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Fragmentation of active continental plate margins owing to the buoyancy of the mantle wedge

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Cordilleran-type orogens are characterized by the formation of mountain chains and ridges near subduction zones. The growth of orogenic systems is sustained by frictional and viscous stresses, which promote surface uplift. However, horizontal extensional stresses[1] also develop, which can contribute to the formation of marginal basins[1] and gravitational orogenic collapse[2]. Here we use a numerical model to assess the effects of the buoyancy of the mantle wedge overlying the subduction zone on the evolution of Cordilleran orogenic systems. Our simulations show that as the subduction velocity decreases, stresses from the buoyancy of the mantle wedge can drive trench retreat and the formation of marginal basins. We find that ultimately, these stresses promote the gravitational collapse of the orogen, detachment of microplates and the break-up of active plate margins. We suggest that the effects of mantle-wedge buoyancy could explain the collapse of the East Gondwana Cordillera[3], constructed along the edge of the Australia/East Antarctic craton as the Gondwana and Pacific–Phoenix plates converged[4–7]. We propose that 105–90 million years (Myr) ago, a change in the absolute plate motion reduced the subduction velocity, ultimately triggering the gravitational collapse of the orogen and the fragmentation of the active margin.

Cordilleran orogens express the dynamic balance between effective ridge-push stresses, frictional stresses at the contact between overriding and subducting plates, viscous stresses originating in the Cordillera crust, buoyancy stresses related to the buoyant mantle wedge and partially melted crust, gravitational stresses resulting from lateral contrast in gravitational potential energy and the effective slab-pull stress. Effective ridge-push stresses, frictional stresses and viscous stresses tend to promote and sustain the Cordillera. In contrast, buoyancy stresses, gravitational stresses and the effective slab-pull stress tend to promote trench retreat and horizontal extension in the Cordillera. In this framework, the role of mantle-wedge buoyancy on the dynamics of active margins has received little attention. Above the Benioff plane, the transformation of strong lithospheric mantle into weaker and buoyant mantle is well documented[8–10]. This transformation is driven by the release of significant amounts of water (up to 2 wt%) from the subducting plate leading to compositional buoyancy and lower viscosities[11,12]. The density of the mantle wedge decreases further with increases in melt fraction, which can reach >15% (ref. 12). In addition, dissolved water decreases the density of basaltic melt from about 2,900 kg m^{-3} to about 2,500 kg m^{-3} as dissolved H_2O increases to 6% (refs 13, 14). Volume forces resulting from lateral contrasts in gravitational potential energy, and those associated with the presence of a buoyant mantle wedge produce horizontal extensional stresses[1] that compete with those promoting the development of Cordillera orogens. A decrease of the tectonic forces would eventually promote extension in the overriding plate and possibly the opening of a marginal basin in a runaway effect not unlike continental break-up and active rifting that may follow gravitational collapse of collisional orogens[2]. On the basis of two-dimensional fully coupled numerical thermomechanical experiments, and using the mid-Cretaceous to Palaeocene evolution of the East Gondwana margin as a prime example, we investigate the stability of Cordilleran orogens as a function of the trench-normal component of motion and buoyancy of the mantle wedge. In our model set-up, the subducting slab has been removed to specifically assess the driving power of the volume forces. Our results show that, on lowering the trench-normal velocity and/or increasing the buoyancy of the mantle wedge, volume forces drive a range of processes dynamically linking the gravitational collapse to the fragmentation of the plate margin through the formation of a marginal basin and the forcing of trench retreat.

Figure 1a shows the initial configuration and thermal state of our model set-up. It includes a 7-km-thick oceanic crust adjacent to a 60-km-thick, 250-km-wide orogenic crust. Away from the subduction zone, a constant trenchward velocity is applied to a small section of the oceanic lithosphere (Fig. 1a). Therefore, motion and dynamics at the junction between ocean and continent are self-consistent. Slab pull combines with volume forces acting on the upper plate to drive extension and slab rollback. To assess the driving power of volume forces alone, our model set-up does not include a subducting slab. We assign to the mantle wedge a density of 3,350 kg m^{-3}, 20 kg m^{-3} lower than the surrounding non-hydrated mantle. The vapour-saturated solidus for the mantle wedge[12] assumes a water content of the vapour-saturated melt of 2.5%. Its solidus at atmospheric pressure is 1,278 °C compared with 1,350 °C for the surrounding mantle. We assign a density of 2,915 kg m^{-3} to the hydrated basaltic melt, a conservative value for hydrated basaltic magmas[14]. We use Ellipsis, a Lagrangian integration point finite-element code, to solve the governing equations of momentum, mass and energy in incompressible flow. Details of the thermal and mechanical parameters are developed in the Supplementary Information. We have tested a few dozen models by varying rheologies, densities and partial melt production. Models with buoyant mantle wedges and moderate trench-normal velocities share first-order characteristics including the horizontal extension and boudinage of the orogenic crust, trench retreat and the initiation of microplate detachment.

Figure 1b–e shows models for decreasing convergent velocities. For convergence velocities >3.25 cm yr^{-1} (Fig. 1b,c), the trench location remains stable and little to no surface deformation affects the Cordillera. This suggests that the forces driving contraction balance those promoting extension. At depth however, the relatively strong lower mafic crust is dragged into the subduction zone. The buoyant mantle wedge rises and spreads at the base of the Cordillera before being squeezed between the subducting slab and the strong subcontinental mantle. For a convergence

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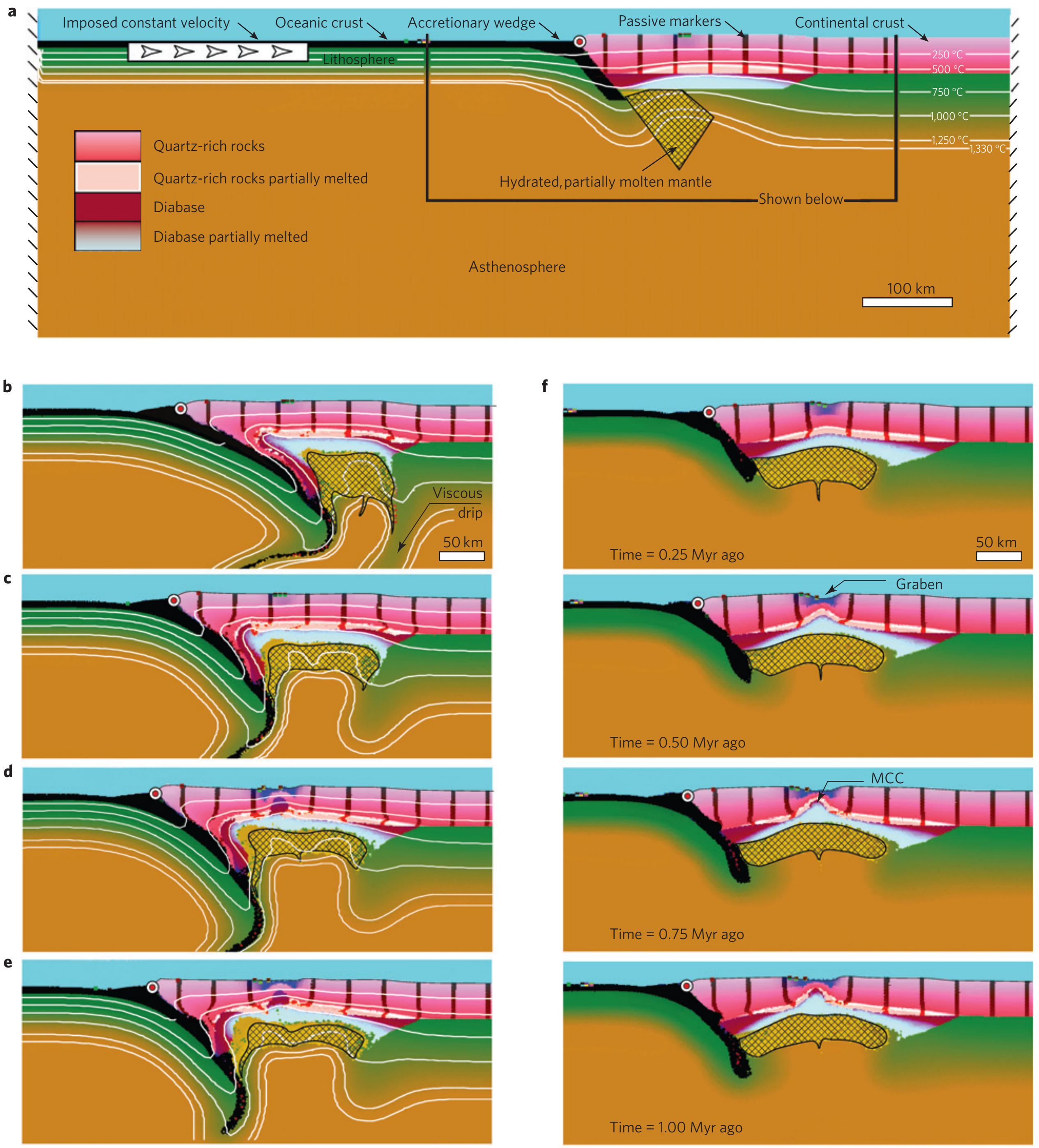

Figure 1 | Ellipsis experiments. a, Initial and boundary conditions (see text for further explanations). **b**–**e**, Snapshots illustrating experiments with trench-normal velocities of 5 cm yr^{-1} (**b**), 3.5 cm yr^{-1} (**c**), 3.25 cm yr^{-1} (**d**) and 2.5 cm yr^{-1} (**e**). All snapshots are at 4 Myr ago. The red dot marks the location of the margin of the continent. **f**, Snapshots showing a time sequence for the experiment in **e**.

velocity of 3.25 cm yr^{-1} (Fig. 1d), a phase of short-lived horizontal extension unfolds before shortening takes over again. This switch back to contraction can be related to the decrease of the basal traction imposed by the buoyant wedge as it spreads and solidifies beneath the overriding plate. In nature, extension should continue as the buoyancy of the mantle wedge is maintained by the progressive dehydration of the underlying slab, a process not included in our model.

When the oceanic lithosphere is pushed towards the continent at a velocity of 2.5 cm yr^{-1} or less (Fig. 1e), volume forces overcome the plate boundary forces as shown in Fig. 1f. In the plateau's upper crust, horizontal surface extension focuses across a symmetric graben (Fig. 1, top two panels). The mafic lower crust is exhumed in a metamorphic core complex (MCC; Fig. 1, bottom two panels). Space for the MCC is provided by the translation towards the ocean of a developing microcontinental block. As the microcontinent surges towards the ocean forcing the trench to retreat, surface extension is focused along the marginal basin whereas contractional deformation occurs at the boundary between the ocean and the continent. In nature, coeval horizontal contraction and horizontal

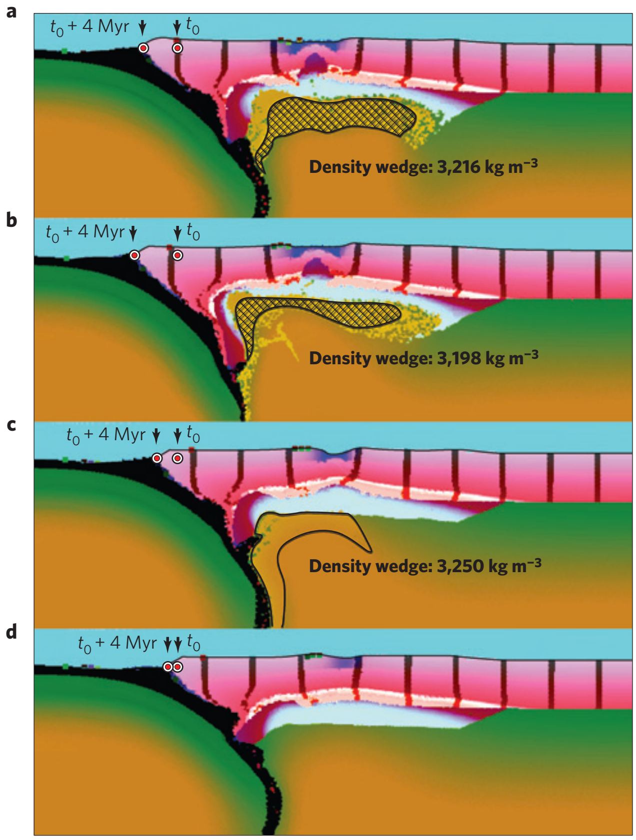

Figure 2 | Sensitivity to the buoyancy of the mantle wedge. Mantle: 3,269 kg m^{-3}. The red circles show the position of the crust–ocean contact at t_0 and t_0+4 Myr; their separation increases with the amount of horizontal extension in the plateau. Densities are calculated at 1,000 °C and, in the mantle wedge, assume a melt fraction of 8%. **a**, The reference model: model in Fig. 1e at 4 Myr ago. **b**, The density of the mantle wedge is reduced, leading to enhanced surface extension. **c**,**d**, Decreasing the buoyancy of the mantle wedge reduces surface extension in the overriding plate.

extension in adjacent areas is a characteristic of gravity-driven mass transfer processes during gravitational collapse[15]. In contrast, trench retreat resulting from slab rollback leads solely to extension in the overriding plate. Horizontal extension in the Cordillera proceeds until a new equilibrium is reached between the forces driving convergence and the forces promoting extension. In nature, however, hydraulic fracturing and dyking may promote oceanization and seafloor spreading. These processes are not accounted for in our model. Consequently, the microcontinent in our model does not fully detach from the mainland.

The buoyancy of the mantle wedge is key to the initiation of the formation of microcontinents. To demonstrate this point, the model in Fig. 1e is shown in Fig. 2 with various mantle-wedge buoyancies, from more buoyant (Fig. 2b) to less buoyant (Fig. 2c), including the case where no buoyant mantle wedge is present (Fig. 2d). Figure 2 shows that the amount of surface extension and trench retreat is proportional to the buoyancy of the mantle wedge.

The experiments presented in Figs 1 and 2 show that volume forces acting on a Cordillera orogen may be strong enough to promote localized upper-plate extension and boudinage, and to initiate trench retreat and the detachment of a microcontinent. We ground-truth our model by discussing the well-mapped tectonic consequences of the change in plate motion from near trench-normal to near trench-parallel that affected the East Gondwana plate in the Late Cretaceous–Palaeocene period.

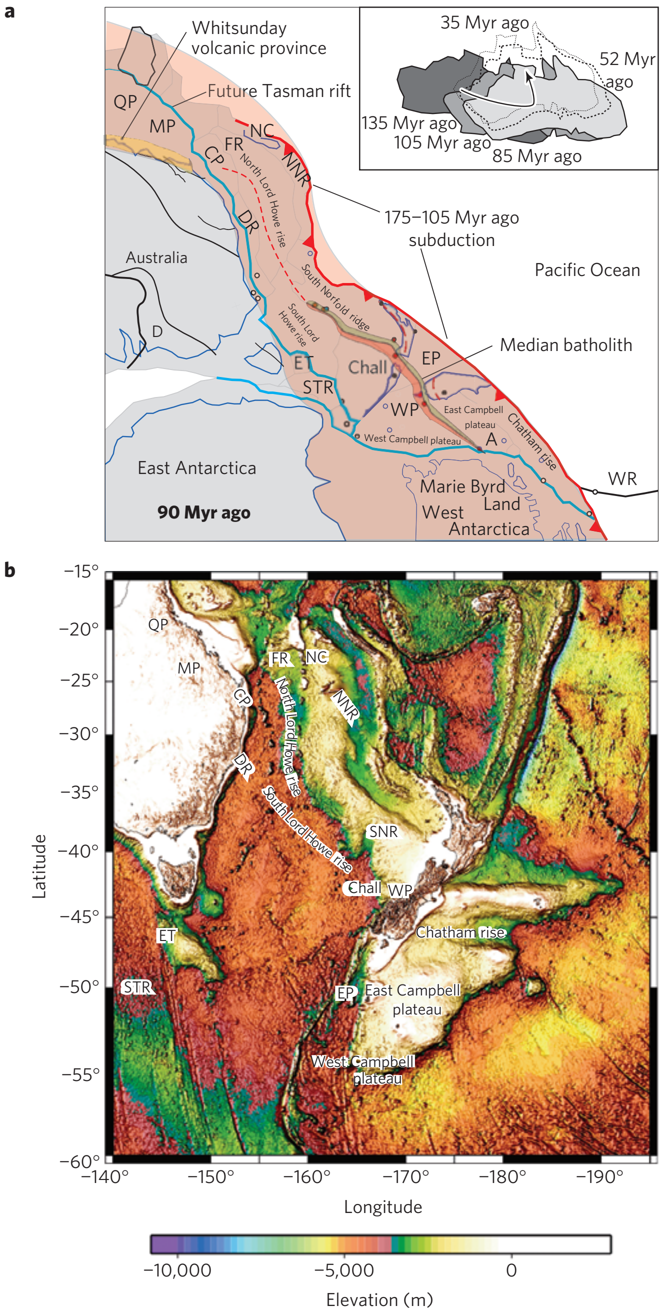

Figure 3 | Fragmentation of the East Pacific Gondwana margin. a, Rigid plate reconstruction of the East Pacific Gondwana margin at 90 Myr ago[7] showing the position of New Caledonia, Lord Howe rise, Greater New Zealand (South and North Islands along with the Challenger plateau, Campbell plateau and Chatham rise) and Marie Byrd Land in East Antarctica after collapse of the Zealandia Cordillera but before break-up. The inset shows Australia's trajectory from 135 to 35 Myr ago. A: Antipodes Island, Chall: Challenger plateau, CP: Chesterfield plateau, DR: Dampier ridge, EP: Eastern Province, ET: East Tasman plateau, FR: Fairbank ridge, MP: Marion plateau, NC: New Caledonia, NNR: North Norfold ridge, QP: Queensland plateau, SNR: South Norfold ridge, STR: South Tasman rise, WP: Western Province of New Zealand, WR: Wishbone ridge. **b**, Elevation map showing the present-day distribution of Gondwana continental fragments. Map produced using The Generic Mapping Tools (http://gmt.soest.hawaii.edu).

Jurassic to lower Cretaceous arc-related rocks[4,5] record westward subduction along Gondwana's Pacific margin (Fig. 3a). Between

125 and 105 Myr ago along New Zealand's South Island, crustal thickening and the burial down to 1,900 MPa of an Early Cretaceous magmatic arc[6,16] contributed to build-up of the Zealandia Cordillera orogen (Fig. 3a). At that time, partial melting of Gondwana's Pacific margin, from eastern Australia to East Antarctica, led to the emplacement of the dominantly felsic Whitsunday volcanic province[17]. From 115 to 95 Myr ago, orogenic collapse led to the formation of metamorphic core complexes[18] and grabens[19] west of the New Zealand Alpine fault, and further south in Marie Byrd Land where MCC, mafic dykes and *A*-type granitoids of the Fosdick Mountains flank the West Antarctic rift system[20,21]. This wide continental extension developed immediately before the fragmentation of the Gondwana margin (Fig. 3b). Extension in the West Antarctic rift system accompanied the separation of New Zealand and Campbell plateau from Antarctica[22]. In New Zealand, the emplacement of the Late Cretaceous French Creek suite (82 Myr ago) was coeval with the initiation of the opening of the Tasman Sea and Ross Sea[23,24], whereas further north the Fairbank and New Caledonia basins formed from 95 to 65 Myr ago through continental stretching[25]. The temporal relationship between the gravitational collapse and extension in the Tasman Sea, Ross Sea and West Antarctic rift system suggests that they are dynamically linked.

Palaeogeographic reconstructions show that from 135 to 100 Myr ago, East Gondwana moved eastwards towards the Pacific–Phoenix plates[26], slowing down from 115 to 100 Myr ago (Fig. 3a). During that time, New Caledonia, Lord Howe rise, New Zealand's South and North Islands, Challenger plateau, Campbell plateau, Chatham rise and Marie Byrd Land were all part of the Zealandia Cordillera[7] (Fig. 3a). From 100 to 90 Myr ago, Gondwana remained stationary before Australia moved northward away from Antarctica[24]. We propose that the gravitational collapse unfolded because of a slowing down of Gondwana, whereas the Tasman Sea, Ross Sea and West Antarctic rift system were initiated as Gondwana's motion switched from eastward to northwestward, hence decreasing further the trench-normal velocity.

It has been suggested that contractional tectonics ceased with the westward subduction of the Pacific–Phoenix plates at around 105 Myr ago and was immediately followed by gravitational collapse and then the opening of the Tasman Sea[3,6,18] and the Ross Sea[27]. Others have suggested that contraction continued until about 82 Myr ago[28] as shown by prograde temperature (485–560 °C) and pressure (600–830 MPa) recorded in the Alpine schist of New Zealand[29]. According to our experiments, extension in the overriding plate is compatible with synchronous shortening in the microcontinent pushed against the oceanic lithosphere. Interestingly, two phases of extension have been documented along the east Gondwana margin[30]. The first phase (101–88 Myr ago) is associated with a rapid cooling during gravitational collapse. The second phase (89 and 82 Myr ago), characterized by slower cooling rates, coincides with the age of the oldest oceanic floor in the Tasman Sea[24] as well as Late Cretaceous crustal reheating[30]. On the basis of our experiments, we argue that the first phase of extension corresponds to the rapid extension and cooling related to the divergent collapse and necking of the orogen, whereas the second stage corresponds to the attenuation of the continental crust driven by active extension controlled by decompression melting.

Our numerical experiments indicate that the combination of gravitational forces in Cordilleran orogens with buoyancy forces in the mantle wedge is strong enough to drive gravitational collapse, active continental extension and oceanic rifting. Therefore, any process reducing the forces promoting and/or sustaining Cordilleran orogens may lead to surface extension and rifting in the upper plate. At around 100 Myr ago, the change in Gondwana plate motion from near trench-normal to near trench-parallel led to cessation of subduction and lowered the dynamic support of the Gondwana Cordillera. Consequently, it recorded a switch to gravitational collapse, then seafloor spreading leading to the fragmentation of the plate margin and dispersion of microcontinents.

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Author contributions

P.F.R. proposed the paper's main concept, designed the numerical experiments and wrote the bulk of the paper. R.D.M. provided the palaeogeographic reconstruction, contributed to the interpretation of the results and the writing of the paper.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at http://npg.nature.com/reprintsandpermissions. Correspondence and requests for materials should be addressed to P.F.R.