Forum

How does the Nazca Ridge subduction influence the modern Amazonian foreland basin?: COMMENT and REPLY

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In a recent contribution to *Geology*, Espurt et al. (2007) advanced a new model to explain the presence of a major structural high, the Fitzcarrald Arch, in the Amazonian foreland basin. This model implies much greater coupling between subducting and overriding plates than previously suspected, and has implications for the tectonics of active margins far from the trench. In Espurt et al.'s interpretation, the presence of the Fitzcarrald Arch can be related to subduction of the buoyant Nazca Ridge in the presence of flat-slab subduction. However, evidence from the Andes and other active margins worldwide indicates that their model is unlikely to be correct.

The Fitzcarrald Arch is 650 m high and extends ~750 km from the trench. This degree of relative uplift is at odds with the general observation that in ridge-trench collision zones temporary uplift is high in the outer forearc but decreases rapidly landward. The vertical tectonic response to Nazca Ridge collision is well known from studies of multichannel seismic profiles and Ocean Drilling Program (ODP) drill sites from the Lima Basin, Peru. These data suggested up to 3 km of uplift close to the trench during the initial collision ~11 Ma, but this value decreased rapidly onshore (Clift et al., 2003). ODP Site 679 showed that the shelf was uplifted by <400 m, and possibly as little as 200 m, during ridge subduction. This value was attained ~130 km from the trench axis, much closer than proposed for the Fitzcarrald Arch.

Constraints are also available from the onshore sedimentary sequences of the Pisco Basin, which presently overlies the crest of the subducting ridge. A backstripped analysis of the stratigraphy and terracing of the coastal zone, aimed at isolating the tectonic component of uplift in the collision area, indicates only ~120 m of post–2 Ma uplift ~160 km from the trench (Clift and Hartley, 2007). Furthermore, the fact that similar Pleistocene uplift is seen along much of the northern Andean margin suggests that much of that value is not linked to ridge subduction. Comparison with other arc-ridge collisions supports the idea that the temporary uplift does not extend far landward from the trench. In Costa Rica, subduction of Cocos Ridge deforms the forearc, but onshore uplift is minimal (Vannucchi et al., 2006). On the Andean margin, collision with the Juan Fernandez and Iquique ridges results in dramatic uplift of the outer forearc regions, but little vertical motion onshore or even in the coastal zones (Laursen et al., 2002; von Huene and Ranero, 2003). As in the Nazca Ridge subduction, these regions are also affected by flat-slab subduction.

Espurt et al. used an orogen-parallel seismic line to argue that the Fitzcarrald Arch was not formed by thrust faulting and is tectonically inactive. However, an across-strike seismic profile would be needed to exclude thrust faulting as a mechanism, and this is suggested by both shallow (<70 km) earthquakes (Engdahl et al., 1998) and a tilted fault block topography. Espurt et al. noted that the southern arch is characterized by radial drainage networks. However, the Subandean zones and Eastern Cordillera also exhibit congruent geomorphological patterns with NW-SE–oriented promontories. Indeed any topographic profile in the eastern Andes between 12°S and 13.5°S would yield a similar pattern to the Fitzcarrald Arch, suggesting a common mechanism for the uplift of the whole region. Marques and Cobbold (2006) modeled the effects of tectonic indenters as causing transfer zones to develop along indenter sides. The eastern Andes can be considered as an intender into the Amazon foreland (Carlotto, 1998), with its core located in the Eastern Cordillera. The area of the Fitzcarrald Arch marks a change in orogenic strike from NNW-SSE to NW-SE going south, and is a large-scale transfer zone, which could have generated arch uplift. Additional mechanisms also contributing to uplift include differential erosion, shear stress along the subduction zone, and inherited heterogeneities from a Permo-Triassic rift. Espurt et al. reported that the Neogene is partially eroded between the Mashansha and Panguana drill sites. We note that this eroded region closely overlies a Paleozoic structure with similar orientation. Reactivation of these structures is the most likely cause of uplift and active tectonism in the arch. Although it is not yet clear what processes control Andean morphology south of the Fitzcarrald Arch, it seems unlikely to be subduction of the Nazca Ridge.

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In their Comment of our *Geology* paper (Espurt et al., 2007), Clift and Ruiz (2008) argue that: 1) the flat-slab subduction of the Nazca Ridge is unlikely to have produced uplift of the Fitzcarrald Arch in the Amazonian retroforeland basin (using geologic data from the forearc area); 2) tectonic indentation, differential erosion, shear stress along the subduction zone, or inherited heterogeneities from a Permo-Triassic rift could also contribute to the uplift of the Fitzcarrald Arch; and 3) thrust reactivation of Paleozoic structures would be the "most likely cause of uplift and active tectonism in the Arch."

Clift and Ruiz suggest that the observed uplift in the ridge-collision zone is temporarily "high in the outer forearc, but decreases rapidly landward" and refer to several works from the forearc zone (see references in Clift and Ruiz). Clift et al. (2003) deal with the tectonic erosion of the Peruvian forearc by subduction of the Nazca Ridge in the Lima basin. From seismic reflection and well data coupled with age and paleowater depth, Clift et al. (2003) showed that the effects of the Nazca Ridge have been predominant near the trench (tectonic erosion of ~3 km), but decrease rapidly onshore (~130 km from the trench axis). In a recent study, Clift and Hartley (2007) present data from above the present-day Nazca Ridge segment (Pisco basin) from backstripped analysis and coastal morphology that shows small Pleistocene uplift (~120 m) at ~160 km from the trench. Similar observations are found in the northern and central Chilean forearc and in the Costa Rica forearc. Nevertheless, we would like to clarify that the geodynamic setting of the Peruvian forearc zone is not comparable to that of the Amazonian retroforeland basin. The Peruvian forearc basin is situated above the "normal" 30°-dipping portion of the Nazca plate (Gutscher et al., 1999), and this is the case for the other forearc basins cited by Ruiz and Clift. Uplift decrease coincides with the end of the "normally" dipping slab, which becomes horizontal below the continental lithosphere at ~150 km from the trench, and these studies do not deal with the effect of the ridge subduction within the Andes and associated retro-basins. Several authors have pointed out the imprints of the Nazca Ridge flat subduction in the Andean Cordillera. For example, McNulty and Farber (2002) emphasized recent extensional collapse in relation to the Nazca Ridge flat subduction, and Rousse et al. (2003) have demonstrated through paleomagnetic studies that Neogene counterclockwise rotations in the Eastern Cordillera were a result of the southward migration of the Nazca Ridge.

Clift and Ruiz also argue that the Fitzcarrald Arch is related to the "eastern Andes" indenter on the basis of Marques and Cobbold's (2006) model experiments. In fact, Marques and Cobbold's models deal with the development of tectonic salients—acting as indenters—as a function of local elevation, inducing transfer zone in the foreland. A simple examination of the tectonic map (see our Figure 2A in Espurt et al., 2007) reveals that the regional Fitzcarrald Arch uplift is precisely situated in a re-entrant and cannot be interpreted in any way as formed in front of an indenter.

Clift and Ruiz suggest that a transversal E-W cross section is needed to exclude thrust faulting as a mechanism to produce the uplift of the Fitzcarrald Arch. Unfortunately, such data are not yet available in the area. Perhaps we were not clear enough; the synthetic NW-SE profile of the Fitzcarrald Arch shows Paleozoic structures incorporated in the regional bulge (see our Figure 3 in Espurt et al.). These structures are unconformably overlain by undeformed Cretaceous strata which preclude reactivation of the Paleozoic structures. Reactivated Paleozoic structures are effectively observed in the Amazonian foreland basin, but they are localized to the north of the Fitzcarrald Arch uplift (see our Figure 2A in Espurt et al.). In any event, it should be stressed that the Fitzcarrald Arch regional arch is a large-scale, very low amplitude (~500 m), large half-wavelength (>500 km) bulge, one order of magnitude greater than the structures observed in the Eastern Cordillera, and we are not aware of such large and very low amplitude bulges formed by thrust-related processes anywhere in the world.

Finally, the argument for the horizontal reconstruction of the eastward continuation of the Nazca Ridge beneath the South American lithosphere is based on a seismic gap observed at the Subandes-Amazonian foreland boundary (Gutscher et al., 1999; Hampel, 2002). A cluster of deep (~660 km) seismic events are recorded beneath the Brazilian part of the Fitzcarrald Arch but are concerned with subduction processes at the upper/lower mantle interface (Okal and Bina, 1994). Therefore, no evidence of a crustal seismicity, which may correlate the tectonic reactivation postulated by Clift and Ruiz, can be found in this area.

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