oblique divergence characterized by Atwater (1970). We provide this articulation of the hit-and-run model to facilitate direct comparison with the shallow slab model (e.g., Dickinson and Snyder, 1979; Saleeby, 2003) and other alternative models (e.g., Hildebrand, 2009; Sigloch and Mihalynuk, 2017; Clennett et al., 2020; Hildebrand and Whalen, 2021a,b) for the mid-Cretaceous-Paleogene tectonic development of western North America.

ACKNOWLEDGMENTS

This manuscript attempts to summarize ~50 million years of tectonic history along a several thousand kilometers of the margin; as a result, we have overlooked the major contributions of many workers in the Cordillera. Further, we have emphasized review articles and work that was particularly germane to strike-slip movement during the Cretaceous.

BT would like to thank W. McClelland, who suggested that he drop research on this topic twenty years ago because no one would take him seriously as a scientist if he pursued this crack-pot idea. It was very good advice for a starting scientist, from someone who is both a friend and is politically astute. BT followed this advice until the premature passing of Tim Wawrzyniec. Tim had a tell-it-like-it-is attitude toward life and science, and he was a good friend. There is no doubt that Tim would have wanted this article published; this article is for him.

Eldridge Moores would have been a co-author on this article; the first versions of the paleogeographic maps were drafted in his house in Davis, California. He is not included only because we thought it inappropriate to include him as co-author if he never read any part of the written document. His intellectual contribution is gratefully and humbly acknowledged; his encouragement and enthusiasm at pursuing this topic ensured that it was written.

Paul Umhoefer was also a critical player in this story: He passed away unexpectedly just prior to the final revision of this manuscript. Paul spent his career encouraging consideration of mobilistic models – particularly variants of Baja BC – for the tectonic development of the western North American Cordillera. Specifically, while a post-doctoral fellow at the University of Minnesota, he encouraged two graduate students (Maxson and Tikoff) to think broadly about their PhD projects, which ultimately resulted in the hit-and-run model. We will particularly miss his enthusiasm, seemingly endless ability to chat about science (or politics), and friendly candor.

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FIGURE CAPTIONS

Figure 1. (a) Geologic terrane map of the North American Cordillera, including Sr_I = 0.706 line, magmatic arcs, Sevier fold-and-thrust zone, and Laramide uplifts. BM = Blue Mountain terranes; KM = Klamath mountains. (b) A tectonic map emphasizing the major faults and granitic batholiths of the North American Cordillera. Base map modified from Colpron and Nelson (2009), with the following supplements: Mexican geology from Centeno-Garcia (2008) and Hildebrand (2014); Cordilleran batholiths from Hildebrand (2013); muscovite-bearing plutonic belts from Miller and Bradfish (1980); anatectic belt from Chapman et al. (2021); Laramide uplifts from Davis et al. (2009).

Figure 2. Cratonic Poles for North America for (a) 130-85 Ma and (b) 80-65 Ma. Each pole is the average of paleomagnetic results from cratonal rocks for a 10 Ma wide window, with 95% confidence indicated. (b) eMK pole is the average of poles used in (a), and represents the NA reference pole for 130-85 Ma. The other poles are from the Adel Mtn volcanics (79 Ma), Elkhorn volcanics (70 Ma), and latest Cretaceous rocks of the Moccasin-Judith Mountains (66 Ma).

Figure 3. NA reference poles for most of Cretaceous time shown in orange (130-85 Ma and 80-65 Ma). Poles from the Insular Superterrane shown in yellow, poles from the Intermontane Superterrane shown in blue. MC (McColl Ridge) and DI (Duke Island) appear to lie on the "Intermontane" CG (Carmacks Group) pole, but are physically located on the Insular Superterrane and show consistent paleomagnetic poles with other Insular Superterrane sites. Site locations and poles from the terranes are in Tables 1 and 2. Abbreviations for the paleomagnetic sites for the Insular Superterrane are: BA: Battlement-Amazon volcanics and sediments, CH: volcanics and sediments of Churn Creek, DI: Duke Island ultramafics, JC: Jamison Creek volcanics and sediments, MC: MacColl Ridge, MSB: Mt. Stuart batholith, MT: Mt. Tatlow volcanics and sediments, MV: Methow valley remagnetized strata, NG: Nanaimo Group sediments, and TA: Tete Angela volcanics and sediments. Abbreviations for the paleomagnetic data for the Intermontane Superterrane are: BM: Blue Mtn plutons and remagnetized strata. CC:

volcanics of Churn Creek; KI: Knight Inlet intrusives, OB: Ochoco Basin, and SB: Spences Bridge volcanics.

Figure 4. Paleogeographic reconstruction of North America, using the two reference poles in Fig. 3, for mid-Cretaceous (100 Ma) (a) and latest Cretaceous (80-65 Ma) (b). Site locations on North America are reconstructed. Their paleolatitudes and 95% confidence limits from the paleomagnetic means are plotted (box plus whiskers), for Intermontane and Insular results as noted. Abbreviations for paleomagnetic sites are same as for Fig. 3. Additional sites that provide latitude estimates from paleontological data are: MV-L: Methow Leaf paleoflora, NG-L: Nanaimo Group Leaf paleoflora, and NG-R: Nanaimo Group Rudistid bivalves. The MV-L is currently located at the MV site; NG-L and NG-R are both currently located at the NG site.

Figure 5. Plot of displacement relative to the study location's current latitude on North America, as a function of age, for the terrane-based results in Tables 1 and 2. The error estimate for displacement combines the 95% confidence limits for both the individual studies and the relevant NA reference pole (Demarest, 1983). Displacements for units older than 85 Ma were calculated using the 130-85 Ma Cretaceous pole, and displacements for units younger than 85 Ma were made using the 80-65 Ma reference pole. Abbreviations are same as for Fig. 3.

Figure 6. The western rifted margin of Laurentia. The orientation of the Palouse promontory and the McCall embayment are noted. The red lines show the portions of the continental margins most affected by northward movement after 100 Ma, principally Idaho and southern California and Arizona. Data from Dickinson and Lawton (2001), Thomas (2006), Lund (2008), and Levy et al. (2020). CCT = California-Coahuila transform; Caborca = Caborca block of Laurentian affinity located SW of the CCT. Modified from Tikoff et al. (2022).

Figure 7. (a) A tectonic map of the western United States, highlighting specific features discussed in the text. (b) Inset of the northwest Nevada region, modified from Trevino et

al. (2021). Abbreviations are as follows; AOB=Antler Orogenic Belt, BCSZ=Bench Canyon shear zone, GF=Garlock fault, IB = Idaho batholith; LCT=Last Chance thrust system, MFTB=Maria fold-and-thrust Belt, SAF= San Andreas fault system, SNB = Sierra Nevada batholith; WISZ= western Idaho shear zone, WNSZ= Western Nevada shear zone.

Figure 8. (a) Paleogeologic map of the North American Cordillera at ~100 Ma, during the hit phase of the Insular terrane with North America. Area of uplifts in Montana are from Carrapa et al. (2019). (b) Paleogeologic map of the North American Cordillera at ~70 Ma, during the run phase of the oblique orogeny. Paleolatitudes are based on the paleomagnetic poles derived from cratonic North American at this time. Map unit colors are the same as Fig. 1.

Figure 9. (a) Summary chart of the hit phase (100-85 Ma) displaying evidence supporting the hit-and-run model at different locations. On the left is the location of terranes relative to the Precambrian margin at 100 Ma. (b) Summary chart of the run phase (85-55 Ma) displaying evidence supporting the hit-and-run model at different locations. On the left is the location of terranes relative to the Precambrian margins at 100 Ma. Insular (yellow rectangles) and Intermontane (blue ovals) site locations for the paleomagnetic data are given. AL = Alisitos, BM = Blue Mountains, F-GV-SN = Franciscan-Great Valley-Sierra Nevada. Abbreviations for the paleomagnetic data given in Fig. 3.

Figure 10. Schematic tectonic history showing the location of terranes relative to the Precambrian margin of Laurentia at 110 Ma, 100 Ma, 85 Ma, and 65 Ma. AL = Alisitos, BM = Blue Mountains, BR = Black Rock, COL EMB = Columbia Embayment, F-GV-SN = Franciscan-Great Valley- Sierra Nevada, IM = Intermontane terranes, IN = Insular terranes, M F&T = Maria Fold and Thrust, NP = Nevadaplano. Pink regions represent areas of thickened crust.

Figure 11. A cartoon of the North American Cordillera from southern Canada to central Mexico. Transpressional deformation occurs in the magmatic arcs, as a result of oblique collision of the Insular Superterrane. The cross sections show different geometries of subducting slabs that are permissive in this model.

Figure 12. The continental margin in the Pacific Northwest during the hit (a) and run (b) phases of tectonic development. The 100-85 Ma western Idaho shear zone forms along a rifted margin during the hit phase. During the run phase (85-55 Ma), the BMAL (Blue Mountain and Adjacent Laurentia) block rotates clockwise ~30°, accommodated by sinistral movement on the Lewis and Clark deformation zone (line). IB = Idaho batholith.

Figure 13. The interbatholith breaks along the $Sr_i = 0.706$ line from Kistler (1990). (a) The margin at 100 Ma requires restoration of the 100-85 Ma dextral shearing in the Sierra Nevada batholith and the rotation of the Sierra Nevada tail. Rotation of the Sierra Nevada tail occurred after 80 Ma. This restoration lines up the northern part of the $Sr_i = 0.706$ line in the Sierra Nevada with the Mina transform fault that formed during Precambrian rifting. (b) Shows the current configuration and is modified from Kistler (1990).

Figure 14. A plot of the latitude versus timing of the Cordilleran anatectic belt. The Idaho batholith is included in this figure because it resulted predominantly from crustal thickening and melting. The areas south of the Lewis and Clark deformation zone (L&C) are distinctly older than those located north of the Lewis and Clark deformation zone. Crustal melting in Idaho and Nevada at ~80 Ma is interpreted to result from the ~100 Ma Insular Superterrane collision. Crustal melting north of the Lewis and Clark deformation zone is attributed to contraction caused by rotation of the Blue Mountains – Adjacent Laurentia block. Modified from Chapman et al. (2021).

TABLES

Table 1. Summary of paleomagnetic data from Intermontane Superterrane. SB: Spences Bridge volcanics, CC: volcanics of Churn Creek, KI: Knight Inlet intrusives, BM: Blue Mtn plutons and remagnetized strata; OB: Ochoco Basin, CG: Carmacks Group. N: number of paleomagnetic sites, A_{95}: radius of 95% confidence for mean pole. Translation is relative to site location as part of North American craton for age-appropriate reference pole discussed in text.

Table 2. Summary of paleomagnetic and paleontological data from Insular Superterrane. Paleomagnetic sites are: MT: Mt Tatlow volcanics and sediments, CH: volcanics and sediments of Churn Creek, BA: Battlement-Amazon volcanics and sediments, TA: Tete Angela volcanics and sediments; JC: Jamison Creek volcanics and sediments, MSB: Mt Stuart batholith, DI: Duke Island ultramafics, MV: Methow valley remagnetized strata, NG: Nanaimo Group sediments, and MC: MacColl Ridge volcanics and volcaniclastic sediments. N: number of paleomagnetic sites, A_{95}: radius of 95% confidence for mean pole. Paleontological sites are: MV-L: Methow valley leaf paleoflora, NG-L: Nanaimo Group Leaf paleoflora, NG-R: Nanaimo Group Rudistid bivalves. Translation is relative to site location as part of North American craton for age-appropriate reference pole discussed in text.

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