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Thermal evolution of a sheared continental margin: Insights from the Ballenas transform in Baja California, Mexico

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ABSTRACT

The Ballenas transform margin in central Baja California offers an unparalleled opportunity to study the thermal behaviour of a sheared continental margin during various stages of its evolution. Apatite fission track and (U–Th)/He results from two transects perpendicular to the coast reveal a pronounced latest Pliocene to Pleistocene (~1.8 Ma) heating event related to the Neogene opening of the Gulf of California. Proximity to a regional pre-rift unconformity indicates that samples remained at near-surface levels since Paleogene unroofing, despite having experienced reheating to maximum paleotemperatures within or above the fission track partial annealing zone. In general, maximum paleotemperatures during overprinting decrease from >100–120 °C near the coast to below 60 °C ca. 5–8 km further inland, suggesting lateral heat flow from a source within the Gulf of California. Heat sources related to the structural development of the Ballenas transform fault, located approximately 1.5–4.5 km offshore from the two sample transects, most likely controlled the observed reheating. Overprinting patterns do not support conductive reheating due to reburial, magmatism or frictional shear. Instead, a pronounced thermal spike in between much less overprinted neighbouring samples strongly favours convective heating by hydrothermal fluids as the dominant overprinting process. Hydrothermal activity may be caused by either deep fluid circulation along newly formed shear zones of the transform fault or, more likely, magmatic leaking along the transform fault. Latest Pliocene to Pleistocene (~1.8 Ma) activity on the Ballenas transform fault is closely linked to extension in the Lower and Upper Delfín basins and provides a minimum age for the structural reorganisation and the relocation of extension in the northern Gulf of California. This study shows that hydrothermal activity can cause significant thermal events in a transform margin before the passage of the spreading centre. Paleotemperatures from the Ballenas transform are similar to those of other transform margins after passage of a spreading centre, which suggests that hydrothermal fluids may have an important thermal buffering effect, moderating the maximum temperatures of the ridge segments near their intersection with a continental transform margin.

1. Introduction

During continental break-up, divergent margins are not only affected by continental extension, but also strike-slip deformation. In intracontinental rift zones, accommodation and transfer zones form important linking structures that result from the heterogeneous distribution of slip on normal faults (e.g. Gibbs, 1984; Rosendahl, 1987; Faulds and Varga, 1998). Following break-up, some of these shear zones may develop into continent–ocean transform faults, before maturing into intra-oceanic transform faults. In accordance with transform fault development, sheared continental margins typically evolve in four stages (Mascle and Blarez, 1987; Sage et al., 2000) (1) early intracontinental shear; (2) continent to transitional crust faulting; (3) a stage of continent–ocean transform faulting which ends with the passage of a spreading centre; and (4) an inactive phase lacking slip along the former transform fault.

Due to post-rift subsidence, transform margins are often submerged and buried by sediments, rendering them inaccessible for direct geological observations. As a result, much of the understanding of transform continental margins is based on geophysical interpretations and modelling of submerged margins, e.g. the Ivory Coast–Ghana margin in western Africa (Mascle and Blarez, 1987; Sage et al., 2000) or the Southwest Newfoundland margin in eastern Canada (Todd et al., 1988; Reid and Jackson, 1997).

Transform continental margins often develop a characteristic basement ridge, but the processes that lead to uplift of the continental crust remain controversial. Two genetic end-members have been invoked: (a) flexural uplift due to tectonic or erosional unroofing (Clift and Lorenzo, 1999; Basile and Allemand, 2002); and (b) thermal uplift driven by conductive and/or advective heating of the continental crust (Todd and Keen, 1989; Reid, 1989; Vågnes, 1997). This thermal uplift

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may be induced by lateral heat conduction across the transform fault (Todd and Keen, 1989; Lorenzo and Vera, 1992), crustal thinning due to viscous coupling across the transform fault (Reid, 1989), or a combination of both (Gadd and Scrutton, 1997; Vågnes, 1997). A common feature of all these models is that heating is most intense during the passage of the oceanic spreading centre. In that case, the time of maximum uplift and erosion of the continental crust should coincide with ridge–transform intersection.

Data from the Ivory Coast–Ghana margin appear to contradict model predictions, because maximum uplift along the margin—inferred from a stratigraphic hiatus—appears to have occurred prior to the passage of the spreading centre (Clift and Lorenzo, 1999; Sage et al., 2000). Yet, several low-temperature techniques reveal a distinct heating event at around the same time as ridge–transform intersection (Bouillin et al., 1997; Bouillin et al., 1998; Holmes, 1998; Lespinasse et al., 1998). Large uncertainties in both the age of thermal overprinting and the passage of the spreading centre however, has made it difficult to address the issue of reheating at the Ivory Coast–Ghana margin.

The Ballenas transform fault extends for more than 340 km along the coast of central Baja California (Fig. 1A) and presents an unparaleled opportunity to investigate the thermal evolution of a transform continental margin, because of its youthful stage and excellent exposure. In a setting where the amount of denudation is constrained by

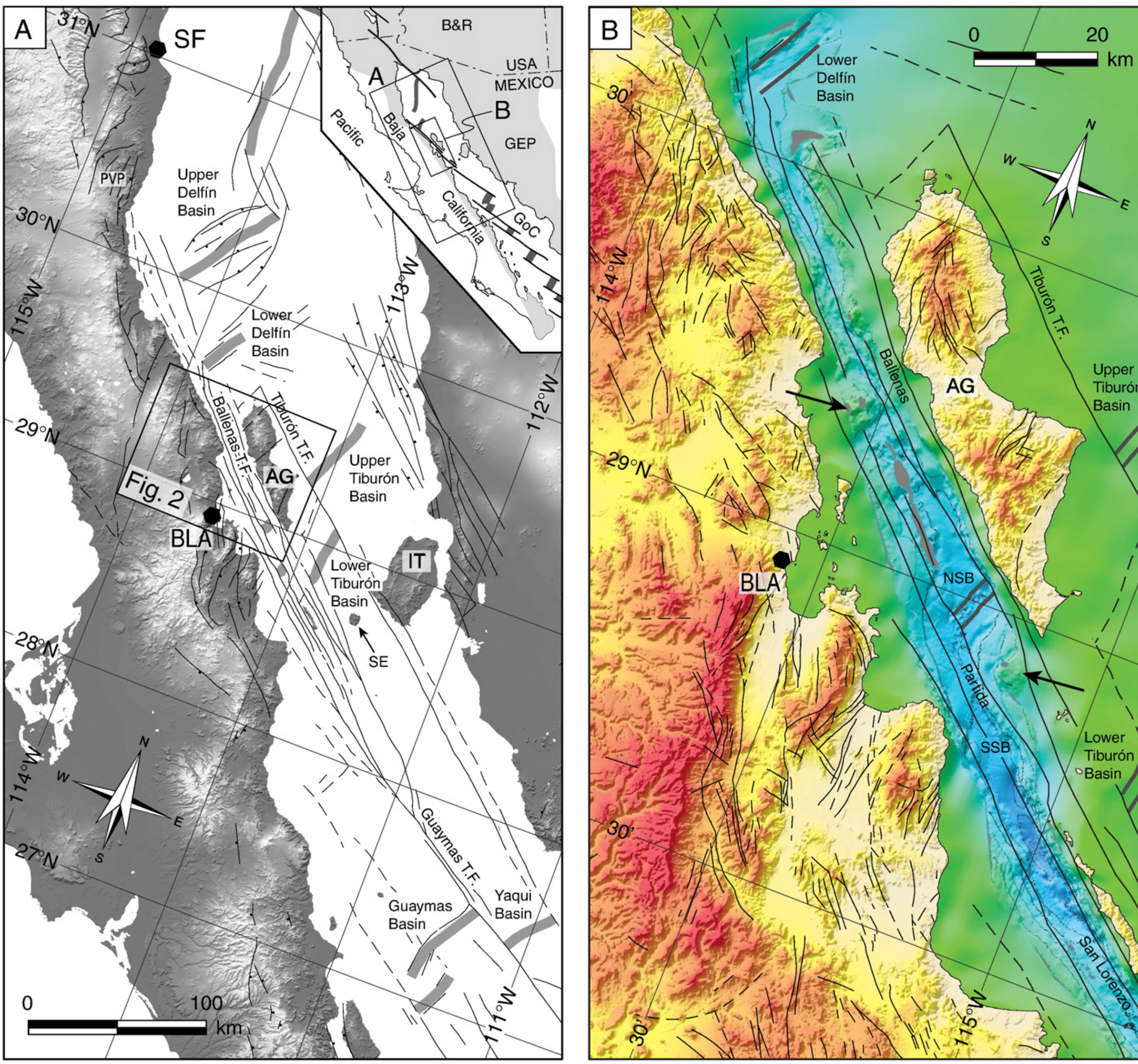

Fig. 1. (A) Location map and shaded DEM of central Baja California showing the main structural features (modified after Fenby and Gastil, 1991; Aragón-Arreola and Martín-Barajas, 2007; Seiler et al., submitted for publication) of central Baja California and the northern Gulf of California. To the north and south of the study area (black outlined box), the Gulf Extensional Province exhibits a basin and range physiography that is separated from the stable central and western portion of Baja California by the Main Gulf Escarpment, the breakaway fault of rifting. Within the study area, the topographic expression is much more subdued, and major rift-related structures are lacking. (B) Multibeam bathymetry (collected on the 2003 DANA research cruise by P. Lonsdale, J. Fletcher and J. Ledesma) with shaded DEM and main structural features (modified after Gastil et al., 1975; Fenby and Gastil, 1991) of the Ballenas transform margin. Black arrows point to the two conjugate NE-trending marginal ridges that bound the ~40 km long North Salsipuedes basin. AG = Isla Ángel de la Guarda, BLA = Bahía de Los Ángeles, B&R = Basin and Range Province, GEP = Gulf Extensional Province, GoC = Gulf of California, IT = Isla Tiburón, NSB = North Salsipuedes basin, PVP = Puertecitos Volcanic Province, SE = Isla San Esteban, SF = San Felipe, SSB = South Salsipuedes basin.