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Collapse of a Hercynian Tibetan Plateau into a late Palaeozoic European Basin and Range province

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The large width, the importance of crustal shortening and the likelihood of thick crust in the late Palaeozoic Hercynian (or Variscan) belt of southern Europe suggest a tectonic evolution analogous to the evolution of the Tibetan Plateau and its neighbouring Himalaya[1], and of the Altiplano and other high plateaux of the Andes. Here we extend Dewey and Burke's analogy[1] of the Hercynian chain with Tibet to include the subsequent stage of pervasive normal faulting and crustal extension and thinning, which characterize the active tectonics of Tibet, parts of the high Andes, and the Basin and Range province of western North America. It appears that normal faulting and rifting also characterize the late Palaeozoic tectonic activity of the Hercynian chain.

The Hercynian belt of southern Europe comprises a roughly easterly-trending zone from the Iberian Peninsula (when reconstructed to France by closing the Bay of Biscay) across most of France and southern Britain, and through Germany and the basement of the Alps into eastern Europe. This belt is commonly associated with widespread, roughly north–south, late Palaeozoic crustal shortening, which probably occurred during a collision of Gondwana with Laurasia during the middle to late Palaeozoic era[2–5]. The involvement of the basement in many of the thrust sheets in the Hercynian belt[6] requires that the deformation include the entire crust of a broad area, and not just a detached sedimentary cover. The large magnitudes of thrust displacement on several thrust faults[2–6] imply that the crustal thickness of the Hercynian belt increased during this stage of deformation. The breadth of the Hercynian belt, the thickness and sedimentary facies of its cover, and the high metamorphic grade[3,5] of rock involved in the thrust faulting imply that initially the crust was not unusually thin. Thus the crust of the Hercynian chain was almost surely thickened significantly during crustal shortening[5].

Whether the Hercynian crustal thickness reached 60–70 km, as it does beneath present-day Tibet[7] and the Andes[8], cannot be determined. Conversely, whereas the evidence for abundant crustal shortening in the Hercynian chain is clear and has been likened to that of the Himalaya[3,5], the evidence for important crustal shortening in Tibet[9] or the Andes[10] is less widely accepted.

The Hercynian chain is renowned for widespread granites, many of which were intruded late in the development of the chain[5,11]. By no means can all of this igenous activity be related directly to subduction of oceanic lithosphere; much of it occurred by melting of (presumably thickened) continental crust far from the ancient active margin that marked the southern edge of the European continent before its collision with Africa[11].

Anatectic granite also characterizes the late Cenozoic igneous intrusions in the Himalaya[12], in at least one locality in northern Tibet[13], and in the Cordillera Orientale of the Andes[14,15]. The geochemical signatures of each of these sequences imply melting of thickened continental crust. Moreover, high heat flow in southernmost Tibet, south of the suture zone, implies that such igneous processes continue[16].

Folding and thrust faulting diminished in importance and probably ceased in most of southern Europe some time in the Carboniferous period[3,5]. Following the cessation of thrust faulting, if not concurrent with it, roughly ENE-trending linear basins developed along at least part of the Hercynian chain[17–20] (Fig. 1). Thick Carboniferous and Permian sedimentary rock was deposited subaerially on basement already consolidated and deeply eroded by late Palaeozoic time[17,19,20]. Between these basins, the basement is now exposed, or younger material has been deposited directly on it. Although in some regions, Mesozoic or Cenozoic erosion could have removed the late Palaeozoic cover, elsewhere the onlap of these sequences onto crystalline rock demonstrates that in late Palaeozoic time deep basins were separated by topographically higher regions. Normal faults can be mapped on the margins of only some of the thick sequences of late Palaeozoic sedimentary rock[18,19] (Fig. 2), but in many cases the evidence for these narrow basins being fault-bounded is simply the existence of abrupt variations in stratigraphic thickness. These basins can be recognized not only in the region shown in Fig. 1, but also over much of southern France[17], and in areas highly tectonized during the formation of the Alps. The Briançonnais domain of the Franco–Italian Alps, for instance, reveals a particularly thick Triassic sequence[19], associated with a well developed Permo-Carboniferous basin[21,22]. These basins might represent only a snapshot of a phase of extension that lasted tens of million years, for extension could have begun well before the extant basins formed, with erosion destroying the record of it. In any case, normal faulting, possibly in association with strike-slip faulting, seems to have been a prevalent style of deformation in late Palaeozoic time[17].

The roughly parallel grabens and half-grabens linked by strike-slip faults in the Basin and Range province of western North America (Fig. 1), in western Turkey and the Aegean, in the Tibetan Plateau, and seen less clearly in the High Andes, seem to be likely modern analogues for the landscape of the Permo-Carboniferous Hercynian belt. The evidence for active and Late Cenozoic normal faulting in Tibet[23,24] and the Andes[25,26] is inescapable, and that in the Basin and Range province is renowned. The Basin and Range province seems to represent a more advanced stage of crustal extension and thinning than Tibet or the Andes[27,28], where normal faulting may have begun only a few million years ago[23,26]. Because as much as 60–100% crustal extension may have occurred in the Basin and Range province[29–31], it is very likely that in that area of Mesozoic crustal shortening the crust was thick before being thinned during Cenozoic time[27,28,32,33]. Thus, although the analogy between the Hercynian chain and Tibet or the Andes might be imperfect if extension occurred for tens of millions of years in Europe in Palaeozoic time, the protracted extension in the Basin and Range province would maintain the analogy asserted here.

During the Triassic period, portions of the Hercynian belt became submerged for the first time after crustal shortening had begun. In the area shown in Fig. 1, the classic Triassic sequence of sandstone, followed by platform limestone, and finally shale interbedded with evaporites, was deposited over the area where Permo-Carboniferous rifting seems to have been particularly active[19,34] (Fig. 1). Correspondingly, the absence of the Triassic sequence where Permo-Carboniferous basins are sparse implies an association of the submergence with crustal extension, but the relatively smooth variations in thickness of the Triassic sequence imply that the tectonic processes that had created individual basins had ceased by Triassic time. Finally, the shallow, transient marine environments and the thickness of only 1,000–2,000 m of material deposited in 40 Myr suggest that submergence was gradual, and hence probably the result of cooling of thinned lithosphere and its underlying asthenosphere[35].

Beneath most of the Hercynian belt, the present crustal thickness is less than 35 km[36–40]. In some areas, including where the Permo-Carboniferous basins are covered by Triassic sedimentary rock, the depth of the Moho is less than 30 km[38,39], and the basement is covered by as much as 1 or 2 km of Mesozoic marine sedimentary rock[19,34,37]. Thus, the crystalline basement is particularly thin. We cannot eliminate Oligocene crustal thinning

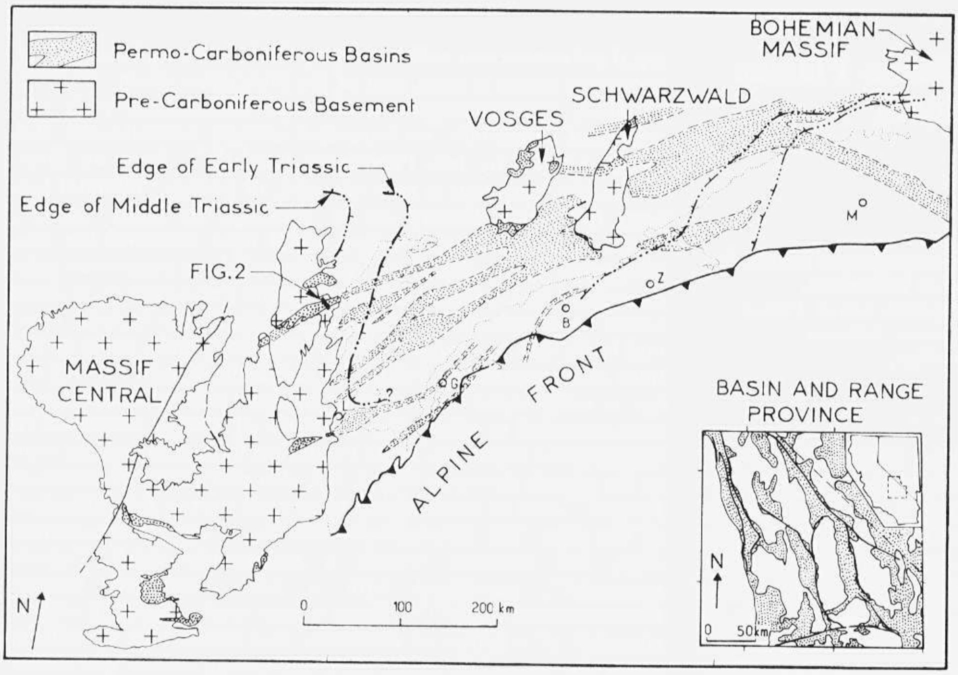

Fig. 1 Maps at the same scale of Permo-Carboniferous basins in central Europe and of the Basin and Range province in eastern California (inset), with basins dotted. Note how outcrops and subcrops[20,34] of Permo-Carboniferous sedimentary rock define linear belts separated by pre-Carboniferous crystalline rock, and how the Triassic sedimentary rock is most extensive where the basins are most prevalent. *M*, München; *Z*, Zürich; *B*, Berne; *G*, Genève; *L*, Lyon.

as a cause of this especially thin crust, but the crustal thickness of <32 km throughout most of the Hercynian belt of France[39,40] suggests that crustal thinning associated with late Palaeozoic extension may have left this region with crust thinner than the normal isostatically balanced 35 km.

Despite a mean elevation of ~1,500 m, the crustal thickness of the Basin and Range province is <30 km[41,42]. At the same time, the high heat flow[43] and the low seismic wave velocities in the underlying mantle[44,45] imply that the temperature within the crust and upper mantle of the Basin and Range province is higher than normal, presumably because the thickened lithospheric root detached after crustal thickening had occurred[33,46]. Accordingly, when the upper mantle cools, the Basin and Range province should also become submerged.

Thus, by analogy with belts of active crustal extension, an initially broad, high Hercynian chain, with a deep crustal root, probably collapsed and subsided, primarily by crustal extension and crustal thinning, and later by thermally induced subsidence. The initial phase of extension would correspond to the normal faulting that characterizes the Tibetan Plateau and parts of the Andes, where the crust is still very thick. Continued extension could have thinned the crust to <35 km, as seems to have occurred in the Basin and Range province. Cooling and thermal contraction of a hot upper mantle, like that currently underlying the Basin and Range province, later would have brought the tectonically inactive late Palaeozoic Hercynian chain below sea level in early Mesozoic time. This evolution and the suggestion of a possibly similar collapse of part of the Caledonian belt in Palaeozoic time[47] are further reminders that some mountain belts, or parts of them, may be destroyed as rapidly by tectonic processes as by erosion.

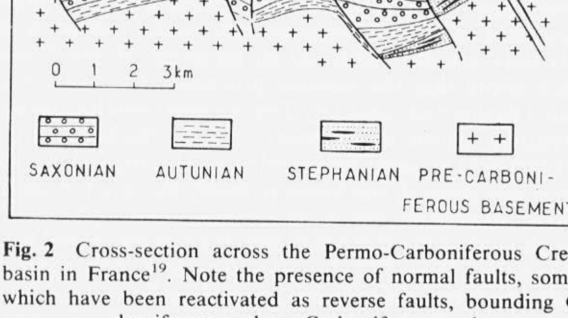

Fig. 2 Cross-section across the Permo-Carboniferous Creusot basin in France[19]. Note the presence of normal faults, some of which have been reactivated as reverse faults, bounding Carboniferous and pre-Carboniferous rock.

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