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Influence of Peruvian flat-subduction dynamics on the evolution of western Amazonia

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ABSTRACT

Convection in the Earth's mantle is mainly driven by cold, dense subducting slabs, but relatively little is known about how 3D variations in slab morphology and buoyancy affect mantle flow or how the surface above deforms in response (i.e. dynamic topography). We investigate this problem by studying the dynamics of an active region of flat-slab subduction located in Peru in South America. Here the slab geometry is well known, based on the regional seismicity, and we have observations from the local geological record to validate our models. Of particular interest is the widespread subsidence and deposition of the Solimões Formation across western Amazonia that coincided with the development of the Peruvian flat-slab during the Mid-Late Miocene. This formation covers an extensive area from the foredeep to the Purus Arch located ∼2000 km away from the trench. Close to the Andes the preservation of several kilometers of sedimentary thicknesses can be easily accounted for by flexure. Based on an estimate of the Andean loading we predict 2.8 to 3.6 km of accommodation space that spans 100 km. The spatial and temporal history of the Solimões Formation however, particularly the thick distal foreland accumulations up to 1.2 km deep, can only be matched with the addition of a longer-wavelength dynamic source of topography. Following the transition from normal to flat subduction, we predict over 1 km of dynamic subsidence (∼1500 km wide) that propagates over 1000 km away from the trench, tracking the subduction leading edge. This is followed by a pulse of dynamic uplift over the flat segment behind it. We therefore propose that a combination of uplift, flexure and dynamic topography during slab flattening in Peru is responsible for the sedimentation history and landscape evolution of western Amazonia that eventually led to the configuration of the Amazon Drainage Basin we know today.

1. Introduction

Subducting slabs represent the primary buoyancy force in Earth's mantle and a critical source of surface deformation via their coupling to the overriding plate. Yet the impact of variations in slab morphology and buoyancy (e.g. slab tears or the subduction of oceanic plateaus) on the dynamics of the mantle and how the upper plate deforms in response are poorly understood. The importance of such along strike variability in subduction models is however becoming increasingly apparent (e.g. Guillaume et al., 2009; Dávila and Lithgow-Bertelloni, 2013; Capitanio and Faccenda, 2012; Jadamec et al., 2013). Of particular concern are episodes of "flat" or "shallow" subduction that represent 10% of subduction zones worldwide today (Gutscher et al., 2000b), and often invoked to account for widespread deformation in continental interiors, such as for the western US during the Laramide orogeny (Dickinson and Snyder, 1978; Bird, 1988).

1.1. Tectonic and geological setting

The Peruvian subduction zone presents itself as an excellent modern-day natural laboratory to study the interaction between this flat-subduction and surface deformation. Extending over 1500 km along strike, the Peruvian flat-slab segment (3°S to 15°S) is by far the most extensive region of flat subduction in the world (Fig. 1). The slab subducts at a normal dip (∼40°) to a depth of around 100 km, most likely directly beneath the overriding continental lithosphere, and travels horizontally for several hundred kilometers before steepening again to the east (Cahill and Isacks, 1992; Phillips and Clayton, 2014). The region is characterized by a distinct lack of contemporary arc volcanism and low heat

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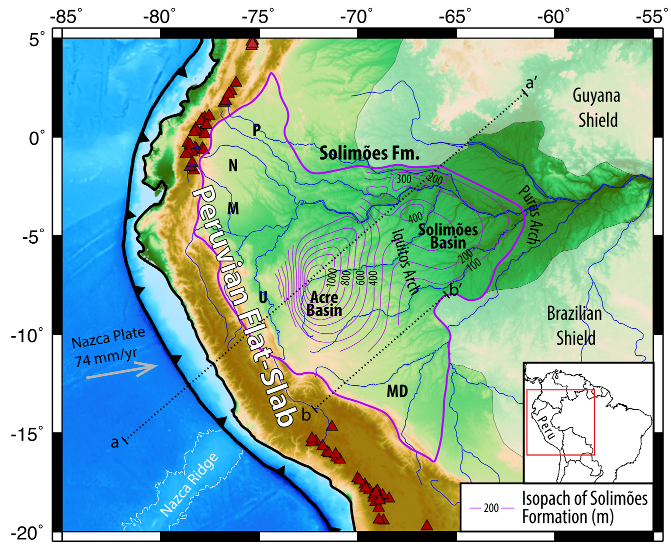

Fig. 1. Tectonic setting of Peruvian flat-slab subduction and western Amazonia. The inset map highlights the study location and political boundaries for context. The total area thought to be covered by the Solimões Formation is outlined by the thick purple line, based on the maps of Hoorn (1994). This includes many different individual basins such as the Acre and the Solimões, as well as other foreland basins represented by the letters (P: Putumayo, N: Napo, M: Marañon, U: Ucayali, MD: Madre de Dios). Isopachs of the Solimões Formation thickness in the Acre and Solimões Basins are available and shown in purple after Latrubesse et al. (2010). Volcano locations (red triangles) are from Siebert and Simkin (2002). The gray arrow represents the absolute plate motion of the Nazca plate from HS3-NUVEL1A (Gripp and Gordon, 2002). The dotted black lines represent locations of cross-sections in Fig. 3(a–a′) and location of the flexural calculation in Fig. 4(b–b′). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

flow (∼20 mW/m^2) (Henry and Pollack, 1988), in contrast to the normally dipping (∼30°) regions to the north and south.

Subduction has been operating along the western coast of Peru since at least the Jurassic (Martinod et al., 2010), with the present plate configuration stable since 23 Ma, following the formation of the Nazca and Cocos plates (Lonsdale, 2005). The presence of the Peruvian flat-slab is however relatively recent in comparison. Although the precise date is unclear and is still a matter of debate, slab flattening is likely to have started around the Mid to Late Miocene (Bissig et al., 2008; Ramos and Folguera, 2009) around the time when the Nazca Ridge first reached the trench (∼11–15 Ma: Hampel, 2002; Rosenbaum et al., 2005) and the pattern of arc volcanism began to change (Aleman, 2006; Bissig et al., 2008). Full flat-slab development is likely a long process that can last from several to 10 Myr (Arrial and Billen, 2013; Espurt et al., 2008; Martinod et al., 2010; van Hunen et al., 2002a, 2002b). The various stages of progression include broadening of the volcanic arc and crustal deformation, adakitic magmatism, thinning and cooling of the asthenospheric wedge resulting in a decline and eventual cessation of volcanic activity (Gutscher et al., 2000a). Over central Peru there is evidence that the arc broadened around 11–12 Ma (Aleman, 2006; Bissig et al., 2008; Ramos and Folguera, 2009), that adakites formed 3–6 Ma (Gutscher et al., 2000a) and that magmatic activity ended by 3–4 Ma (Soler and Bonhomme, 1990; Rosenbaum et al., 2005; Pilger, 1981; Espurt et al., 2008; Martinod et al., 2010).

Whilst shallow subduction was beginning to take hold beneath Peru, the surface above was also going through its own transformation. Eventually this transformation would lead to the development of the largest drainage basin in the world, the Amazon River system, and the most diverse habitat on the planet, the Amazon Rainforest. Initially, during the Early-Mid Miocene, it has been suggested that regional drainage of Amazonia escaped towards the north into the Caribbean Sea (e.g. Hoorn et al., 1995), or exited towards the west through the Guayaquil gap into the Pacific Ocean (e.g. Potter, 1997), as the Andes had not yet grown into a full orogenic barrier. During the Late Miocene however, the northern Andes rose rapidly, shutting off drainage pathways to the north and west, and deepening and broadening the foreland basins to the east (Jordan and Gardeweg, 1989; Kroonenberg et al., 1990; Hoorn et al., 1995, 2010a, 2010b; Nobret et al., 1996; Garzione et al., 2006). At the same time, a wide but relatively shallow subsiding system developed in western Amazonia, from eastern Peru to the Purus Arch (Fig. 1), represented by the Solimões/Pebas Formation (Hoorn, 1993, 1994; Campbell et al., 2006; Wesselingh et al., 2006b; Gross et al., 2011; Latrubesse et al., 2010; Rodrigues Nogueira et al., 2013). Deposition of this Solimões Formation ceased in the Mio-Pliocene, as the accumulation rate of terrigeneous material on the offshore Amazon fan increased dramatically (Dobson et al., 2001; Latrubesse et al., 2010). This indicated a switch in the destination of the bulk of Andean derived sediment, from deposition in the western Amazonian basins, to large-scale transportation across the continent via a fully fledged Amazon River to the Atlantic margin (Campbell et al., 2006; Figueiredo et al., 2009; Latrubesse et al., 2010).

At the time of deposition, the Solimões Formation recorded a wide area of subsidence that resulted in simultaneous partial infilling of many different pre-existing sub-basins in the western Amazonian region (labeled in Fig. 1), both foreland (e.g. Madre de Dios) and intra-cratonic (e.g. Solimões) (Hoorn, 1994). The E–W trending series of Acre, Solimões, and Amazonas basins overlie the Amazonian Craton subdividing the craton's exposure at the surface into the northern Guyana and southern Brazilian Shields (Fig. 1), the result of an extensional event during the Mid-Proterozoic (Wanderley-Filho et al., 2010). Following on during the Late-Proterozoic some of the original extensional grabens were positively inverted to form basement arches which now separate the individual sub-basins, for example the Purus Arch which partitions the Solimões basin from the Amazonas basin and is the eastern limit of the Solimões Formation, was an inversion of the Cachimbo Graben (Wanderley-Filho and Costa, 1991). These Precambrian structural highs have therefore played an important role in sub-division and configuration of sedimentary deposits across western Amazonia ever since.

1.2. Sources of topography and their effect upon the landscape

The evolving landscape and drainage of lowland Amazonia has typically been attributed to interaction of climate, sea level and the developing Andean mountain belt. In particular the intense period of uplift during the Miocene is thought to have increased erosional rates, sediment fluxes, and the deformation of inland Amazonia via flexural processes (Hoorn et al., 1995, 2010a, 2010b; Figueiredo et al., 2009; Mora et al., 2010; Latrubesse et al., 2010). Overall most of the hypotheses for how Andean loading and flexural subsidence initiated widespread deposition of the Solimões Formation are generally qualitative in nature, and, as far as we are aware, no detailed flexural calculations have yet been made to demonstrate such extensive subsidence. Given that the Solimões Formation extends considerably far inland (as far east as the Purus Arch, ∼2000 km from the trench), affecting the pericratonic foreland, such as the Solimões Basin (Fig. 1), additional explanations for such a broad episode of subsidence are warranted. The concurrent relationship between basin development and drainage reorganization with the arrival of the Peruvian flat-slab has been noted previously (e.g. Latrubesse et al., 2010), but only isostatic or flexural influences associated with plate interactions during flat-subduction were considered (i.e. rapid uplift of the Eastern Cordillera and