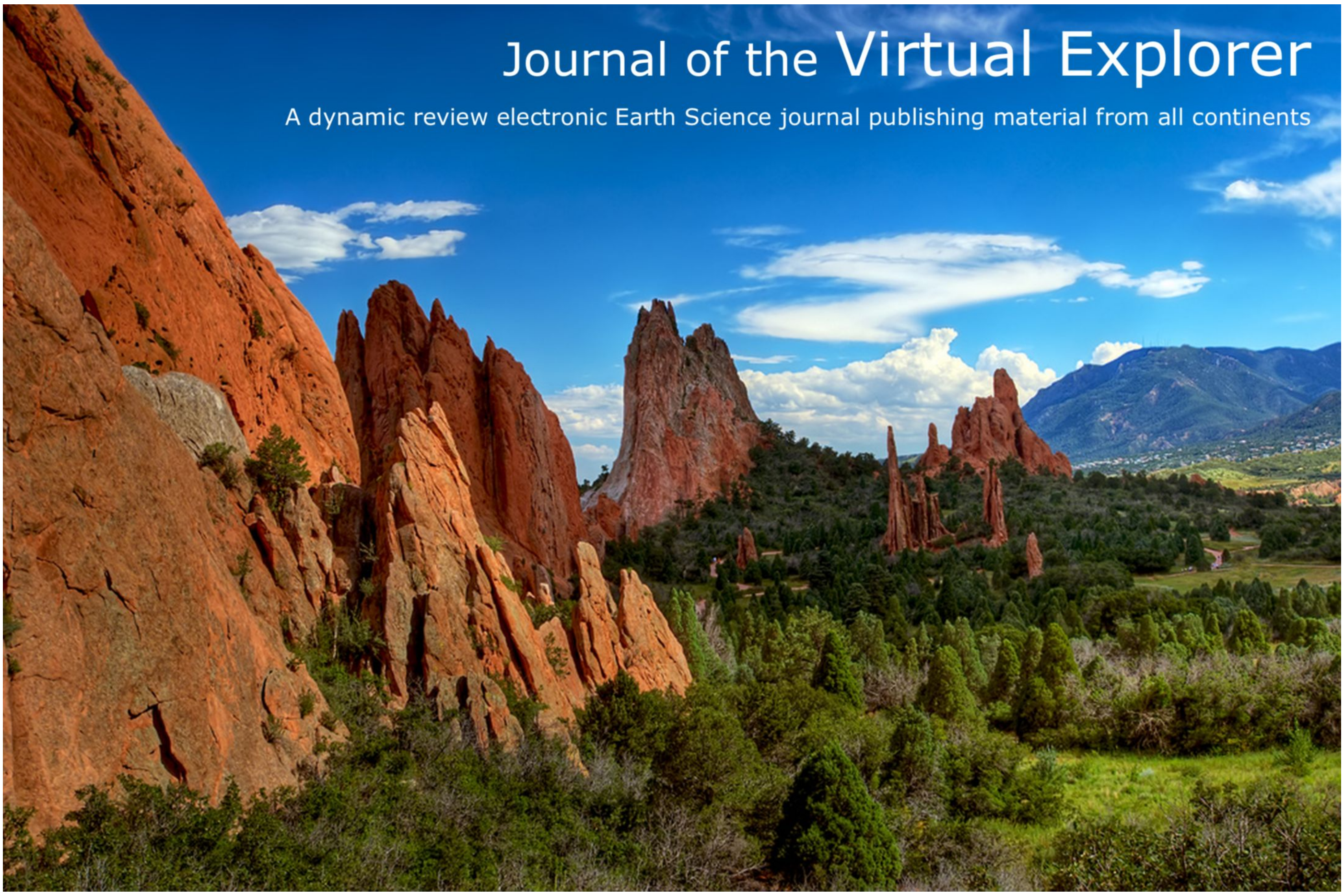

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Mesh-based tectonic reconstruction: Andean margin evolution since the Cretaceous

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Abstract: In this contribution we demonstrate an example of what can be described as mesh-based tectonic reconstruction. This differs from conventional 2D + time reconstructions that treat the Earth as an assemblage of rigid plates. Instead a deformable mesh is overlaid on the region of interest, in this case the Andean margin of western South America, and allowed to deform based on constraints and assumptions inferred from geochronological and geological data. Here we take data that allows estimates of crustal shortening, and the timing of terrane accretion, to quantitatively estimate the starting geometry, from Early Cretaceous time (i.e. 145 Ma). Removal of strains straightens the Central and Southern Andean margin, and predicts the former existence of marginal basins to the east of the present mountain belt. This example of deformable mesh-based tectonic reconstruction illustrates the power of the method, incorporating such effects as simple isostasy, and the calculation of strain trajectories though time.

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Introduction

Since the advent of the plate tectonic theory, attempts to reconstruct past configurations of our planet have traditionally followed the doctrine that the Earth's surface is made of rigid plates. An Euler pole and rotation describe movement of such plates. However the presence of mountain belts illustrates that continental lithosphere behaves in a ductile manner. Deformation of intervening regions is required when data such as variable shortening estimates or differing palaeomagnetic rotations are taken into account by considering motion relative to an adjacent stable region such as a cratonic zone. This deformation may have taken place in any number of ways, for example as the result of relatively uniform horizontal shortening or extension, differential motion as required by thrust imbrication, or even movement along tears or faults in wrench fault zones.

These principles led to the creation of the mesh-based *Pplates* software (Smith *et al.* 2007). In this paper we utilise the deformable mesh capabilities of *Pplates* in reconstructing the Cretaceous to present evolution of the Andean Margin of South America. We have analysed various data and interpretations to compile a meshed, deforming model of the entire Andean margin, encompassing the terrane accretion in the Northern Andes, the evolution of the Bolivian Orocline in the Central Andes, and the formation of the Patagonian Orocline in the Southern Andes. Our model highlights the dynamic history of the region, illustrating compressive and extensional tectonic processes, in addition to the bending of an initially straight orogen.

Tectonic setting

The western rim of the South American Plate has been the locale of terrane accretions, collisions, and various subduction dynamics. Subduction first occurred following the breakup of Rodinia in the Late Proterozoic, and since then there have been numerous phases of rifting and subduction re-activation (e.g. Ramos, 2009). Intraplate magmatism and extension was focused along the sutures between the accreted terranes and the cratonic zones of central South America during the Triassic, while subduction initiated along the Andean margin in the Early Jurassic, coeval with the breakup of Gondwana (Ramos, 2009). Development of the modern Andes commenced during the Cretaceous, under a convergent boundary not dissimilar to the Laramide orogeny of North America.

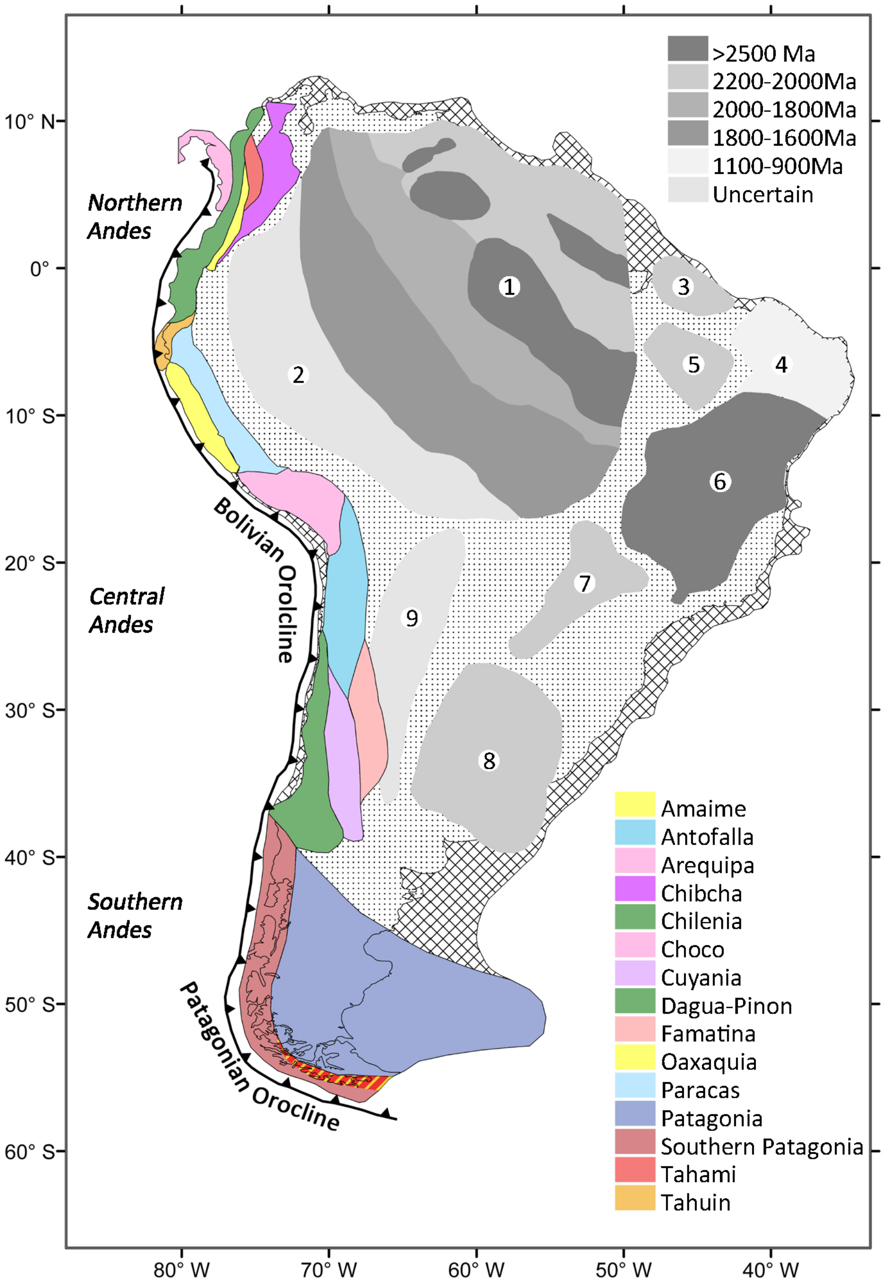
Northern Andes

The Northern Andes are located on the plate boundary between the Nazca and Caribbean Plates, and the northwestern basement of South America. Adjoining this basement is the Western Cordillera terranes, comprising dextrally sheared (e.g. Kennan and Pindell, 2009) slices of oceanic plateau and island arc volcanics (e.g. Kerr *et al.* 2003), and related sedimentary units. For this reconstruction we have followed Ramos (2009) and incorporated the Choco, Dagua-Pinon, Amaime, Tahami, and Chibcha terranes (Figure 1). The relationships of these Western Cordillera terranes suggest a Caribbean origin (Kennan and Pindell, 2009).

Central Andes and the Bolivian Orocline

The Central Andes is predominately comprised of deformed Paleozoic accreted terranes, situated along the western margin of the Amazonian Craton and the Grenville-aged Pampian terrane (Figure 1). Deformation in this region has been the consequence of orogen-normal shortening (Isacks 1988; Allmendinger *et al.* 1997; Kley and Monaldi 1998), and resulted in the formation of an extraordinary geological feature - the Bolivian Orocline (e.g. Isacks, 1988). This is an archetypal example of orocline formation, whereby an initially linear orogen is deformed into a more curved geometry in plan view as the result of tectonic processes (Carey, 1955), such as stagnation, indentation, and trench advance at the centre of the orogen, and slab rollback to its north and south (Schellart, 2008). The oroclinal curvature is also expressed by the pattern of block rotations as revealed by palaeomagnetic data, with counterclockwise rotations in southern Peru clockwise in northern Chile (e.g. Beck, 2004). For this region we have segregated the tectonic boundaries for the reconstruction based on Ramos (2009).

Figure 1. Tectonic map of the Andean margin of South America.



Northern Andean terranes compiled from Ramos (2009) and (Kennan and Pindell, 2009). Central Andean terranes modified from Ramos (2009). The Gastre Fault System separates Patagonia and Southern Patagonia from mainland South America, and is based off Rapela and Pankhurst (1992). Cratonic regions are modified from Fuck *et al.* (2008), and are named as follows: (1) Amazonian Craton, (2) Inferred extent of Amazonian Craton, (3) Sao Luis Craton, (4) Borborema Province, (5) Parnaiba Block, (6) Sao Francisco Craton, (7) Paranapanema Block, (8) Rio de la Plata Craton, (9) Pampia Terrane. Stippled region represents present-day South America, cross-hatched region represents continental shelf, while the red-yellow striped zone symbolizes the area of the Cordillera Darwin Complex and Rocas Verdes Basin basalts. For the Inferred extent of Amazonian Craton, (2), and Pampia Terrane, (9), we follow Fuck *et al.* (2008) in that they are high grade metamorphic rocks of an "uncertain" tectonic setting, and formed approximately between 1300–1100 Ma.

Southern Andes and the Patagonian Orocline

The southern extremity of the Andean system forms a dramatic change in the structural trend by an angle of approximately 90°, known as the Patagonian Orocline (Carey, 1955) (Figure 1). Palaeomagnetic studies of the region appear to confirm the orogen has been rotated with respect to stable South America (Burns *et al.* 1980; Cunningham *et al.* 1991; Beck *et al.* 2000; Rapalini *et al.* 2001; Iglesia Llanos *et al.* 2003). In addition to the orocline, a belt of basic rocks in the back arc region (Dalziel *et al.* 1974), and a Mesozoic high-grade metamorphic core (Dalziel, 1981; Dalziel and Brown, 1989; Kohn *et al.* 1995), also distinguish the region.

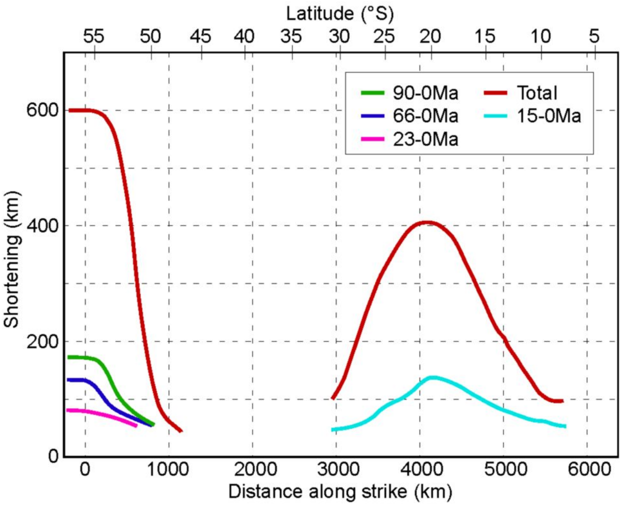
Data and Method

To accurately model and simulate different deformation scenarios, reconstruction software has to be able accommodate such tectonic scenarios, and in a way that allows quantitative paramterisation. Thus the *Pplates* software (Smith *et al.* 2007) was designed to allow structural geology and tectonics research concerned with the effects of heterogeneous deformation and faulting, from regional through to planetary scales. As described within Smith *et al.* (2007), the *Pplates* software does this by allowing the use of deformable and tearable meshes (irregularly tessellated polyhedrons) involving triangular mesh faces. Nodes are connected using a Delaunay algorithm and correspond to a mesh surface represented in three dimensions to conform to the surface of the Earth (Smith *et al.* 2007).

Motion data can be imposed on individual nodes while the node-connecting springs can be kept rigid or be used to distribute stress and strain among the mesh faces. If a point of latitude and longitude within the interior of a mesh face is moved, the equivalent Cartesian coordinates are calculated and expressed as a vector (Smith *et al.* 2007). The addition of this vector and the rotation matrix gives a new vector of Cartesian coordinates that are used to provide the new latitude, longitude, and altitude of the moved point. A transformation matrix, calculated using the three initial and final Cartesian vectors, provides the movement and deformation of the individual mesh face. The transform matrix replaces the Euler rotation matrix whenever points associated to a deforming mesh face are moved (Smith *et al.* 2007). Deformation on any mesh face can thus be applied to any data carried by the mesh, for instance in this reconstruction of the Andean Margin the meshes carry the NOAA ETOPO2 data in order to allow variations in crustal thickness implied by mesh deformation to be monitored.

To constrain mesh deformation we predominately utilised geological data provided by balanced cross sections (Figure 2). Such shortening data, and associated geological data present in the referenced sources, provide one constraint as to the timing and degree of deformation occurring during the formation of the Patagonian and Bolivian Oroclines. A lack of published data exists regarding the specific amount and location of deformation associated with the formation of the Peruvian Orocline, and hence its evolution is not considered in this reconstruction. Data for constraining the deformation associated with the Patagonian Orocline was provided by the work of Kraemer (2003), while for the Bolivian Orocline shortening estimates from Kley and Monaldi (1998), McQuarrie (2002), and Arriagada *et al.* (2008), were used. Numerous studies of various geochronological, geological and geophysical were used to define the boundaries and timing of accretion of the numerous terranes modelled in the reconstruction. There are numerous alternative and contradictory hypotheses regarding the timing of terrane accretion, and causes for orocline formation. Concerning the Bolivian Orocline, we are incorporating the hypothesis that orocline evolution is attributable to differential shortening and block rotations (e.g. Arriagada *et al.* 2008). Fundamentally, the model presented here is the compilation of numerous palaeogeographic models and various geochronological, geological and geophysical data, from where we demonstrate the implications of this combined model.

Figure 2. Variations and timing of along strike shortening in the Central and Southern Andes.



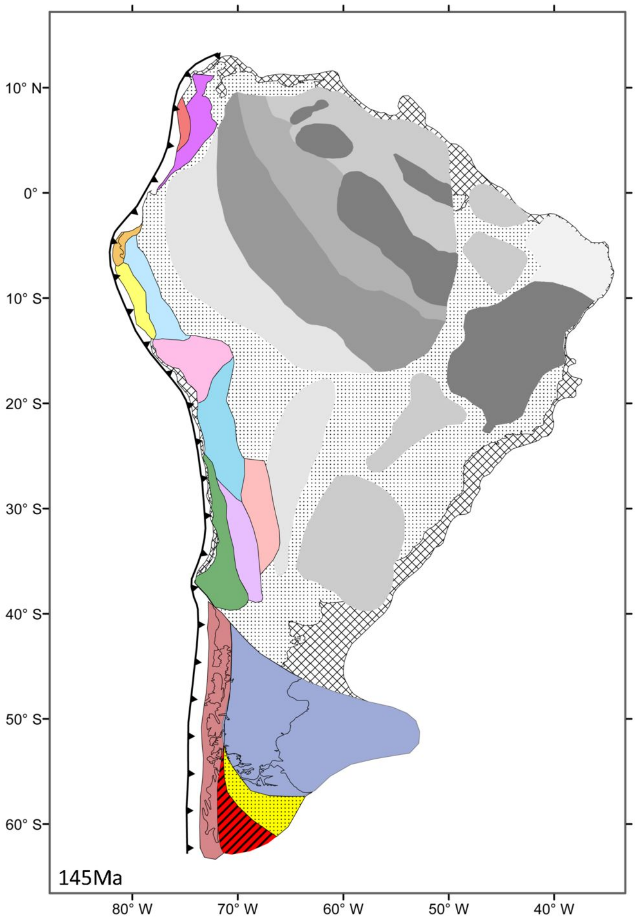
Data for the Southern Andes and Patagonian Orocline (between latitudes 58°S and 48°S) derived from Kraemer (2003). Data for the Central Andes and Bolivian Orocline (between latitudes 30°S and 10°S) is modified from Kley and Monaldi (1998), McQuarrie, (2002), and Arriagada *et al.* (2008). The total shortening for the Patagonian Orocline includes data from the Early Cretaceous to present (data for the periods Early Cretaceous–90 Ma, 90–66 Ma, 66–23 Ma and 23–present), while the total shortening for the Bolivian Orocline is from 45 Ma to Present (periods 45–15Ma and 15–0 Ma). Shortening data for the Patagonian Orocline, derived from balanced cross sections (Kraemer, 2003), illustrates the high along-strike total shortening gradient that evolved as a consequence of the hinged-point, with greatest shortening occurring at the southern extremity of the arc. The majority of shortening occurred during the mid-Cretaceous. The results from Arriagada *et al.* (2008) illustrate a large degree of shortening between 15 and 45 Ma. Note: the shortening curves are cumulative.

Tectonic model

145 to 130 Ma (Figure 3a-b)

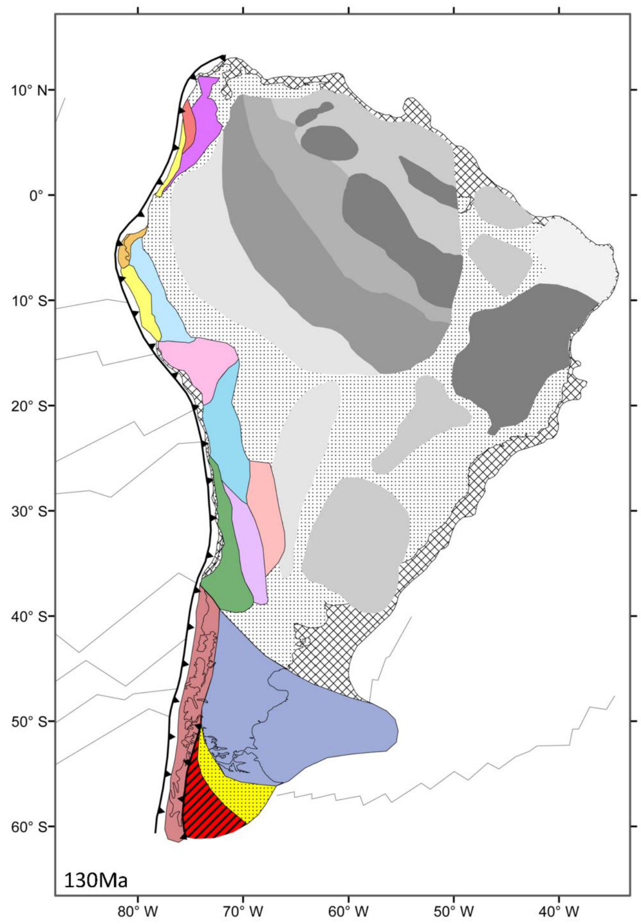
As a consequence of restoring the Bolivian and Patagonian Oroclines the Central and Southern sections of the Andes form a sublinear trend at the start of the Early Cretaceous. Extensional forces associated with Gondwanan break-up results in the development of the Rocas Verdes Basin of Southern Patagonia. The Rocas Verdes Basin reaches its full extent during the Early Cretaceous (Kraemer, 2003). The western margin of the Rocas Verdes Basin is composed of magmatic arc fragments, while the eastern margin is composed of units including the Cordillera Darwin Complex (e.g. Kraemer, 2003). Continued break-up of Gondwana also results in westwards displacement of Patagonia relative to South America, along the right-lateral Gastre Fault System (Rapela and Pankhurst, 1992).

Figure 3a. Geodynamical reconstructions 145 Ma.



Refer to text for details. Colours are the same as in Figure 1. Isochron data for Figure 3b-j from Müller *et al.* (2008).

Figure 3b. Geodynamical reconstructions – 130 Ma.



130 to 90 Ma (Figure 3b-d)

Patagonia reaches its present-day position as major displacement along the Gastre Fault System ceases (Konig and Jokat, 2006). Rotation of the Southern Patagonian magmatic arc initiates, with a hinged-point, located at approximately 50°S, resulting in the majority of rotation occurring at the southern extremity of the arc. Rifting continues between Africa and South America and results in changes in convergence rates, and intensifies compression in southern Patagonia (Diraison *et al.* 2000). A compressive event occurring in the mid-Cretaceous causes orogenic shortening that reaches a maximum of 430 km during this time period (Kraemer, 2003). This compression is related to an 87–90 and 100–110 Ma deformational event, as described within Halpern and Rex (1972). Orogenic shortening is accommodated by folding and thrusting of the Cordillera Darwin Complex, and reverse subduction of Rocas Verdes Basin oceanic lithosphere beneath the Southern Patagonian magmatic arc (Kraemer, 2003). This reverse subduction results in the closure and eventual inversion of the Rocas Verdes Basin (Halpern and Rex, 1972; Dalziel *et al.* 1974). As detailed by Diraison *et al.* (2000), during the Late Cretaceous the Cordillera Darwin experiences a major period of uplift and cooling (Dalziel and Palmer, 1979; Nelson *et al.* 1980; Nelson, 1982; Dalziel, 1985; Dalziel and Brown, 1989; Kohn *et al.* 1993; 1995; Cunningham, 1995). In this reconstruction we have modelled this uplift as overthrusting to the NE and left-lateral wrenching (Klepeis, 1994; Diraison *et al.* 2000; Kraemer, 2003).

Accretion of the Amaime island arc occurs along the western margin of the Cordillera Real (Aspden and Litherland, 1992; Litherland *et al.* 1994). The Romeral-Peltetec faults system exhibits high-pressure assemblages and metamorphic units and is inferred to have been the suture along which this accretion event occurred (Bosch *et al.* 2002; Ramos, 2009). Blueschists associated with the Raspas Ophiolitic Complex have been K-Ar dated at 132, Ma and are considered to represent the emplacement of the Amaime arc terrane (Feininger *et al.* 1982; McCourt *et al.* 1984). This accretion event occurs prior to the Late Cretaceous collision of a plateau, as detailed by Pindell and Tabbutt (1995) and Alemán and Ramos (2000).

Figure 3c. Geodynamical reconstructions – 115 Ma.

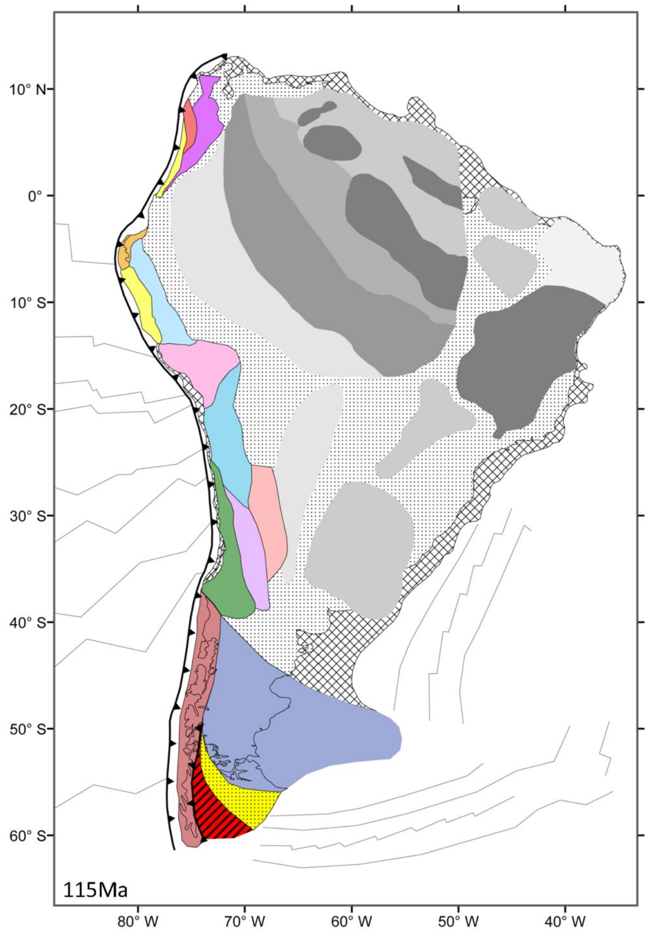
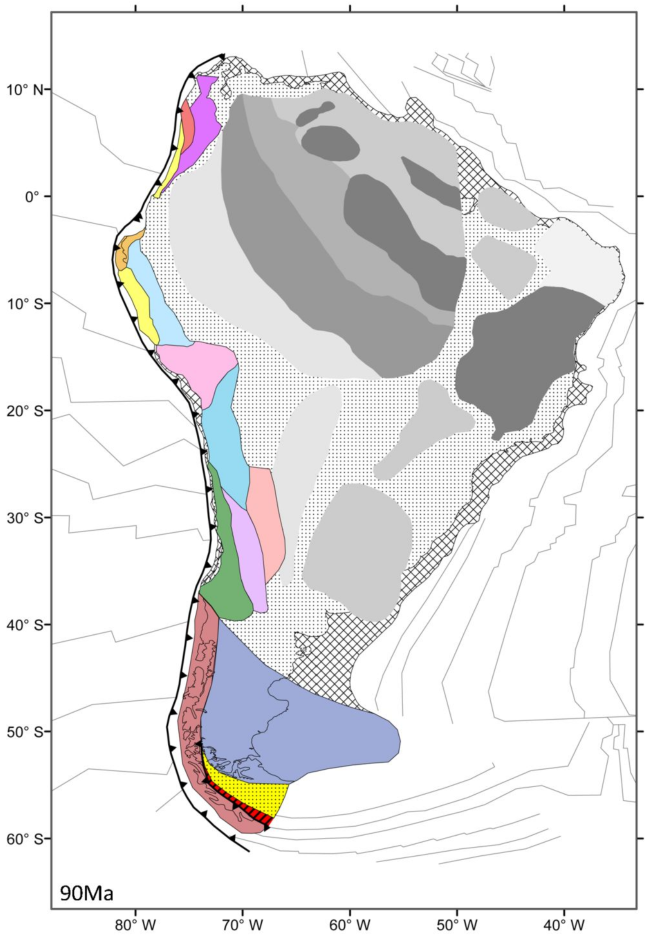


Figure 3d. Geodynamical reconstructions – 90 Ma.



90 to 60 Ma (Figure 3d-f)

The Northern Andean margin experiences a collision with an oceanic plateau during the Late Cretaceous (Pindell and Tabbutt, 1995; Alemán and Ramos, 2000). Palaeomagentic data suggest that a single oceanic plateau collides with the Northern Andean margin and later fragments (Luzieux *et al.* 2006), contrasting to the concept of a series of collisions as proposed by Kerr *et al.* (2002). U-Pb SHRIMP data validate the single collision concept (Vallejo *et al.* 2006). This is modelled as the accretion of the Dagua-Pinon terrane, which extends from Columbia down through Ecuador, and is dated as accreting between 75-65 Ma (Alemán and Ramos, 2000; Cediel *et al.* 2003). A magmatic arc on the Central Cordillera of Columbia and Cordillera Real of Ecuador is active until the Late Cretaceous (Ramos, 2009). Ramos (2009) suggests the

Paleocene granites associated with the Antioquia batholith may be related to an episode of slab break-off that occurs in the northern Central Cordillera.

Closure of the Rocas Verdes Basin and crustal shortening of the Cordillera Darwin continues, with approximately 40 km occurring during the Late Cretaceous (Kraemer, 2003).

Figure 3e. Geodynamical reconstructions – 75 Ma.

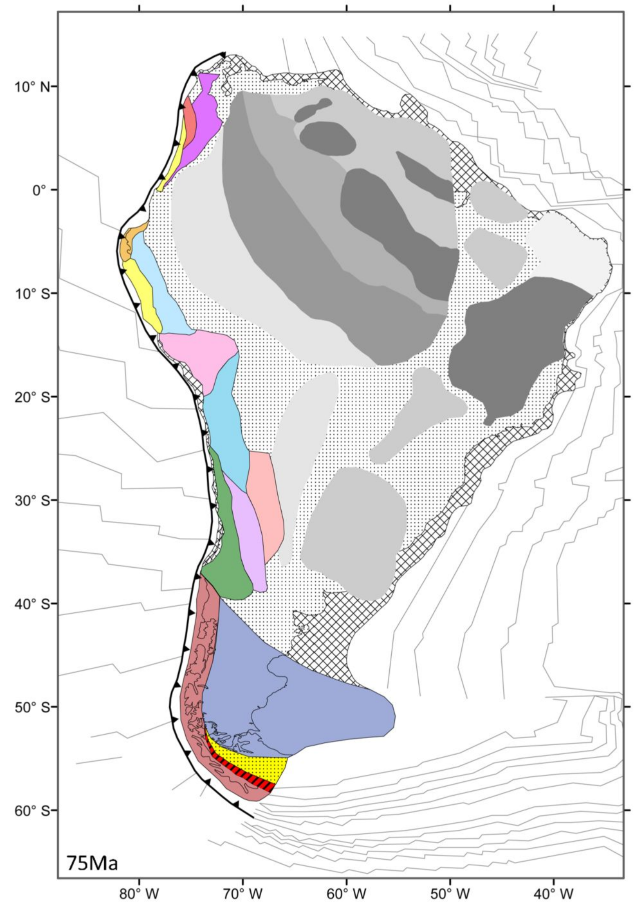
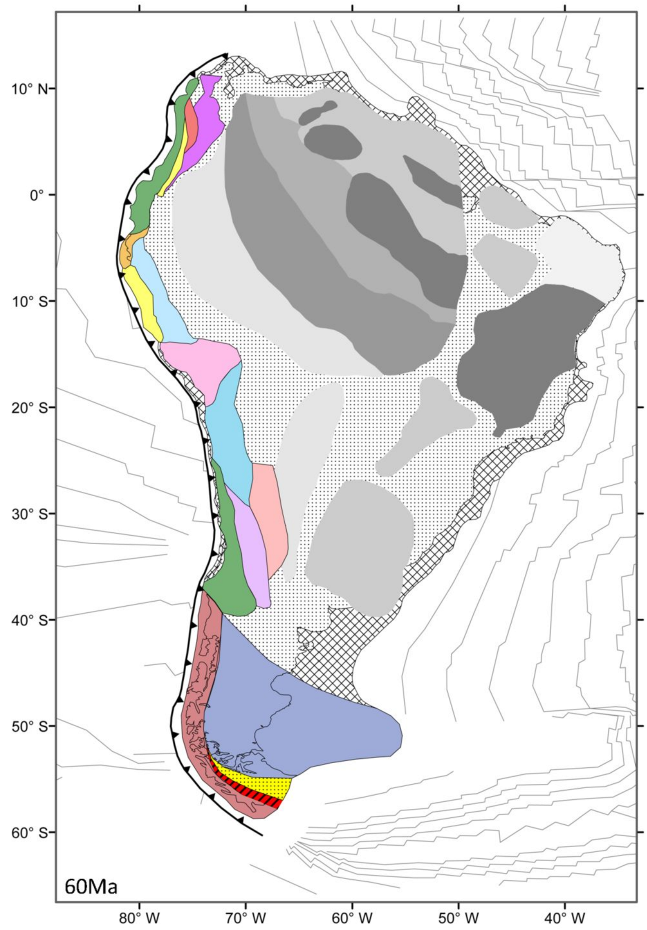


Figure 3f. Geodynamical reconstructions – 60 Ma.



60 to 30 Ma (Figure 3f-h)

Crustal shortening of the Central Andes commences during the Mid-Eocene (McQuarrie, 2002; Arriagada *et al.* 2008), likely as a consequence of the Central Andean 37 to 25Ma flat-slab episode (O'Driscoll *et al.* 2012). Horizontal shortening is focused in the Eastern Cordillera (Arriagada *et al.* 2008). Varying degrees of along-strike shortening causes bending of the Central Andes and formation of the Bolivian Orocline (Arriagada *et al.* 2008). The relationship between the basement highs and the physiographic boundaries of the Andean Plateau suggests shortening is controlled by the duplexing and stacking of basement megathrusts (McQuarrie, 2002). This protracted shortening generates crustal thicknesses of ~70 km below the highest topography in the Eastern and Western Cordillera (Beck and Zandt, 2002).

Figure 3g. Geodynamical reconstructions – 45 Ma.

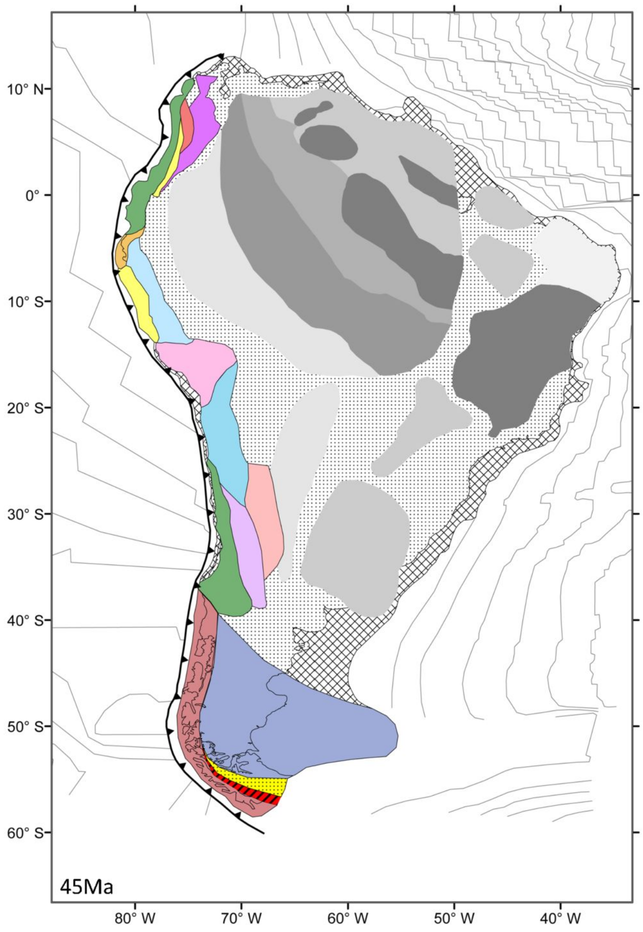
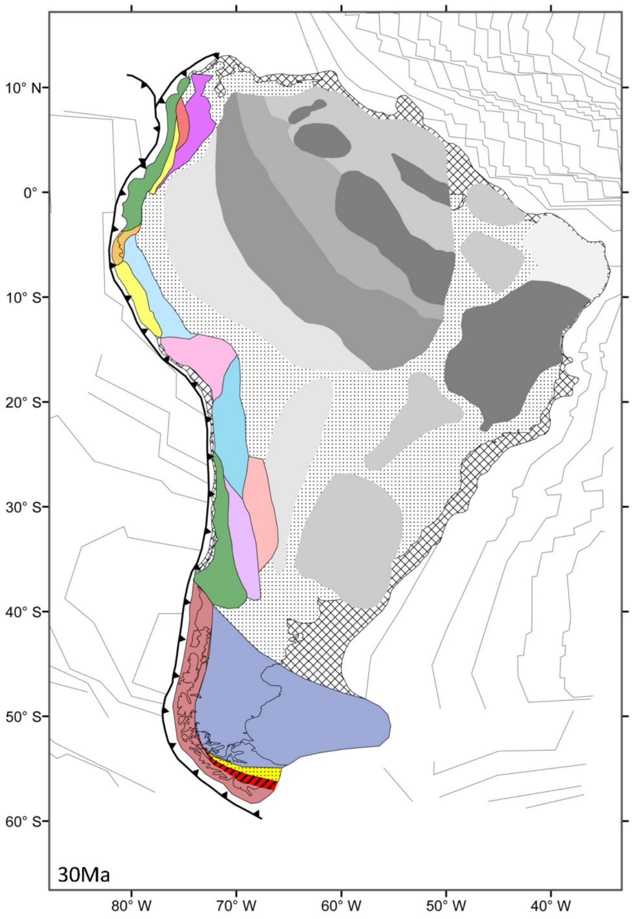


Figure 3h. Geodynamical reconstructions – 30 Ma.



30 Ma to Present (Figure 3h-j)

Differential crustal shortening of the Central Andes continues. Despite the extensive crustal thickening associated with this shortening, paleoelevations were less than 2 km in the Altiplano, and 2.5-3.5 km in the Eastern and Western cordilleras until ~10 Ma (Hoke and Garzione, 2008). Removal of dense eclogite and mantle lithosphere changes the internal structure of the Andean lithosphere between approximately 10-6 Ma, triggering regional surface uplift of approximately 1.5-2.5 km (Garzione *et al.* 2008). The low-relief landscape presently observed in the Andean Plateau was enhanced by way of mass redistribution caused by continued lower-crustal flow, erosion, and sedimentation, from 6 Ma to present (Garzione *et al.* 2008).

During the Neogene the Rocas Verdes Basin and Cordillera Darwin deformation continues, with approximately 80 km of shortening occurring (Kraemer, 2003). The Patagonian Orocline completes its presently observed 90°

rotation (e.g. Cunningham *et al.* 1991; Maffione *et al.* 2010).

To the north the Choco terrane accretes onto the Cordillera Occidental (Duque-Caro, 1990). Geochemical and isotopic data suggest the Choco terrane is derived from a different part of the Caribbean Plateau to that of the Dagua-Pinon fragment (Kerr and Tarney, 2005). Duque-Caro (1990) argued that presence of exotic upper Paleocene planktic foraminiferal assemblages suggests the Choco Block originated as distant as the northern latitudes of Guatemala and Mexico. Biostratigraphic dating constrains the age of Choco accretion at approximately 13 Ma (Duque-Caro, 1990). This accretion occurs along the Uramita Fault Zone, which sutures the Choco terrane and the Cordillera Occidental, and entailed major deformation of Middle Miocene formations (Duque-Caro, 1990), the details of which are not modelled in the continental-scale reconstruction presented here.

Figure 3i. Geodynamical reconstructions – 15 Ma.

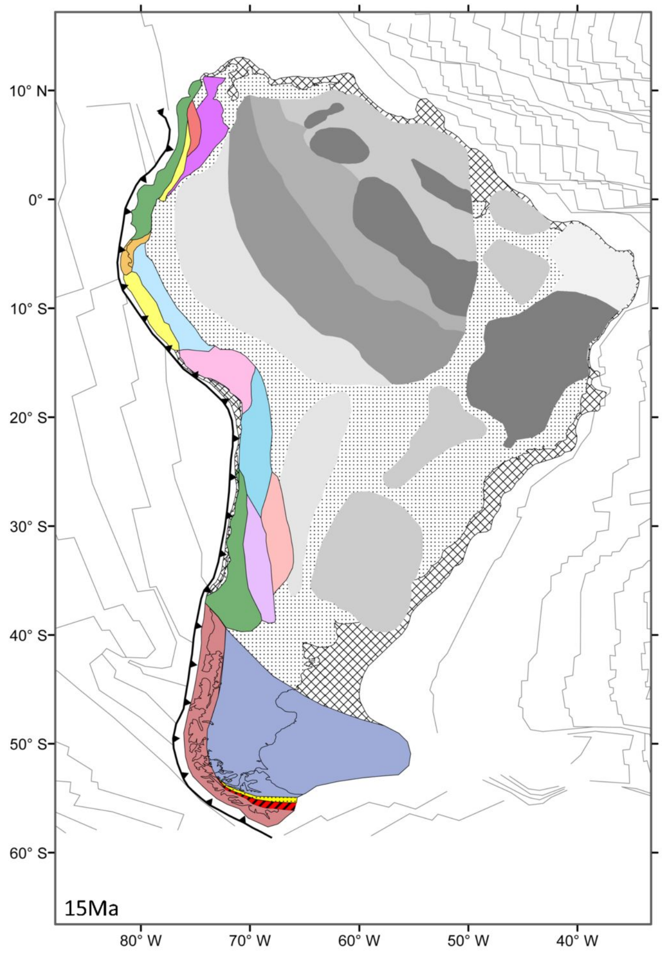
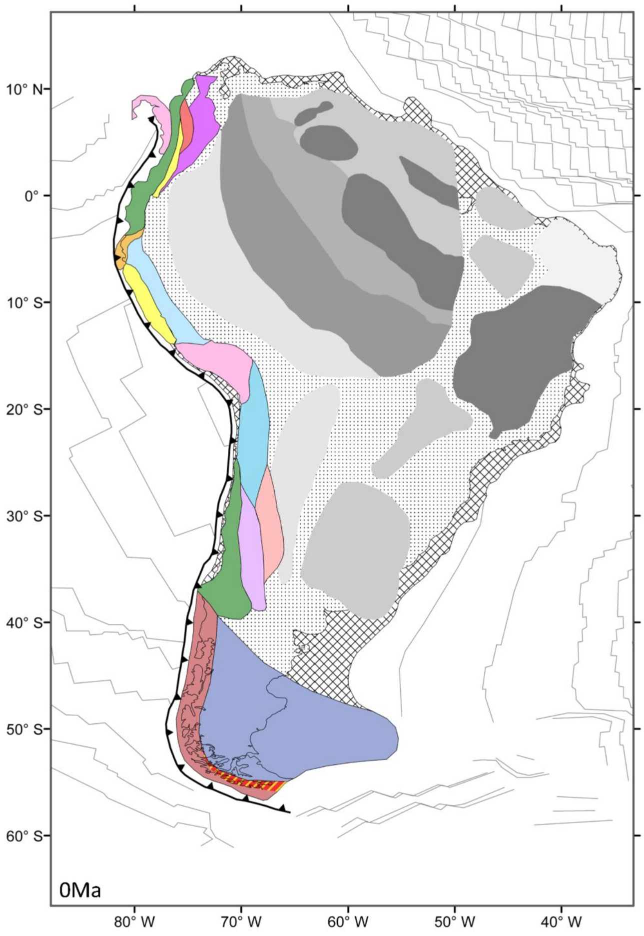


Figure 3j. Geodynamical reconstructions – 0 Ma.



Discussion

The Central Andean terranes and evolution of the Rocas Verdes Basin

A major constraint in the reconstruction of the Southern Andes regards the original extent of the Rocas Verdes Basin. Mafic volcanics, attributed to the Rocas Verdes Basin, are found from the southern tip of Patagonia through to the Sarmiento Complex (Dalziel *et al.* 1974). These volcanics suggest the Basin did not extend north of approximately 50°N (Fosdick *et al.* 2011). This observation was incorporated into the Southern Andean tectonic models of Cunningham (1993), Cunningham (1995), Diraison *et al.* (2000), (Kraemer, 2003), and this paper. In the tectonic models of such studies the Rocas Verdes Basin is a small marginal basin that opens behind an active andesitic island arc during the Cretaceous.

However, a recent study by Vérard *et al.* (2012) presents a different model, whereby the Rocas Verdes Basin is up to 3000 km wide, and extends from Patagonia to the Central Andes. Vérard *et al.* (2012) suggest the width of the basin is constrained by the Early Cretaceous collision of cross-Pacific GDUs (a term given to the various geological units that originated in the 'Pacific magnetic triangular zone' of Müller *et al.* (2008)), and terranes rifting from South America during the formation of the Rocas Verdes Basin. However, the data for this collisional event (Thomson and Herve, 2002; Herve and Fanning, 2003; Willner *et al.* 2004) is derived from work undertaken in the Southern Andes only. However Vérard *et al.* (2012) have included the rifting of Central Andean terranes (such as Arequipa) off the Andean margin as part of the Cretaceous opening of the Rocas Verdes Basin. We have not applied the same reasoning, and have taken the approach that the Central Andes followed a different evolution to that of the Southern Andes – one that does not involve the Rocas Verdes Basin.

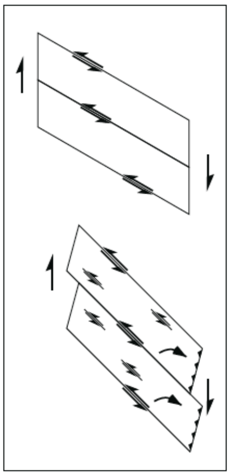
Palaeozoic samples, from the Sierra de Almeida of northern Chile, show discordance from the Gondwanan palaeomagnetic path only for the latest Cambrian-earliest Ordovician (Forsythe *et al.* 1993). Forsythe *et al.* (1993) explained this discordance whereby the Arequipa block rotated about a nearby pole but was resutured to Gondawana during the Silurian. Prior to this event Arequipa was rifted during the breakup of Rodinia in the Neoproterozoic (Sempere, 1995), however has remained *in situ* since this Silurian reaccretion event.

While there is conjecture as to whether the Arequipa and Antofalla terranes are part of the same block (Ramos 2009), there are numerous data advocating that the Antofalla terrane reaccreted to the continental margin by the Late Ordovician (Ramos, 2008 and references therein). The Famatina and Cuyania terranes accreted during the Middle Ordovician, as evidenced by significant deformation during the Famatinian orogeny (Astini *et al.* 1995; Pankhurst *et al.* 1998; Quenardelle and Ramos, 1999). Various geochronological and geological data suggest the Chilenia terrane is likely to have accreted during the Late Devonian (Ramos, 2010). These data suggest the Central Andean terranes have remained as a part of South America since their Palaeozoic accretion and/or reaccretion, and thus were not involved in any Mesozoic rifting related to formation of the Rocas Verdes Basin. Subsequently our model follows that of Cunningham (1993), Cunningham (1995), Diraison *et al.* (2000), and (Kraemer, 2003), whereby the Rocas Verdes Basin is a small marginal basin that opens behind an active island arc.

Crustal deformation in the Central Andes

The model we have developed uses data suggesting that during the Mid-Eocene to Mid-Miocene shortening was focused in the region of the central Bolivian Andes (16°–24°S), with a total shortening ~400 km as presented by Arriagada *et al.* (2008). This amount of shortening, and the inherent bending of the Bolivian orocline during the Mid-Eocene to Pliocene, may not fully account for the observed total palaeomagnetic rotations of >25° north and south of the Arica Bend for this time period (Arriagada *et al.* 2008). That said, it should be emphasized that this difference between the observed and predicted palaeomagnetic data is not conclusive, and may simply be a consequence of data resolution. However if one were to examine the implications that the palaeomagnetic data suggest, either the orogen was actually straighter prior bending, or that *in situ* block rotations have contributed (Figure 4). Beck (1998) proposed that sub-crustal ductile flow is likely to have caused significant local block rotations, and thus would be a plausible mechanism to explain the additional rotations observed within the palaeomagnetic data.

Figure 4. Regional-scale structural kinematics of the Bolivian Orocline, after Randall *et al.* (1996) and Beck (1998).

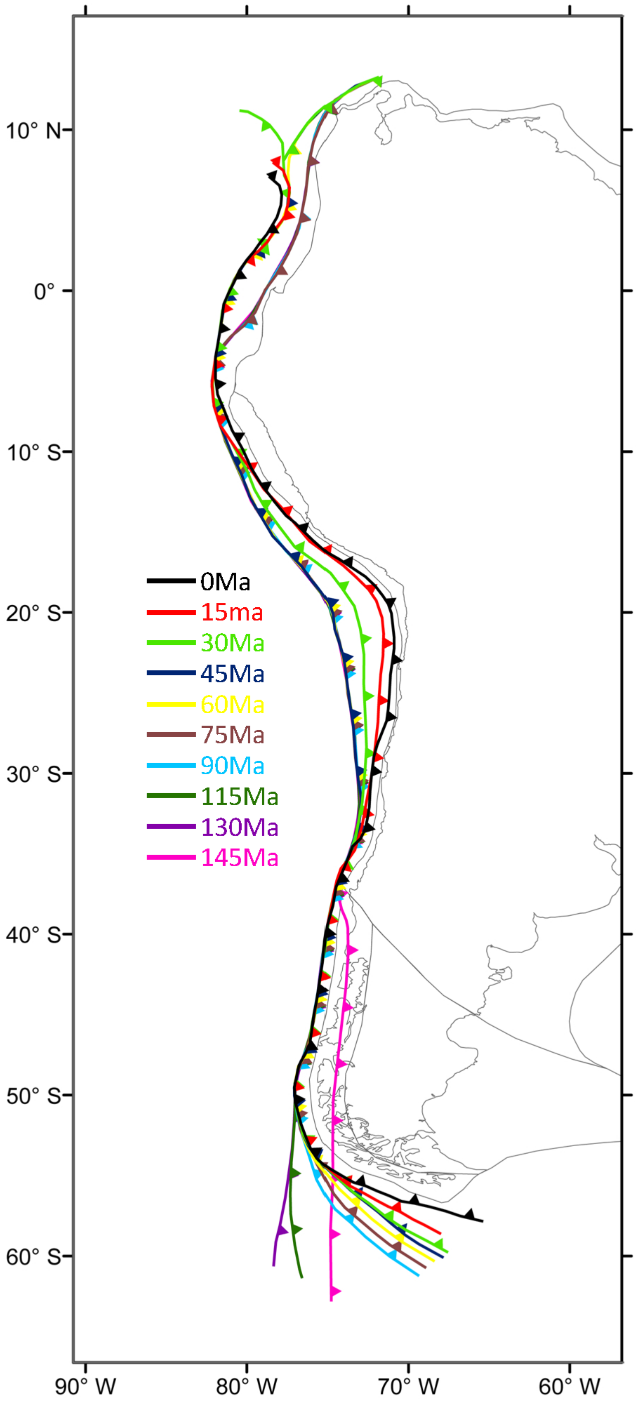


The strike-slip domino model (starting configuration a., final configuration b.), that occurs as a consequence of oblique convergence, and results in the formation of left-lateral antithetic faulting between the dominant – in this case right-lateral – strike-slip systems. This faulting contributes to oroclinal bending, and additional rotation of fault-bounded blocks as observed by several palaeomagnetic studies. Note that in order for crustal volume to be conserved the deformation zone must lengthen and/or crust thicken.

Dynamics of the Andean subduction zone

The Cretaceous to present Andean subduction zone records a dynamic history with respect to cratonic South America (Figure 5). The Northern Andean subduction system is relatively stable, with the only movement being westward as a result of the addition of crust through accreted terranes. The Central Andean region experiences a large Eocene/Miocene shift subduction zone location as a result of orogenic shortening and orocline formation. Oroclinal formation also has a large influence on subduction in the Southern Andes, with the southern extremity of the system potentially experiencing migration upwards of 600 km relative to South America. This illustrates the potential forces subjected to lithosphere subducting beneath South America. Such forces are likely to be amplified when absolute motion of the overriding plate is considered. Studies analysing tectonic processes occurring along the Andean margin, and its subduction system, must consider the lateral movements of the subduction system through time. Subduction dynamics are likely to have had a large influence on magmatism, metamorphism, mineralisation, and the morphologic evolution of subducting lithosphere. However, it is important to note we have not accounted for subduction erosion of the forearc, a process that is likely to have affected the lateral positioning of the palaeo-subduction zone, and thus subsequent conclusions.

Figure 5. Trench dynamics of the Andean subduction system from 145 Ma to present, relative to stable South America.

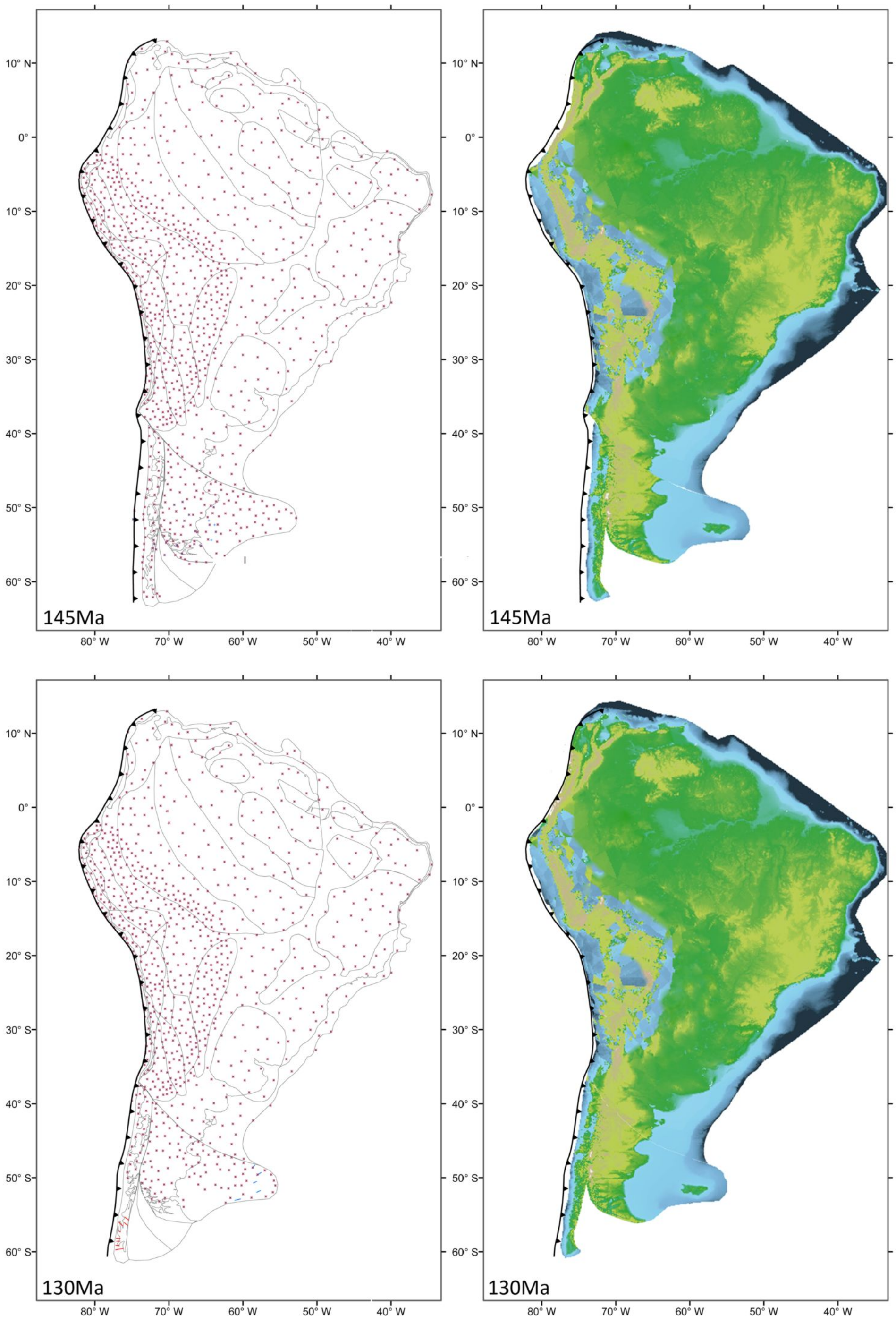


Subduction zone location for distinct times is indicated by coloured lines, with numbers indicating time in Ma. Present-day continental outline is used to illustrate South America.

Strain, dynamic topography, and deformation

The mesh-based feature of *Pplates* allows the calculation of strain through time. The starting configuration (in this case 145 Ma) of the meshes have zero-strain, and thus the strain reconstruction figures (Figure 6a-j) is presented illustrating the accumulation of strain from 145 ma to the present-day only. Our model predicts the high degree of strain associated with the formation the Patagonian and Bolivian Oroclines. In the Southern Andes it can be seen that the greatest episode of compression occurred between 130-90 Ma, and not only images the strain accumulation associated with closure of the Rocas Verdes Basin, but also the counter-clockwise rotation and associated shortening in the Tierra del Fuego region. The strain model we present here illustrates the high degree of compression (~275 km) that may have occurred during the Mid-Eocene to Mid-Miocene in the Central Andes, with the greatest level of compression occurring in the region of the oroclinal axis. Such data, although of a continental-scale, is potentially useful when quantifying and comparing the degree of deformation to real-world geological data, and alternative palaeogeographic models. As the level of detail within the input data is increased, so is the usefulness of this modelling feature.

Figure 6a-b. Reconstruction illustrating dynamic strain and dynamic topography – 145-130 Ma.



Dynamic strain is illustrated by red lines (compression) and blue lines (extension), while starred points represent no strain. Dynamic topography is depicted by Present-day topography data (NOAA ETOPO2) held by mesh faces. Crustal volume is maintained, although effects of erosion of elevation through time have not been simulated. The model illustrates the presence of basins in the Central Andes prior to the formation of the Bolivian Orocline.

Figure 6c-d. Reconstruction illustrating dynamic strain and dynamic topography – 115-90 Ma.

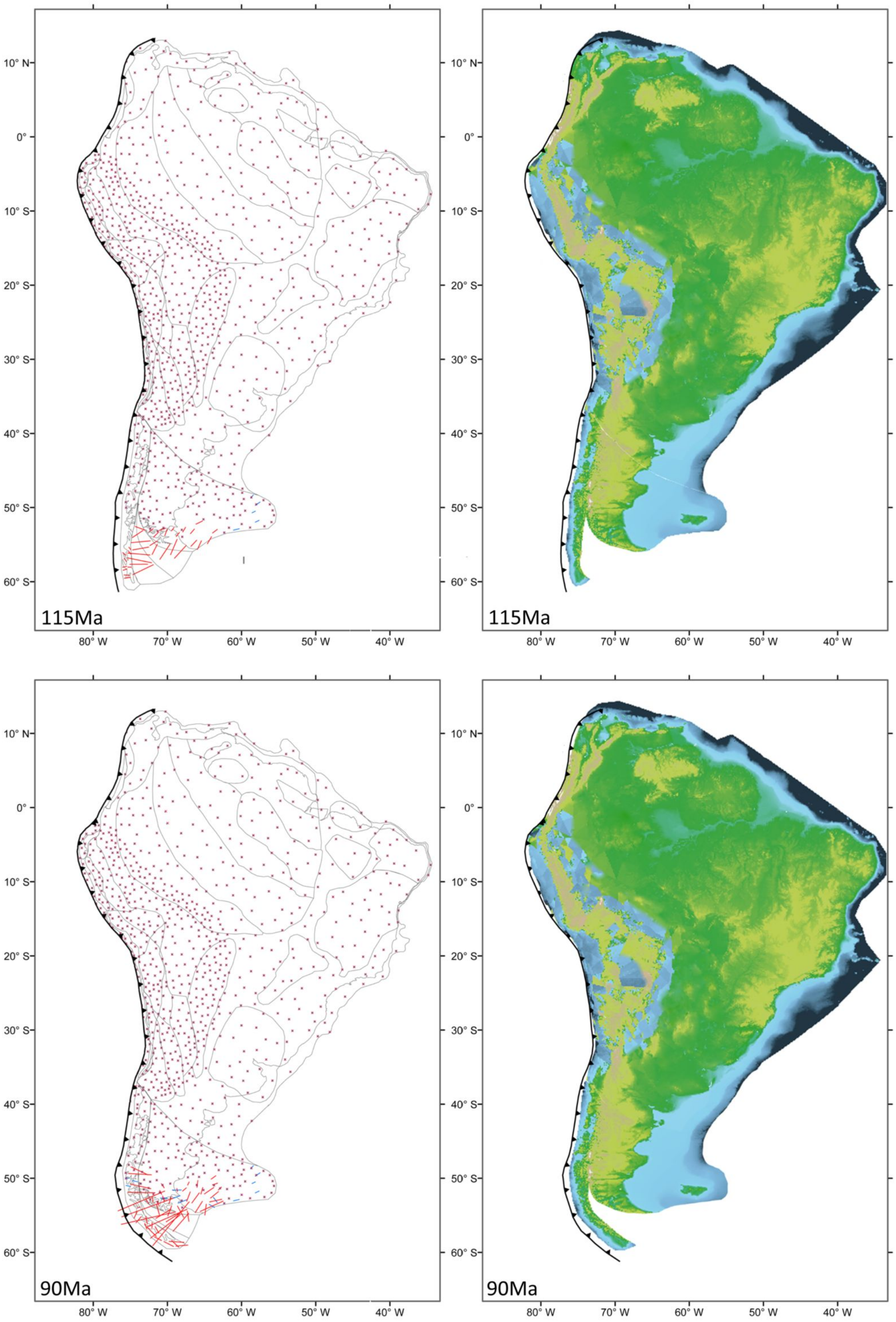


Figure 6e-f. Reconstruction illustrating dynamic strain and dynamic topography – 75-60 Ma.

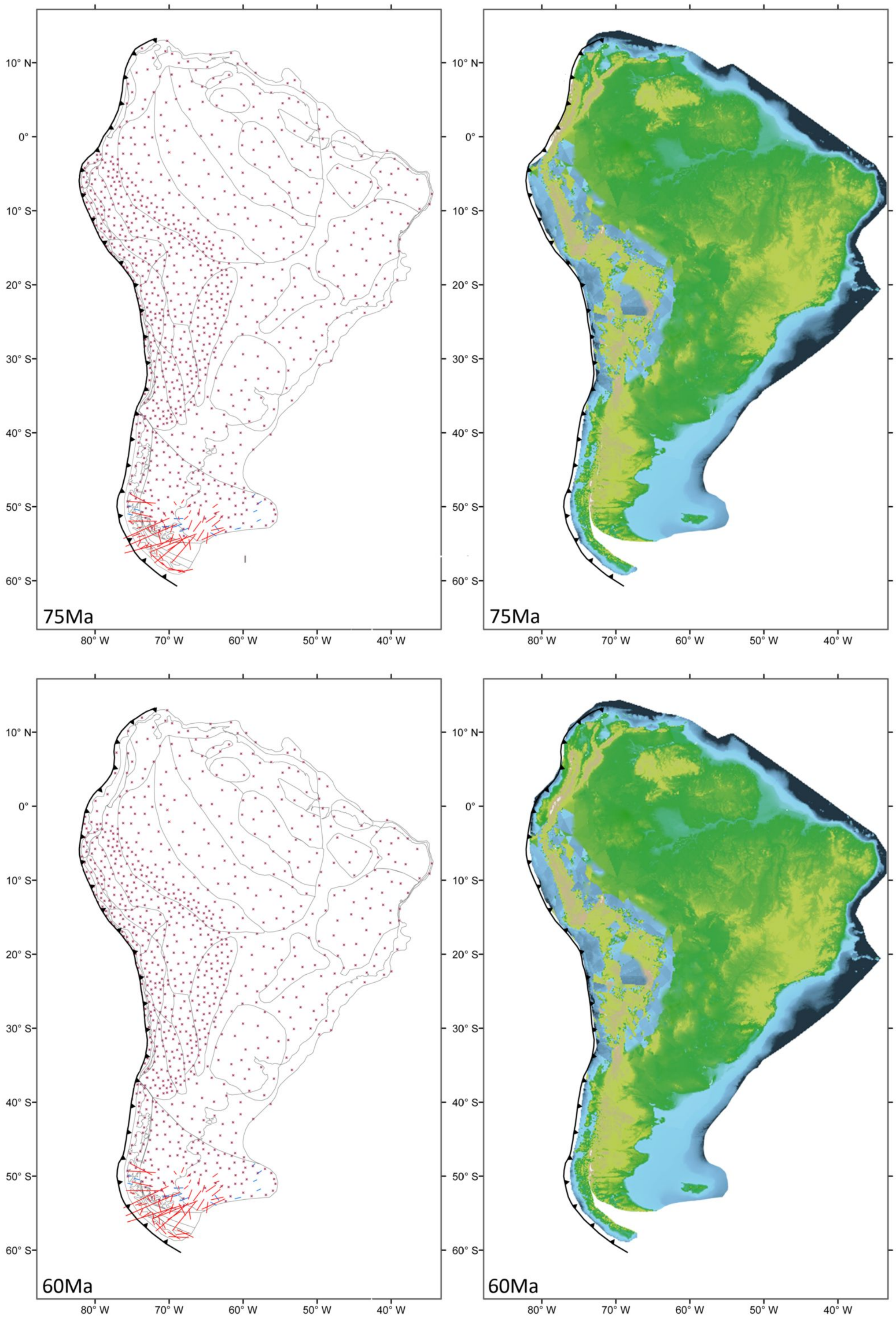


Figure 6g-h. Reconstruction illustrating dynamic strain and dynamic topography – 45-30 Ma.

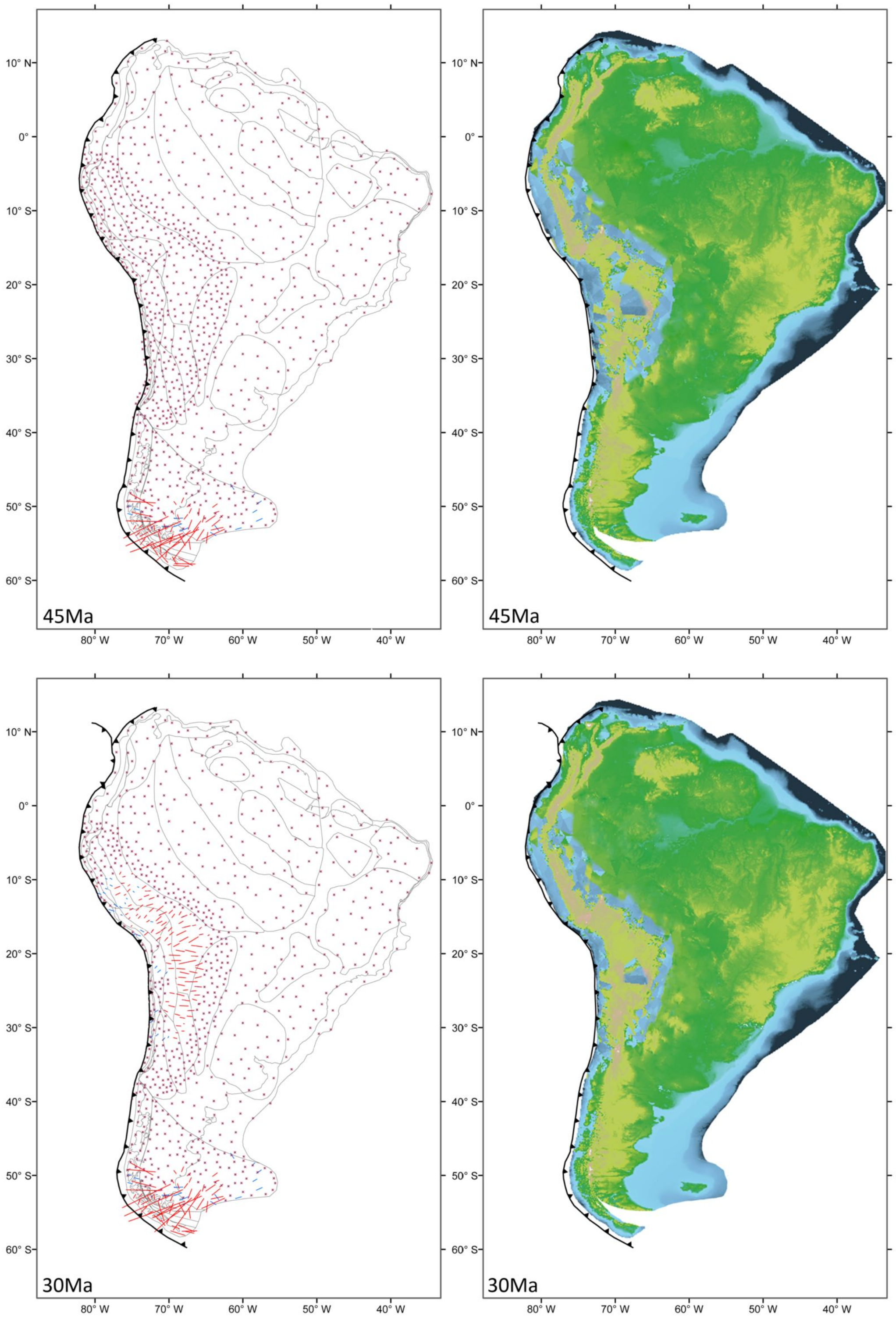
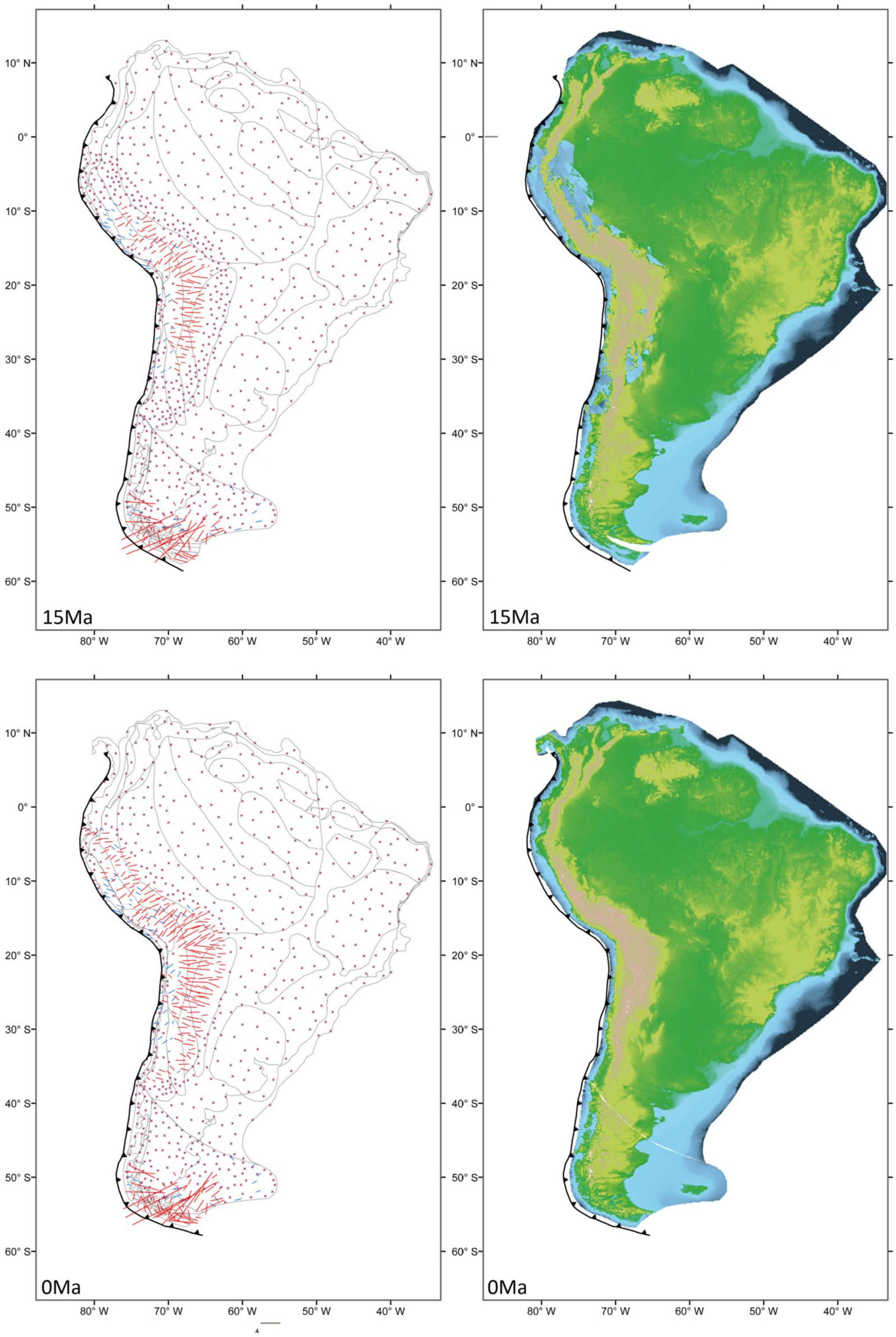


Figure 6i-j. Reconstruction illustrating dynamic strain and dynamic topography – 15-0 Ma.



The deforming mesh model of South America also allows changes in topography to be observed (Figure 6a-j). As detailed by Smith *et al.* (2007), the method for calculating dynamic topography involves the reconstruction starting with present-day topography, assuming isostasy and a standard crustal model, and conserving crustal volume. This calculation illustrates the changes that are forced by uniform stain, as imposed by the reconstruction. While these calculations do not account for erosion, changes in palaeo-altitude caused by crustal thickening are quantified. If the deformations in the model are realistic, such changes in palaeo-altitude could correspond to the depth to basement of the sediment in modern-day basins (Smith *et al.* 2007).

The dynamic topography model illustrates the potential presence of basins in the Central Andes prior to the formation of the Bolivian Orocline. While this somewhat qualitative information is interesting, the scale of the tectonic reconstruction does not allow genuinely useable conclusions to be drawn regarding basin formation and inversion. Increasing the density of mesh nodes, and incorporating additional geochronological and geological data would go someway to resolving this.

Conclusions

Current plate tectonic reconstruction theory needs to begin to confront the challenges associated with modelling penetrative deformation of the continents. The model presented here is the compilation of numerous palaeogeographic models and various geochronological, geological and geophysical data within a deformable, mesh-based framework. While there are competing interpretations for Andean evolution, particularly regarding the formation of the Bolivian Orocline, this deformable model of Cretaceous to present Andean evolution demonstrates several interesting implications in terms in terms of strain, topography, geometry and relative translations. Our model presents that the Central and Southern Andes formed a sub-linear belt during the Cretaceous. After a period of large-scale extension in the Jurassic, crustal shortening associated with Rocas Verdes Basin closure produced the Patagonian Orocline. In the Central Andes we have assumed that both differential shortening and crustal block rotation, from the Mid-Eocene to present, formed the Bolivian Orocline. Crustal growth has occurred in the Northern Andes by means of episodic terrane accretion throughout the Mesozoic-Cenozoic. This study was developed within the *Pplates* mesh-based software, allowing us to quantify the implications of the model through assessable predictions. However, there are several other geodynamic explanations that may fit the data utilised here. Thus the next step would be to test alternative palaeogeographic models and datasets, and see how these compare to the model presented here, specifically in terms of the evolution of individual Andean basins, tectonic block rotations, terrane accretions, and subduction zone dynamics. This could easily be achieved with use of the *Pplates* software, and such models could be updated as new or additional data are evaluated. Such an approach is required if we are to overcome the problem associated with modelling and testing the fluid-like evolution of Earth's orogenic zones.

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