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A new model for the Hercynian Orogen of Gondwanan France and Iberia: reply

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1. Introduction

We thank Pereira and Silva for their interest in initiating this discussion. In their introductory comments they note the lack of agreement amongst those who have already proposed regional models for the development of the Hercynian Orogen of France and Iberia. We agree that this is so, and it provides an obvious motive for engaging in discussion and putting forward new ideas such as the Shelley and Bossière (2000) model. Pereira and Silva are also correct when they point out that the roles of the dextral Porto–Tomar and sinistral Badajoz–Córdoba Shear Zones in the development of the Orogen are not well established. Indeed, in some models, such as that of Badham (1982, figure 5), there is no recognition of the Porto–Tomar Shear Zone or any of the sinistral movements in Iberia. Nevertheless, as Pereira and Silva point out, most previous workers have recognised that these are important shear zones and kinematic indicators which must be incorporated in any geodynamic model for the Hercynian Orogen.

2. The nature of the Badajoz–Córdoba Shear Zone

Pereira and Silva are concerned that we omitted reference to a lot of the literature on the Badajoz–Córdoba Shear Zone. We apologise if that seems to be the case, but we do not agree that we have not fairly summarised the main characteristics of the shear zone. Thus, we noted (Shelley and Bossière, 2000, p. 767) that the zone was considered by some workers (e.g. Abalos, 1992) to be a Late Proterozoic Cadomian (Pan-African) structure, reactivated or overprinted by Hercynian shearing, exactly as Pereira and Silva propose in their discussion. We also made reference to the Lower Paleozoic extensional events and related magmatism (pp. 767–768), though we did not discuss that in the particular context of the Badajoz–Córdoba Shear Zone. We are aware, from the literature, that the relative importance of these various events, from the Pre-Cambrian through the Carboniferous, is controversial (Abalos et al., 1993; Azor et al., 1993), and some of the differences of opinion were clearly expressed at a recent international conference in Galicia (Díaz García et al., 2000).

If we are to understand completely the development of the Hercynian Orogen, it is obviously important to determine to what extent the disparate stratigraphies in the region of the Badajoz–Córdoba Shear Zone are a consequence of Pre-Cambrian rather than Hercynian terrane movements and deformation. However, it was never the purpose of the Shelley and Bossière (2000) paper to resolve all the detailed geological problems that remain in France and Iberia. That would have been unrealistic. The reality is that the subject will progress by a combination of broad-brush regional models, such as ours, and the detailed work of the geologist on the ground in the various parts of the region. If, as Pereira and Silva suggest, the Badajoz–Córdoba Shear Zone is in a setting which is fundamentally a Cadomian suture zone, and if the major disparities in geology relate primarily to Cadomian events, then it is easier to support our model in which the Badajoz–Córdoba Shear Zone is not a site of mega Hercynian displacement.

3. The relationship between the sinistral Badajoz–Córdoba and dextral Porto–Tomar Shear Zones

Pereira and Silva assert that the dextral Porto–Tomar Shear Zone is simply a late Hercynian feature, and that it cross-cuts and is later than the Badajoz–Córdoba Shear Zone. It is on this matter that we cannot agree, and we are puzzled that Pereira and Silva omit reference to the observations of Dias and Ribeiro (1993, 1995), which show that both the Porto–Tomar and Badajoz–Córdoba Shear Zones were active in the late Devonian and Carboniferous,

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observations at odds with the assertion of Pereira and Silva. If Dias and Ribeiro (1993, 1995) are correct, the geometrical relationship between the two shear zones is analogous to C and S planes. This demands a greater strain along the dextral shear, and relatively small displacements, of bookshelf type, along the sinistral shears, such as the Badajoz–Córdoba Shear Zone. In this context, we note that Ribeiro et al. (1995, p. 179) concluded "…the main sense of rotation in the Variscan Fold Belt is dextral and the sinistral sense of shear in the Iberian side of the Cantabrian indenter is of local significance, and antithetic to the main sense".

To support their assertion, Pereira and Silva note that mylonitic rocks of the sinistral Badajoz–Córdoba Shear Zone are cut by the Martinchel–Tramagal Granite, and that the granite is then deformed by the dextral Porto–Tomar Shear Zone. But this does not prove that the Porto–Tomar Shear Zone is simply later than the Badajoz–Córdoba Shear Zone. All it tells us is that at this locality, the Porto–Tomar Shear Zone continued its movement after this particular granite was intruded. Similarly, the work of Ribeiro et al. (1980) does not prove that the Porto–Tomar Shear Zone is simply later. In fact, if the two shear zones were simultaneously active, in a regional sense, one can expect and predict the cross-cutting relationships described by Pereira and Silva. Thus, drawing further analogy with smaller-scale strain partitioning structures, C planes in CS mylonites often appear to be later than S planes, and high strain zones tend to grow and encroach on lower strain zones as deformation proceeds (e.g. Bell et al., 1986). The observation of Pereira and Silva, that the Porto–Tomar Shear Zone appears to cross-cut and be later than the Badajoz–Córdoba Shear Zone is, in fact, not at odds with their contemporaneity.

4. The relationship between the Badajoz–Córdoba and Porto–Tomar Shear Zones and various tectonic models for the Orogen

Contemporaneous movement along the two shear zones is a requirement of the indentor model (Matte and Ribeiro, 1975; Matte, 1986) in which the Porto–Tomar and Badajoz–Córdoba Shear Zones act together to form an escape structure during the Hercynian Orogeny. However, there are several major differences between the indentor and Shelley and Bossière (2000) models.

First, we envisage a direct link between the Porto–Tomar Shear Zone and the Armorican dextral shear zones. The indentor model connects the sinistral shears of Iberia, such as the Badajoz–Córdoba Shear Zone, with the dextral Armorican shears.

Second, we propose a total of several thousand kilometres of movement along the dextral shears, very much greater than that required in the indentor model. A question is, how much of this movement could have taken place along the Porto–Tomar Shear Zone? In Armorica, there are several dextral shear zones along which the total displacement might have been distributed. In Iberia, could it be that there are other shear zones, no longer exposed, perhaps off-shore, which run along the west coast of the peninsula? In any case, it is clear that the Porto–Tomar Shear Zone is very important. Ribeiro et al. (1980) reported the width of the zone as approximately 4 km. They analysed the ductile strain within the shear zone, and suggested it represents a minimum 60–83 km of movement. They suggested if one takes brittle discontinuous deformation into account, the total movement might be 100 km. However, it is clear these measurements are minima. As noted by Tikoff et al. (1999), translation may be the dominant component of a deformation even though this cannot be measured by finite strain analysis, and translation is often the most difficult of the components of a deformation to quantify. By way of comparison with the Porto–Tomar Shear Zone, we note that the shear zone of the Alpine Fault of New Zealand, which has a well established minimum displacement of around 500 km, is only of the order of 1 km (Sibson et al., 1979).

Third, we suggested that much of the bending to form the Ibero–Armorican Arc resulted from the wrapping of the dextral shear zones around an Iberian indentor. This is not simply an equivalent or mirror image statement of the indentor model. In our model, the shear zones predate the formation of the arc, whereas in the indentor model, the shear zones formed at the same time as indentation. Again, the observations of Dias and Ribeiro (1993, 1995) are crucial, because they prescribe a Devono–Carboniferous date for the shear zones, predating the formation of many of the folds and thrusts in the Ibero–Armorican Arc, and the bending of the arc, which, according to the latest work of Weil et al. (2000) and Kollmeier et al. (2000) in Cantabria–Asturias, took place in the late Carboniferous and Permian, respectively.

The new work of Weil et al. (2000) and Kollmeier et al. (2000), based on paleomagnetism and stress–strain axis directions from calcite twins in Cantabria–Asturias, suggests that a linear N–S belt related to E–W shortening (in present day coordinates for Spain) formed in the late Carboniferous, and that curving of the arc was the result of N–S shortening in the Permian. This work gives no support to the indentor model for the Ibero–Armorican Arc. Sinistral faults such as the Badajoz–Córdoba Shear Zone are much too early to be related to Permian indentation, and the N–S shortening direction determined by Weil et al. (2000) and Kollmeier et al. (2000) is at a high angle to the ESE–WNW (in present day coordinates) shortening direction of the indentor model.

The change from E–W to N–S shortening during the course of the orogeny is consistent with our model that the dextral shears of Iberia and Armorica were linked, ran NE–SW, and were later bent to form the Ibero–Armorican Arc. It may, however, be necessary to remove altogether the idea of an indentor from the model. It seems from the latest work referred to above that the bending of the earlier Devono–Carboniferous shear zones does not require it.

Interestingly, in Armorica, it has long been suggested that the shortening direction rotated from E–W towards N–S from the Devonian through the Carboniferous (Rolet et al., 1994). In much of Armorica, the orogenic belt is dominated by dextral shear zones which extend to great lithospheric depths (Granet, 1999; Judenherc et al., 1999; Judenherc et al., 2000), and thrusting is relatively unimportant. Nevertheless, late thrusting affects Namurian Coal Basins in the Ancenis area (Diot and Blaise, 1978; Marchand et al., 1988), for example, and the thrusting from north to south here could be related to the clockwise swing in compression direction.

In summary, we believe the geometrical relationship between the dextral Porto–Tomar and sinistral Badajoz–Córdoba Shear Zones, and their contemporaneity, indicate the greater importance of the dextral movement. If the early E–W shortening demonstrated in Cantabria–Asturias by Weil et al. (2000) and Kollmeier et al. (2000) was already operative along the outer margins of Gondwana, in the late Devonian, it would be consistent with our proposal that the Porto–Tomar Shear Zone is part of a mega shear zone that ran NE–SW or ENE–WSW, linking the Porto–Tomar Shear Zone with the Armorican shear zones. These shear zones were subsequently bent anticlockwise in Iberia and clockwise in France as a result of N–S shortening and the formation of the Ibero–Armorican Arc. In this model, the sinistral Badajoz–Córdoba Shear Zone represents bookshelf-type shear in conjunction with the dextral movement, and its initial orientation, pre Ibero–Armorican Arc formation was probably closer to N–S.

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