Vol 448|26 July 2007|doi:10.1038/nature06035

LETTERS

Variation in styles of rifting in the Gulf of California

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Constraints on the structure of rifted continental margins and the magmatism resulting from such rifting can help refine our understanding of the strength of the lithosphere, the state of the underlying mantle and the transition from rifting to seafloor spreading. An important structural classification of rifts is by width[1], with narrow rifts thought to form as necking instabilities[2] (where extension rates outpace thermal diffusion[3]) and wide rifts thought to require a mechanism to inhibit localization, such as lower-crustal flow in high heat-flow settings[1,4]. Observations of the magmatism that results from rifting range from volcanic margins with two to three times the magmatism predicted from melting models[5] to non-volcanic margins with almost no rift or post-rift magmatism. Such variations in magmatic activity are commonly attributed to variations in mantle temperature. Here we describe results from the PESCADOR seismic experiment in the southern Gulf of California and present crustal-scale images across three rift segments. Over short lateral distances, we observe large differences in rifting style and magmatism—from wide rifting with minor synchronous magmatism to narrow rifting in magmatically robust segments. But many of the factors believed to control structural evolution and magmatism during rifting (extension rate, mantle potential temperature and heat flow) tend to vary over larger length scales. We conclude instead that mantle depletion, rather than low mantle temperature, accounts for the observed wide, magma-poor margins, and that mantle fertility and possibly sedimentary insulation, rather than high mantle temperature, account for the observed robust rift and post-rift magmatism.

The Gulf of California is an oblique rift system with short spreading segments connected by long transform faults (Fig. 1)[6]. Rifting in the gulf began ~12–15 million years (Myr) ago when subduction ended west of the Baja California peninsula. As the East Pacific Rise (EPR) approached the palaeo-trench, the subducting Farallón plate broke into a number of microplates; as subduction stalled, those microplates and the Baja California peninsula coupled to the Pacific plate, resulting in the onset of rifting and eventually the modern plate boundary within the Gulf of California in the vicinity of the former arc[7–10]. The peninsula now moves nearly completely with the Pacific plate, with ~48 mm yr^{-1} of spreading across the Gulf of California representing ~92% of Pacific–North America relative motion[11,12]. No shear zones cut across the peninsula south of the Agua Blanca fault (Fig. 1 inset), and the Pacific–North American Euler pole is sufficiently distant that the rift segments of the southern gulf have all experienced the same net extension rate since rifting began.

Previously, little was known about the variation in rifted-margin crustal structure along the gulf, with constraints limited to geologic observations, seafloor bathymetry, gravity transects, sparse seismic refraction measurements[13], and the CORTES-P96 (ref. 14) crustal-scale seismic transect in the northern gulf (Fig. 1). The seafloor expression of rift structure is masked by sediments in much of the gulf, and the considerable variation in sediment thickness, from thick sediments in the north to little sediment input in the south, gives the impression that rift structure varies from narrow in the south to wide in the north. This impression is enhanced by the obscuring effect of sediment on the development of seafloor-spreading magnetic lineations[6], such that diagnostic magnetic lineations are only observed across the southernmost segments of the gulf. Our results indicate that a simple north-to-south variation does not exist in the southern gulf, south of Tiburon Island (Fig. 1). Instead, distinct styles of rifting and rift magmatism occur within the southern gulf, and this variation appears to be related to pre-rift magmatic history.

We acquired wide-angle and multi-channel seismic data across the northern Guaymas, Alarcón, and the San José del Cabo to Puerto Vallarta (Cabo–PV) segments of the southern Gulf of California as part of the PESCADOR experiment. Each of these transects was instrumented with ocean-bottom seismometers spaced 10–15 km apart and similarly spaced seismometers on land recording the offshore shots to ~100 km inland. Excellent-quality data from this dense source and receiver coverage enable imaging of detailed crustal structure across these rift segments[15–17] (Fig. 2 and Supplementary Information). Each transect reveals a rifting style that is distinct in terms of structure and magmatism.

The Guaymas basin is a narrow rift[1] segment (a total conjugate-margin width less than 200 km) that has been robustly magmatic since continental break-up. We estimate the location of the continent–ocean transition here from the well-constrained rapid shallowing of the Moho and coincident lateral increase in seismic velocity to ~6.8 km s^{-1}, a value typical of gabbroic composition rock. We interpret the crust seaward of the continent–ocean transitions to be new igneous crust formed at an oceanic spreading centre that accommodated the majority of extension in this segment since lithospheric rupture. The spreading centre has been robustly magmatic, forming new intrusive igneous crust 6–8 km thick, with an additional unknown volume of igneous material intruded into the overlying sediments. The ~280 km width of new igneous crust and spreading rates of ~48 mm yr^{-1} imply that lithospheric rupture occurred ~6 Myr ago. Lithospheric rupture followed at least 70 km of continental extension, the amount estimated across the thinned continental-margin crust of the velocity model. It is likely that the low-lying crust of the coastal plain beyond our transect to the southeast was also extended.

The Alarcón segment is a wide rift. This segment experienced ~350 km of continental extension before the onset of seafloor

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spreading 2–3 Myr ago, which has produced ~135 km of oceanic crust ~6 km thick[15]. The continent–ocean boundary is marked by a sharp transition from a shallowing to a flat Moho below normal-thickness oceanic crust with clearly identifiable magnetic anomalies (Supplementary Fig. 1). In this segment, the transition to seafloor spreading appears to be coincident with the northward propagation of the EPR[6,18]. Earlier, extension localized beneath the Tamayo trough thinned the continental crust there to ~7 km, but left little evidence there or elsewhere within the segment for syn-rift magmatism apart from a layer 250–500 m thick with seismic velocities of 2.5–2.8 km s^{-1}, which overlies basement along much of the transect and may represent volcanic or volcaniclastic strata[15]. The Alarcón segment was thus magma-poor during rifting, suggesting that the underlying 'continental' asthenospheric mantle did not readily melt upon decompression. We speculate that as the EPR propagated northward, dykes sourced from the presumably more fertile EPR asthenospheric mantle ultimately enabled rupturing of the continental lithosphere[19].

The Cabo–PV segment is a narrow rift. The continent–ocean boundary at the western margin is similar to that in Alarcón, juxtaposing EPR-sourced oceanic crust against extended continental crust. In this segment, however, seafloor spreading initiated ~1 Myr before the propagation of the EPR into the gulf ~3.5 Myr ago. The initial spreading centre is preserved in the southeast as the María Magdalena rise[6,20]. The crust produced at the María Magdalena rise was presumably derived from 'continental' asthenosphere and is ~1 km thicker than the crust formed at the EPR. The EPR propagated into the segment along the western continent–ocean boundary, and it is believed that a brief period of coincident spreading at the two spreading centres resulted in convergence along the eastern margin[6]. Estimating pre-rift extension in this segment is thus complicated, but the steep western margin indicates that this is a narrow rift segment (Supplementary Fig. 5). There is little direct evidence of syn-rift magmatism in this segment, but the rapid transition to magmatic seafloor spreading suggests that this segment is neither magma-poor nor magma-rich and that the underlying continental asthenosphere produced melt as would be expected during rifting.

The crustal structure of the Alarcón segment challenges the common notion of how wide[1] rifts (conjugate-margin width >200 km) form. A mechanism of wide-rift formation in which buoyancy-driven lower-crustal flow inhibits localization[1,4] does not apply to this segment, because substantial Moho topography persists to the present. The localized extension beneath the Tamayo trough indicates that the lithosphere resisted rupture even after substantial thinning, suggesting that the lithospheric mantle was strong and that the asthenosphere did not produce sufficient melt to rupture the lithosphere via dyking[19] before the arrival of the presumably more fertile EPR mantle. The adjacent Pescadero and Farallón segments north of Alarcon have rifted-margin morphologies that are similar to Alarcón (Supplementary Fig. 5). These segments differ from Alarcón in that

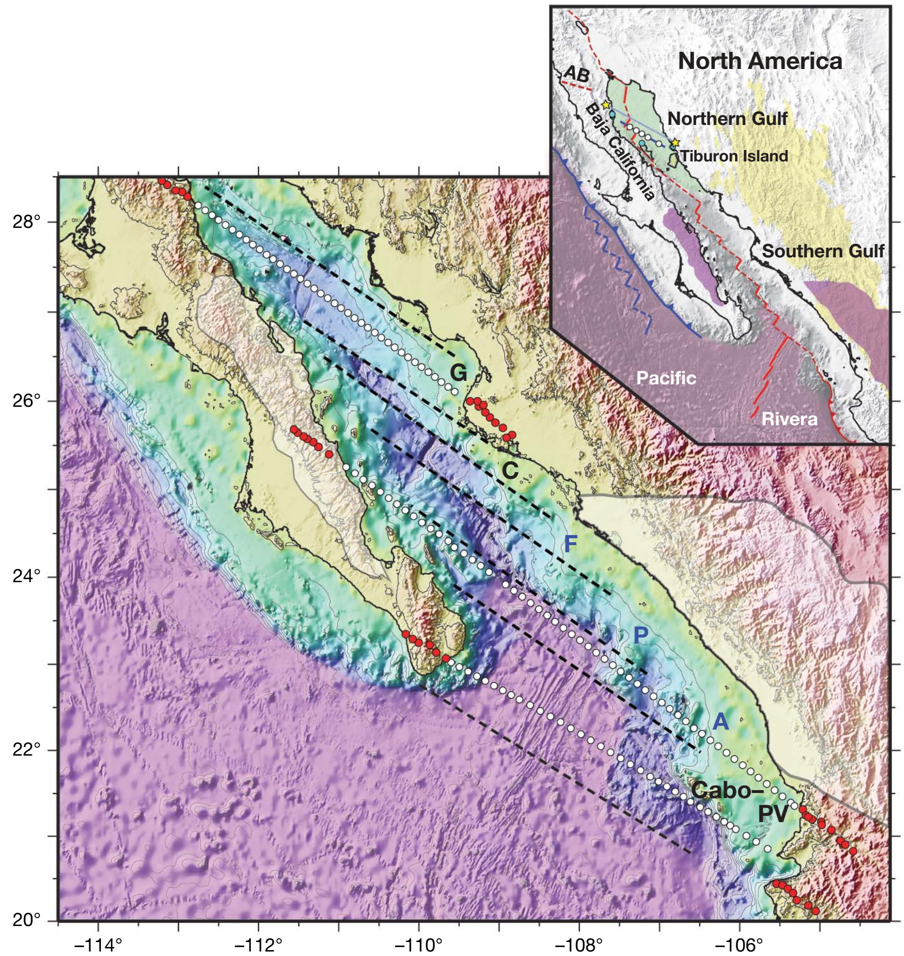

Figure 1 | Map of the PESCADOR experiment in southern Gulf of California. The Guaymas (G), Carmen (C), Farallón (F), Pescadero (P), Alarcón (A) and the San José del Cabo to Puerto Vallarta (Cabo–PV) segments are separated by dashed lines. Blue labels indicate south-central segments, white and red dots are the instrument locations of the three seismic transects, and white shading indicates the extent of early Miocene ignimbrite volcanism[21]. In the inset, green shading denotes the northern gulf and pink shading EPR-sourced crust, and extinct and modern plate boundaries are shown in blue and red. AB, Agua Blanca; white and blue dots, CORTES-P96 (ref. 14) instruments. The geologic constraints on northern gulf spreading[27] is indicated by yellow stars; yellow shading shows the mapped extent[21] of the Oligocene and purple shading indicates early Miocene ignimbrite events.

their spreading centres are defined by narrow bathymetric deeps that indicate only nascent seafloor spreading or none (Supplementary Figs 4–6). This suggests that the EPR mantle has not propagated into them and that these are also magma-poor segments underlain by continental mantle that does not readily melt. We call these wide-rift segments collectively the south-central domain.

The south-central segments rifted over the locus of voluminous early-Miocene ignimbrite volcanism[21] (Fig. 1). This early Miocene event, which followed a more extensive early Oligocene event, deposited 1–2 km of ignimbrite and lava over a wide area and may have left the residual mantle both depleted and dry, reducing its ability to melt and deform[22]. Magmatic depletion of the mantle may thus be a primary factor controlling the evolution of rifting in the south-central domain. The relatively abrupt transition in rift style between the south-central domain and the surrounding segments may be related to the focused magmatism characteristic of volcanic arcs and indicated by their long-lived volcanic centres, which may be manifested in part in the mantle. Alternatively, the triggering mechanism of ignimbrite magmatism, perhaps slab foundering[21], may have been laterally discontinuous. Either situation could enable voluminous arc volcanism to impart depleted mantle signatures that vary over small spatial scales, thus explaining the relatively abrupt variation in rifting style between the south-central domain and the segments to the north and south.

Magmatism within the Guaymas basin is anomalous with respect to the south-central segments and with respect to globally averaged mid-ocean ridge crustal production[23] (~6 km). The average thickness of the plutonic component of new igneous crust (average $V_P = 6.8\ \mathrm{km\ s^{-1}}$) in the northern Guaymas segment is greater than 7 km, and velocities of 4.0–5.5 km $\mathrm{s^{-1}}$ in the overlying 2–3-km-thick layer of sediments and igneous rocks[24] suggest an additional 1 km or more equivalent igneous thickness. It is likely that the southern Guaymas segment, which hosts a basaltic shield volcano[25], is similarly magmatic. It is possible that the underlying mantle here is more fertile and/or hotter than that beneath the south-central domain and the average MORB-source mantle. The mantle may be 'charged'[26] in a similar fashion to how the mantle beneath the south-central domain was charged before the early Miocene ignimbrite event. That ignimbrite event did not extend northward beneath the Guaymas basin, however, and so the inherited fertility/hydration beneath the Guaymas basin has been expressed as ongoing robust magmatism since continental break-up, with this magmatism probably contributing to lithospheric rupture after only moderate extension.

A second factor possibly contributing to the anomalous magmatism in the Guaymas basin may also explain crustal structure within the northern gulf and has implications for sedimented spreading centres and mantle melt extraction generally. The crustal structure of the Delfín–Tiburón segment in the northern gulf[14] is similar to the northern Guaymas segment, with a thick layer (>5 km) of intruded sediments overlying a thick igneous layer with mafic (6.5–6.8 km $\mathrm{s^{-1}}$) seismic velocities. Geologic evidence suggests that ~275 km of extension has occurred across the Delfín–Tiburón segment between points separated by 300 km (ref. 27; Fig. 1), and so it is likely that most of this extension was accommodated by the creation of new igneous crust. A common feature shared by the Guaymas and Delfín-Tiburón segments, and not shared by the Cabo–PV segment, is a thick sedimentary layer, and we speculate that this sediment blanket may enhance mantle melt extraction. It is unlikely that melt extraction beneath mid-ocean ridges is 100% efficient, and so the global average oceanic crustal thickness probably underestimates the available melt. The thermal structure near mid-ocean ridges may place controls on melt

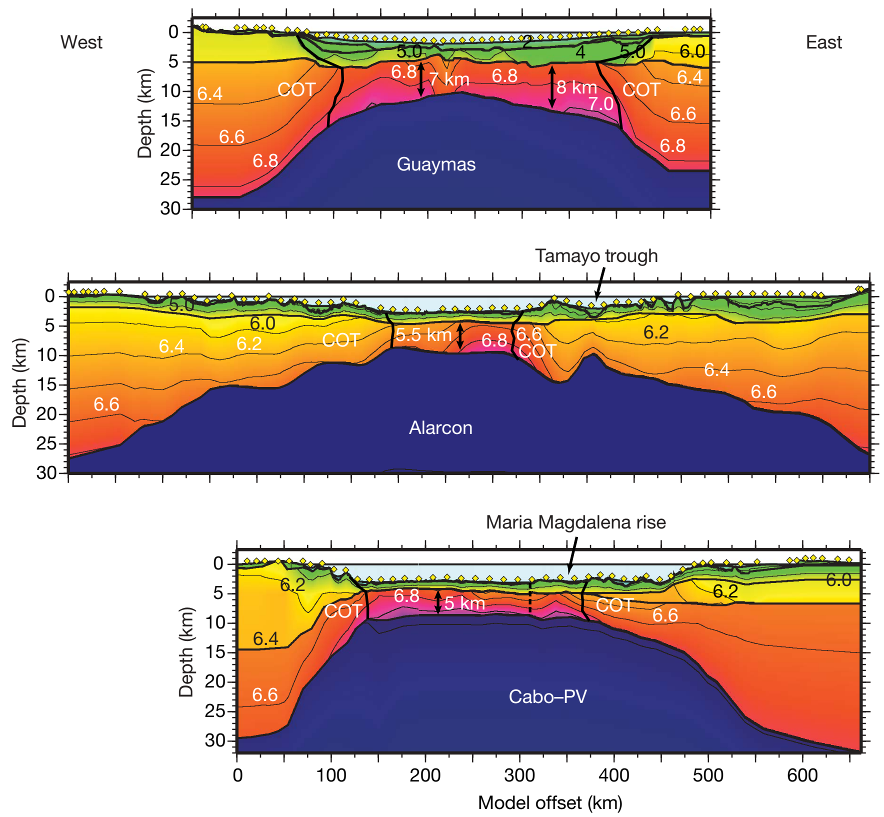

Figure 2 | Models of seismic velocity structure along the Guaymas, Alarcón and the San José del Cabo to Puerto Vallarta transects of the PESCADOR experiment. Velocity contours are colour-coded and labelled in units of km $\mathrm{s^{-1}}$. Yellow diamonds are the instrument locations. COT indicates the interpreted continent/ocean transition. The dashed line in the Cabo–PV model indicates the interpreted boundary between oceanic crust formed at the María Magdalena Rise and the EPR. Models were determined using a combined forward/inverse travel-time modelling approach[30]. Examples of data are presented in the Supplementary Information.

extraction[28], and hydrothermal circulation is a robust mechanism for enhancing heat flux[29]. It might thus be expected that a thick blanket of sediment, by inhibiting hydrothermal circulation, would enhance melt extraction, resulting in new igneous crust thicker than that at unsedimented mid-ocean ridges.

The results presented here highlight the importance of inherited mantle fertility/hydration and possibly of sediments as controlling parameters of the rifting process. Our primary observations are variations in rift width and magmatism over small spatial scales, with wide, magma-poor rift segments formed over mantle that sourced voluminous pre-rift arc magmatism, and magma-rich segments associated with thick sediments. Many rifts initiate or localize at formerly convergent boundaries in response to ridge subduction, in back-arc settings, or along suture zones following continent–continent collision. Substantial along-strike variations in the expression of rifting, with these variations controlled by pre-rift tectonics and magmatism of the formerly convergent margin, may thus be common along many rifted margins. Similarly, substantial along-strike variability in syn-rift sedimentation is likely in many rifts, depending on topography, climate and regional drainage patterns.

Received 1 February; accepted 18 June 2007.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Acknowledgements We thank the captains and crew of the RV *Maurice Ewing* and RV *New Horizon*, the OBSIP teams, J. Urban, and A. Gorman for his efforts as Chief Scientist on the RV *New Horizon*. The Lamont Earth Observatory Marine Office and CICESE provided support before and during the experiment. This work was funded by a grant from the US NSF-MARGINS programme.

Author Contributions D.L., P.J.U., G.M.K., W.S.H., A.J.H., A.G.-F., J.M.F. and G.J.A. were the principal investigators on this project and each contributed substantially to this work. F.S., P.P. and H.E.B. analysed data from the Alarcón and Cabo–PV segments as portions of their PhD theses. D.L. analysed data from Guaymas and wrote the paper. All authors discussed the results and commented on the manuscript.

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