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Reply to Discussion on "A new model for the Hercynian Orogen of Gondwanan France and Iberia"

David Shelley[a,*], Gérard Bossière[b]

[a]Department of Geological Sciences, University of Canterbury, Private Bag 4800, Christchurch, New Zealand
[b]Université de Nantes, Laboratoire de Planètologie et Géodynamique (UMR CNRS-6112), BP 92208, 44322 Nantes Cedex 3, France

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We thank Cartier et al. (2002) for their paper which provides a further platform for discussing our model of the Hercynian Orogen. They raise many details which we discuss below. First, we deal with the bigger issues.

1. Plate tectonic setting

Cartier et al. (2002) make no reference to the plate tectonic setting before the Hercynian Orogeny, yet this is a principal ground for our model and speculation about the magnitude of dextral displacements. Kent and Van der Voo (1990), Dalziel et al. (1994), Dalziel (1995), and Torsvik (1998) all suggest Laurentia was tucked into the west of South America in the Devonian. We acknowledge that not everyone accepts that particular plate reconstruction, but if it is correct, it requires the massive dextral displacement of Laurentia against Gondwana during the Hercynian Orogeny. From that one can predict the mega displacements of terranes we suggest in Shelley and Bossière (2000). Further testing of our model is, in effect, a testing of those plate reconstructions.

Cartier et al. (2002) refer to our model as being in line with that of Badham (1982). This is true in that Badham emphasises the importance of transcurrent movements, but it is misleading in that Badham did not link the Armorican Shear Zones with the Porto–Tomar and NW African Shear Zones, and Badham's model lacks the key driving force of the relative movement of Laurentia and Gondwana.

2. Relative timing of dextral movements, thrusting, and other structures

In their conclusions, Cartier et al. (2002) suggest that we did not pay enough attention to polyphase deformation and the timing of deformation. Their assertion that the Armorican Shear Zones in France are simply late dextral structures, cross-cutting most others, is similar to the assertion of Pereira and Silva (2001) that the Porto–Tomar Shear Zone in Iberia is a late structure. Cartier et al. (2002) omitted reference to Shelley and Bossière (2001a), but in that reply to Pereira and Silva (2001) we pointed out that their view is inconsistent with the work of Dias and Ribeiro (1993, 1995) who demonstrated that both the Porto–Tomar and Badajoz–Córdoba Shear Zones were active in the late Devonian and Carboniferous. We also suggested the apparent cross-cutting relationship may be much the same as in CS mylonites, where dominant C planes often seem later than contemporaneous S planes.

With regard to the start of dextral movements in France and Iberia, and the total movement on any one fault or shear zone, Cartier et al. (2002) suggest that it is pure speculation to suggest anything earlier than the syntectonic granites, or a greater displacement than that recorded by those granites. In answer, first, we point out that such speculation is a necessary part of terrane modelling. Second, we must remember that the shear zones extend to depths greater than 100 km, according to Granet (1999), Judenherc et al. (1999, 2002), and Granet et al. (2000), and it seems highly unlikely that such large-scale lithospheric discontinuities can be the product of a 'minor process' such as '40 km displacement', which is what Cartier et al. (2002) insist on. Third, such faults could not be the conduits for granites unless already well developed, at which time we may presume substantial displacement had already occurred. It is not speculation, therefore, to invoke displacement before the syntectonic granites. The only question is: 'how much displacement?'

Cartier et al. (2002) also concluded that we did not pay enough attention to flat-lying foliations and low angle shear zones. Indeed, Cartier et al. (2002) and Faure and Cartier

* Corresponding author. Tel.: +64-3-364-2700; fax: +64-3-364-2769.
E-mail address: d.shelley@geol.canterbury.ac.nz (D. Shelley).

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(1998) have the view that thrust movements and flat-lying foliations are incompatible with contemporaneous transcurrent shearing and the production of vertical foliations. Thus Faure and Cartier (1998) describe both flat-lying and steep foliations in the Lanvaux Terrane, and conclude the flat-lying one predates the steep foliation associated with Carboniferous transcurrent movement. However, it is known that transpressional strains may be partitioned into separate but contemporaneous convergent and transcurrent components, or in other words, separate thrusts and transcurrent faults (Dewey et al., 1998). Thus, the important thrusting in Hercynian France (we referred specifically to Lefort et al., 1997 and Matte, 1998 in Shelley and Bossière, 2000) is not inconsistent with contemporaneous mega dextral shearing. It is also possible for one fault to act in part as a thrust and transcurrent shear zone, and we refer to the Nort-sur-Erdre Fault, which displays both types of movement (Diot and Blaise, 1978; Marchand et al., 1988). In New Zealand, the modern Alpine Fault is a major transcurrent shear zone (at least 500 km displacement), which also accommodates substantial fault normal displacements in the form of thrusting (Norris et al., 1990; Norris and Cooper, 2001).

3. Sinistral transcurrent movement in the Hercynian Orogen

A major concern of Cartier et al. (2002) is that they believe we ignore the reported episodic sinistral transcurrent faulting in Armorica. In fact we do not ignore it, we reject it. Thus, for Ancenis, we reject the sinistral pull-apart model for the reasons given in Bossière and Shelley (2000) and Shelley and Bossière (2000, 2001b). To summarise: the outcrop shape of the Ancenis Culm is secondary, the result of deformation; bedding attitudes, rotated by deformation, support a dextral rather than sinistral pull-apart; the outcrop shape is analogous to a mica-fish in dextrally sheared mylonite; finally, we suggest dextral shearing caused transportation of the Ancenis Terrane as an exotic duplex. For the Mortagne Terrane, in Shelley and Bossière (2000, p. 769) we noted our discomfort with the interpretation of sinistral pull-apart, and since then we have become aware of Román-Berdiel et al. (1997) who show that the Mortagne granites were emplaced during dextral, not sinistral, shearing. In Shelley and Bossière (2000) we concluded that the only evidence of substance for sinistral shearing was that of Cogné et al. (1983) for pre-Hercynian granitoids in the Lanvaux Terrane. This shearing predates, or seems to predate, the dextral shearing in the Hercynian shear zones, and we have three suggestions to explain it. The first is that the sinistral shearing occurred in a setting related to pre-Hercynian tectonism and volcanism offshore from the site of stable Gondwanan shelf sedimentation, and that the Lanvaux Terrane represents a slice of that offshore material. The second is that the shearing is bookshelf type. In our original paper we suggested the sinistral Badajoz–Córdoba Shear Zone in Iberia is a bookshelf structure with respect to the dextral Porto–Tomar Shear Zone, and in Shelley and Bossière (2002) we propose that the sinistral faults in northern Brittany, shown by Rolet et al. (1994, fig. 19(III)), are bookshelf structures that merge with (rather than cross-cut) the dextral North Armorican Shear Zone. Support for this explanation of the Lanvaux shears is found in their orientation, on planes striking 105°, oblique to the 135° strike of the main Hercynian foliation (Cogné et al., 1983). The third possible explanation is inspired by descriptions in Faure and Cartier (1998): granitoids display flat-lying foliations with top-to-the-NW or -SE zones of shear, and upright NW–SE folds rotate the flat-lying foliation into steep attitudes. We suggest shear zones with top-to-the-NW shearing would have become vertical sinistral shear zones on one limb of these folds; top-to-the-SE shear zones would have become sinistral on the other.

We reiterate, therefore, that there is no substantial evidence for episodes of mainly sinistral shearing alternating with mainly dextral shearing during the Hercynian Orogeny.

4. Terminology

Cartier et al. (2002) suggest ‘unit’ rather than ‘terrane’ as the appropriate term for the French fault-bound areas of contrasting geology, but we do not accept that. To quote Rolet (1994): “The Armorican Massif is cross-cut by several major late Carboniferous shear zones which subdivide it into seven geographically distinct zones. Each of these is characterised by its own lithotectonic pile. This explains the striking inhomogeneity of the Armorican Massif…”. This is precisely the context for which the concept of ‘suspect tectonostratigraphic terranes’ was developed (Howell, 1995, p. 90). In contrast, the word ‘unit’ completely fails to connote a setting of fault-bound disparate regions. It is incorrect for Cartier et al. (2002) to state that terrane modelling does not allow consideration of convergent displacements, and that such modelling assumes no links between the terranes. In fact, several Iberian and French terranes expose the Gondwanan shelf sediments and the widespread late Precambrian low-grade sediments affected by Pan African (Cadomian) tectonometamorphic events. However, these elements are so widespread in the region that this is not incompatible with mega displacements. More important are the marked differences between adjacent terranes. In terrane modelling, one considers whether two neighbouring terranes may have developed apart from each other. The answer may sometimes be that they did not.

5. Terrane stratigraphic columns

Cartier et al. (2002) complain that we present the lithostratigraphy of each terrane as a column independently of its neighbours, and that this does not represent the relationship between terranes well. But this is where they miss the point: tectonostratigraphic terranes are, by definition, separated by tectonic breaks, and the essential lithostratigraphic facts for each terrane must be presented first before one can start to discuss the nature of the breaks. Our approach is the standard for terrane geology and, for Armorica, the independent nature of those terranes (or the lithostratigraphic columns) is very well established. We can refer to Rolet (1994) again, and we can refer to the plethora of stratigraphic names established by workers in the field, which are symptomatic of the distinctive characteristics of each terrane. Therefore, we cannot support Cartier et al. (2002) when they suggest an interpretation based on tectonic superpositions can substitute for the clear presentation of those facts.

In the remainder of this discussion we comment on some of the other details raised in the discussion paper. For the Lanvaux Terrane, we accept that granitic activity extends back further in time than we had realised. The dates quoted by Cartier et al. (2002) must actually be revised according to the new constant of 1.42×10^{-11} year^{-1} which would give 572, 490 and 448 Ma. Despite all this, the essential facts have not changed: the Lanvaux Terrane consists of older granitoids, deformed before the Hercynian Orogeny, and lower Paleozoic sediments, different from shelf sediments of neighbouring terranes. We also acknowledge that the St-Georges-sur-Loire Terrane overthrusts the Lanvaux Terrane, and we cannot explain how we described this as the reverse. But, Cartier et al. (2002) are incorrect in stating that we included the St-Julien-de-Vouvantes basin in the Lanvaux Terrane. With regard to the St-Julien-de-Vouvantes rocks, it is interesting to note what Janjou et al. (1998, p. 19) write: "…St-Julien-de-Vouvantes peut être considérée comme une entité lithostructurale à part entière, insérée tectoniquement entre des domaines isopiques originellement éloignés les uns des autres". In other words, this is a distinctive tectonostratigraphic terrane, emplaced tectonically between terranes that originally developed a long way from each other. In essence, this is similar to our interpretation of Ancenis, and accordingly, in our model, St-Julien-de-Vouvantes should be instituted as yet another tectonostratigraphic terrane. Clearly it is more than a Carboniferous intermontane basin that opened up along a major shear zone, an interpretation confirmed by Janjou et al. (1998, p. 46).

Concerning St-Georges-sur-Loire Terrane, we do not agree that our summary statements are inadequate in the context of our paper. We do not dispute the terrane is complex (two units according to Ledru et al. (1986), three according to Lardeux and Cavet (1994)), but the salient point is that it is different from neighbouring terranes.

Concerning the Namurian deposits along the Nort-sur-Erdre Fault, we discuss those in our Ancenis paper (Shelley and Bossière, 2001b), and we do not disagree with what Cartier et al. (2002) write.

Concerning Champtoceaux and its neighbouring terranes, we do not agree that those terranes are 'ambiguous and unsatisfactory'. Although we are responsible for labelling them formally as terranes, the names otherwise are well established, and the names reflect the fact that each terrane is different in some important way. We do not dispute that some structures in this area can be interpreted as nappes (see Section 2, above), but we refer the reader to Sections 2 and 3, above, and Shelley and Bossière (2001b) for our views on the relative timing of these structures.

With regard to Champtoceaux specifically, Cartier et al. (2002) suggest that its very high pressure metamorphism, and the implied subduction and exhumation, weakens the model we propose for the Orogen. In fact, such complexes were the main catalyst for proposing mega displacements. Our joint work started with the high pressure rocks of Ile de Groix (Shelley and Bossière, 1999), part of a terrane that contains oceanic volcanics, subduction complexes, and remnants of volcanic arcs. The terrane's seemingly incompatible juxtaposition against terranes that expose stable shelf sediments of the same age, and display little or no sign of volcanism and tectonism, remains the principal reason for advocating mega displacements. In the case of Champtoceaux, Ballèvre et al. (1994) noted that the terrane consists of thinned continental crust, and we suggested (Shelley and Bossière, 2000) this might represent a fragment of Gondwana that drifted into the Rheic Ocean during Cambro–Ordovician extension and thinning, which got caught up in a subduction zone within the Rheic Ocean, and ultimately became sliced in amongst the Gondwanan shelf terranes during the oblique movement of Laurentia against Gondwana. The recent work of Judenherc et al. (2002) seems to us relevant here, and we quote "…this paper illustrates the complexity of the collage of several continental and oceanic pieces that were accreted during successive stages that led to the Hercynian Range".

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