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WICKHAM AND OXBURGH reply— Matte and Mattauer raise two objections to our interpretation of the Hercynian orogeny in the Pyrenees as a rifting event[1,2,3], the first relating to the Hercynian deformation style, the second to the regional tectonic interpretation of the entire Hercynian belt of Western Europe.

In the matter of Hercynian deformation style, we have no serious disagreement concerning many of the features described by Matte and Mattauer. We do not, however, believe that it is possible unambiguously to deduce the regional tectonic setting from such features. To the best of our knowledge no-one has a clear idea of the strain pattern expected in the middle crust during a strike-slip rifting event. We could certainly imagine heterogeneous deformation in such a setting that gave rise to features similar to those observed.

The second point raised by Matte and Mattauer is that rifting in the Pyrenees is not consistent with regional interpretations of the tectonic setting of the Hercynian of western Europe[4]. The Hercynian belt covers a very large area, and metamorphism and plutonism extended from the Devonian to the Permian[5,6]. We do not believe that it is reasonable to ascribe a single tectonic mechanism to all of these events. Studies of recent orogenic belts have revealed considerable complexity in the spatial and temporal juxtaposition of different tectonic styles and thermal regimes[7-11]. For example, the North Island of New Zealand contains an active rift zone characterized by high heat flow, hydrothermal systems and silicic magmatism[8,10]. The crust of this region has many geological and geophysical similarities to the Hercynian crust of the Pyrenees[1-3]. Yet this zone is located only 300 km west of an active subduction zone within which low-temperature, high-pressure metamorphism and compressional deformation are occurring.

It is unlikely that large-scale crustal thickening occurred in the Pyrenees during the Hercynian orogeny because late Carboniferous uplift was not great. Post-orogenic Upper Carboniferous and Lower Permian red beds and volcanics commonly rest unconformably on marine Carboniferous and Devonian sediments, but never directly overlie high-grade basement rocks[2,12]. This is in marked contrast with the large-scale uplift and deep erosion levels observed in modern collision belts, such as the Alps[13] or the Himalayas[14]. Furthermore, there is a correlation between stratigraphic age, intensity of deformation and grade of metamorphism experienced by the Hercynian basement rocks in the Pyrenees. Upper Palaeozoic rocks have in general been only weakly deformed and metamorphosed, whereas Lower Palaeozoic metasediments experienced strong ductile deformation and amphibolite-facies metamorphism. This observation precludes the transport of near-surface material to deep structural levels in the crust, which is a common feature of overthrust terrains and collision belts.

The timing of the Hercynian metamorphism is fundamental to any tectonic interpretation. Age determinations on syn-metamorphic granites in the Pyrenees have yielded ages of 335 ± 15 Myr (whole-rock Rb-Sr on the "granite profond" at Canigou[15]) and 338 ± 5 Myr (ion-probe U-Pb on leucogranite zircon from the Trois Seigneurs massif; I. S. Williams, S. M. Wickham and W. Compston, in preparation). These Visean to Namurian ages are contemporary with Upper Carboniferous marine sedimentation documented throughout the entire Pyrenean region[16]. Metamorphism was contemporary with marine sedimentation at the surface. This situation is radically different from that expected in collision belts, where uplift precedes metamorphism by tens of millions of years[13,17] but is entirely compatible with a rift setting[1-3,18].

The comments of Matte and Mattauer do not address two of the most remarkable features of the Hercynian Pyrenees, which we believe to be diagnostic of a rift setting. These are the exceptional thermal regimes which existed locally during metamorphism[3,12,19], and the deep hydrothermal systems which resulted in infiltration of the high-grade Palaeozoic metasediments by surface-derived marine fluids[20,21]. Neither of these features is compatible with the known thermal and mechanical effects of crustal thickening[9], but they are very similar to the observed geological and geophysical features of continental rift zones[1,10,18,22-24]. A rift setting is further supported by the total absence of any high-pressure metamorphic rocks in the Pyrenees, by the lack of ophiolitic or oceanic rock types, and by the contemporaneity of marine sedimentation at the surface and metamorphism at depth. We re-state our conclusion that Hercynian metamorphism in the Pyrenees occurred within localized rift zones, accompanied by intrusion of mantle-derived mafic material at depth. Rifting affected a deep, laterally extensive Palaeozoic sedimentary basin and promoted the low-pressure regional metamorphism, crustal anatexis and deep hydrothermal systems that characterize Hercynian metamorphic terrains in the Pyrenees.

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