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Paleomagnetism, Oroclines, and Growth of the Continental Crust

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Strikingly curved mountain ranges have fascinated geologists as long as maps have been around to portray them. I am no exception—as an undergraduate I often stared at the festoon-shaped structural trends in maps of the Paleozoic uplands of Europe. And then, just as I was contemplating, as a beginning graduate student, what my dissertation should be about, I attended a department-wide seminar at the University of Utrecht given by S.W. Carey. He talked about sphenochasms, rhombochasms, and oroclines and how his mobilistic concepts implied that horizontal movements of the continental crust caused these geometrical patterns (Carey, 1955). While continental drift was a familiar enough theory for us students, endorsed as it was by several of the faculty at Utrecht, plate tectonics had not yet been invented! I found Carey's talk most exciting (he was a very dynamic lecturer), and I began searching for techniques to test his ideas. Soon after, I realized that paleomagnetism was the answer, given that the declination values of ancient magnetizations could reveal relative rotations.

Carey's definition of oroclines implied that these curved orogenic belts were originally straight, or at the very least, straighter. In his talk, he examined curved Alpine belts in the western Mediterranean, but in reading his 1955 paper, I noticed that he also discussed an older (Paleozoic) strongly curved belt, which exists in a so-called Ibero-Armorican Arc that stretches from Portugal and Spain to Brittany and Normandy in western France. Others (e.g., Ries et al., 1980; Perroud, 1986; Hirt et al., 1992) worked on the paleomagnetic signatures of the Cantabrian segment of the Ibero-Armorican Arc in the following decades. It would take me some three decades and a sabbatical in 1990–1991 in Barcelona before I found an opportunity to collect samples in the core of the arc, where I suspected we might learn something new about possible evidence for oroclinal bending. Here I present a summary of our studies in northern Spain, which provides an opportunity to examine some concepts relevant to oroclinal bending, and then I will summarize recent paleomagnetic work we have been doing in eastern Kazakhstan, where strongly curved structures exist as well. A comparison between the structures of Kazakhstan, as part of the Paleozoic Ural-Mongol orogenic belt, and structures in Hercynian Europe shows similarities on a large scale, and suggests that the deeper parts of the crust and perhaps even the upper mantle have been involved in the bending processes in these areas. For this to be possible, the continental crust involved in the oroclines must have had "room to maneuver" and this, in turn, seems to imply that this crust consisted of long strips, called ribbon continents. Toward the end, I will speculate about the prevalence of this bending model and draw some analogies with what we infer about the amalgamation of Archean terranes.

The Ibero-Armorican Arc (Fig. 1) reveals a Paleozoic backbone that curves from the Centro-Iberian Zone across the (then-still-closed) Bay of Biscay to the Armorican Massif in western France. Eastward, this zone is mostly covered by Mesozoic and younger rocks of the Paris Basin, but it reemerges in the Saxothuringian and Moldanubian zones of the Germanic subdivisions of Central Europe. The change in trends in France and Germany shows less curvature than that in the Ibero-Armorican Arc, but still amounts to some 60°. Some of the boundaries between the subzones in Hercynian Europe are thought to be suture zones where ancient oceans were subducted—these boundaries are shown by the heavy dashed color lines in Figure 1.

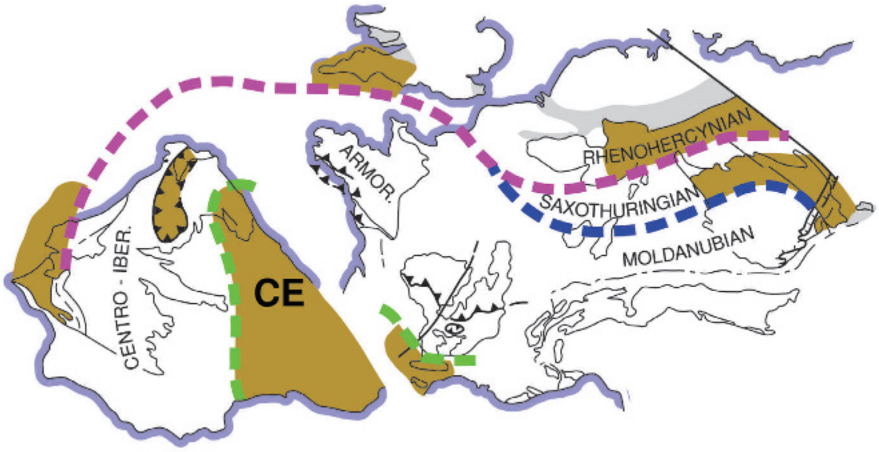

Figure 1. Paleozoic reconstruction, with the Bay of Biscay closed, of Variscan Europe (modified after Franke and Engel, 1982, and used with permission of the authors and the copyright holder, Geosciences Southwest England, as successor to the Ussher Society). Tan represents Carboniferous synorogenic clastic (flysch and Kulm-type) sedimentary rocks. Heavy dashed lines distinguish different structural domains that may have been separate microcontinents or ribbon continents before late Paleozoic amalgamation during the Hercynian orogeny. CE—Cantabria-Ebro block.

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In the core of the Ibero-Armorican Arc in northern Spain, the Cantabria-Ebro block (CE in Fig. 1) contains a Carboniferous basin filled with synorogenic clastic and coal-bearing sediments, which at its western apex in Asturias and Cantabria followed the deposition of early Carboniferous and older carbonate sequences. The paleomagnetic signatures of the Devonian carbonates were studied by us (Parés et al., 1994; Van der Voo et al., 1997; Weil et al., 2000, 2001). These rocks turned out to be remagnetized, which at first seemed disappointing but then was used to our advantage when we learned that the magnetizations were acquired precisely during the late Carboniferous–Early Permian deformation phases of this Cantabrian belt. The paleomagnetic declinations are presented here in two fashions: (1) as large-scale averages represented by the large arrows in Figure 2A, and (2) in a diagram where declinations and generalized strike directions are plotted against each other for each site (Fig. 2B).

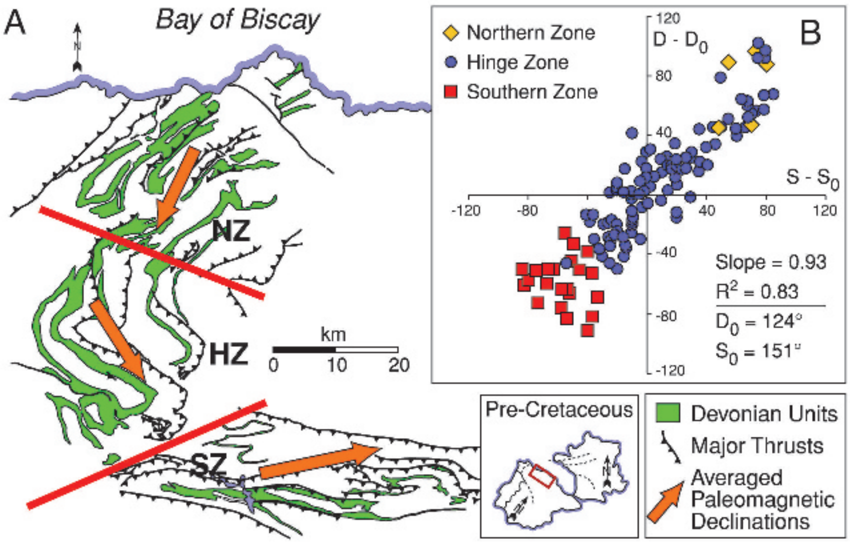

Figure 2. (A) Map of the western end of the Cantabrian orocline, showing thrust sheet traces and outcrop areas (green) of the Devonian rocks studied by Weil et al. (2000, 2001) and Kollmeier et al. (2000). Reproduced with permission of Elsevier, ©2000. Large arrows represent averaged paleomagnetic declinations. NZ, HZ, and SZ are the northern, hinge, and southern zones, respectively. (B) Declinations (D) and strikes (S) plotted against each other for each of the paleomagnetically studied sites, minus reference values where D_0 is the averaged declination for the area and S_0 is the average strike. For a detailed discussion of this type of plot, see Schwartz and Van der Voo (1983). Different colors represent results from NZ, HZ, and SZ areas (from Weil et al., 2001, fig. 5).

It is clear from Figure 2A that the averaged declinations track the curving trends of the Cantabrian zone very well. Moreover, in the detailed comparisons of declinations and strikes (Fig. 2B) the aggregate of the site means indeed shows an excellent correlation (R^2 = 0.83). The slope of the best-fit correlation line is very close to one, indicating that undoing the oroclinal bending leads to a nearly straight original belt. Previous studies had indicated that a significant original curvature existed before bending, amounting to about 50% of today's structural trends. This turned out to be incorrect, caused by a lack of recognition that the studied rocks were remagnetized during deformation; as a result the application of 100% tilt correction to the paleomagnetic directions overcorrected and produced erroneous results. The other interesting conclusion from our studies is that the oroclinal bending occurred after folding and thrusting had been nearly completed; thus, the initial fold-axes and thrust-traces ran more or less straight and parallel to present-day north-south in the late Carboniferous. In a separate study, we were able to show that stress directions determined from calcite-twinning orientations were everywhere more or less perpendicular to the thrust traces; assuming that these stress directions originally were all parallel, Kollmeier et al. (2000) could confirm that nearly 100% oroclinal bending had to have occurred to produce the present-day fan-shaped pattern of the stress directions.

The calcite-twinning orientations and paleomagnetic directions collectively present a clear picture of an originally straight fold and thrust belt that subsequently was deformed during the Early Permian into the horseshoe-shaped belt it is today. What is intriguing is that this oroclinal bending occurred primarily about near-vertical axes, that is, without much further tilting of the already folded thrust sheets. We can tell that from the paleomagnetic inclinations, which do not need much correction from "untilting" (see discussion in Weil et al., 2000). This implies that, wherever the major décollement planes are to be found, they are more or less horizontal, because movement over inclined surfaces would undoubtedly have caused a detectable tilt. But what we cannot ascertain, of course, is how far the oroclinal rotations perpetuate downward. In other words, at what depth did detachment occur? It is likely that the deformation in the Cantabrian fold and thrust belt is thin-skinned, as seems to be the case for most other relative rotations in fold and thrust belts (e.g., Grubbs and Van der Voo, 1976; Eldredge and Van der Voo, 1988; Kent, 1988; Butler et al., 1995; Collombet et al., 2002; Bayona et al., 2003; Sussman et al., 2004; van der Pluijm and Ong, 2004).

Whereas the kinematic scenario of the Cantabrian oroclinal core of the Ibero-Armorican Arc seems unambiguous enough, it is not at all clear what the dynamics of the bending may have been. For instance, what happened in the backbone of the Ibero-Armorican Arc all around Cantabria (see Fig. 1)? Was the Ebro block an indentor? There are indications of relative rotations in the Carboniferous paleomagnetic data from Brittany and Central Europe (Bachtadse and Van der Voo, 1986; Perroud, 1986), but the distribution of sampling sites for these results is not sufficient to make any arguments for oroclinal bending in Portugal and western Spain. Results from Siluro-Devonian rocks in Hercynian Europe are very scarce—in essence, there are only four relevant paleomagnetic results (Perroud et al., 1985; Parés and Van der Voo, 1992; Tait et al., 1994; Tait, 1999) and their reliability is low, especially where the ages of magnetization are concerned. The results from Spain, Portugal, and the Czech Republic do show declinations that can be taken as support for oroclinal rotations, but the result from western Brittany (Tait, 1999) does not agree and so, for the time being, one has to allow that any oroclinal bending of the backbone's crust in Hercynian Europe, which of necessity would have been thick-skinned, remains enigmatic.

The geological setting in Kazakhstan has certain similarities to that of Hercynian Europe, but here the evidence for thick-skinned oroclinal bending is emerging more clearly. Figure 3 shows a geological map of Kyrgyzstan and eastern Kazakhstan, in which different colors highlight the three age groups of island-arc magmatism that characterizes the Paleozoic history of this part of the Ural-Mongol orogenic belt. Concentric horseshoe-shaped belts encircle Lake Balkhash, with the youngest of these subduction-related volcanic arcs on the inside. This is intriguing in terms of subduction geometry: how can it be possible to have outward-directed subduction of oceanic crust under a steadily tightening overriding plate that keeps converging on the vanishing oceanic area? Naturally, the idea that the horseshoe-shaped belts are the result of oroclinal bending has occurred to scientists studying the area and has led to models of complex oroclinal deformation (e.g., Şengör and Natal'in, 2004), whereas others have proposed amalgamation and collision of arc segments without large-scale rotations (Didenko et al., 1994; Filippova et al., 2001).

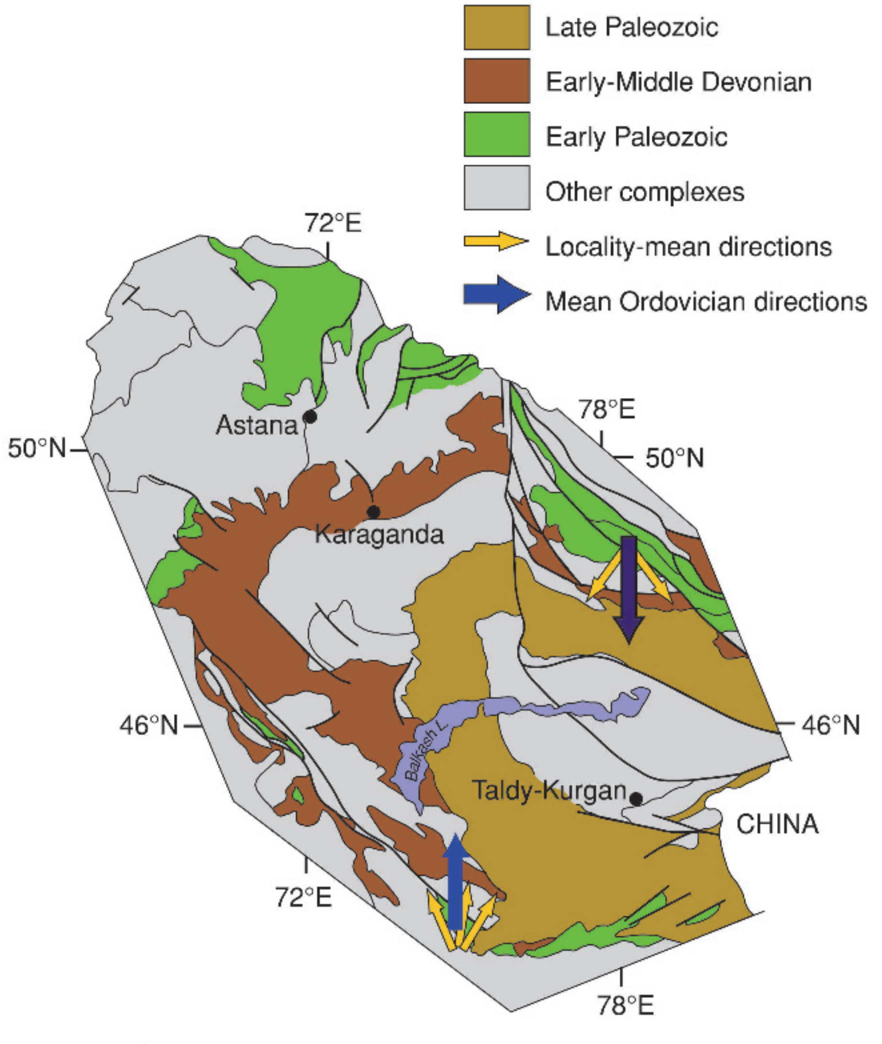

Figure 3. Map of northernmost Kyrgyzstan and eastern Kazakhstan, where subduction-related volcanic arcs of different ages are shown in different colors (reproduced from Levashova et al., 2003, with permission of Elsevier, ©2003). Light-colored smaller arrows represent mean declinations for individual formations of Ordovician and Silurian ages (from Bazhenov et al., 2003; Collins et al., 2003; Levashova et al., 2003) and large dark arrows represent the regionally averaged declinations for this interval. The northern sampling localities (Chingiz Range) have generally southerly declinations, whereas the results from the North Tien Shan are northerly, indicating nearly 180° of relative rotation between these two areas.

Our recent paleomagnetic results (Bazhenov et al., 2003; Collins et al., 2003; Levashova et al., 2003) have indicated that rotations in the Kazakh belts are significant, however. In Figure 3, the most illustrative of these results are shown and include declinations from Ordovician and Silurian rocks from two areas, the North Tien Shan and the Chingiz Range. Positive tilt and conglomerate tests for several of these results indicate that the magnetizations are primary or, at the very least, were acquired early; moreover, the directions do not resemble magnetization directions observed in younger, post-Silurian rocks. Because the drift of the two sampling areas must generally have been northward during much of the Paleozoic, in order for them to end up as part of the northern-hemisphere Laurasia assembly by Permian time, the polarity of the two sets of results can reasonably be assumed to have been normal (see discussion in Levashova et al., 2003). Field and laboratory work in progress is designed to test our polarity assignments and to complement the data distribution in a spatial sense with new results from the hinge areas of the arcs. Assuming for the time being that our polarity assignments are correct and that the northern Chingiz area is rotated about 180° with respect to the southern area in the North Tien Shan, we have a ready explanation for the geometrical oddity of the tightening arcs around Lake Balkhash. Late Permian directions on both sides of the orocline appear to be more or less parallel, indicating that the rotations were largely completed by that time. Middle Devonian paleomagnetic directions (Levashova et al., 2003) are in need of confirmation, but suggest that the rotations occurred afterwards.

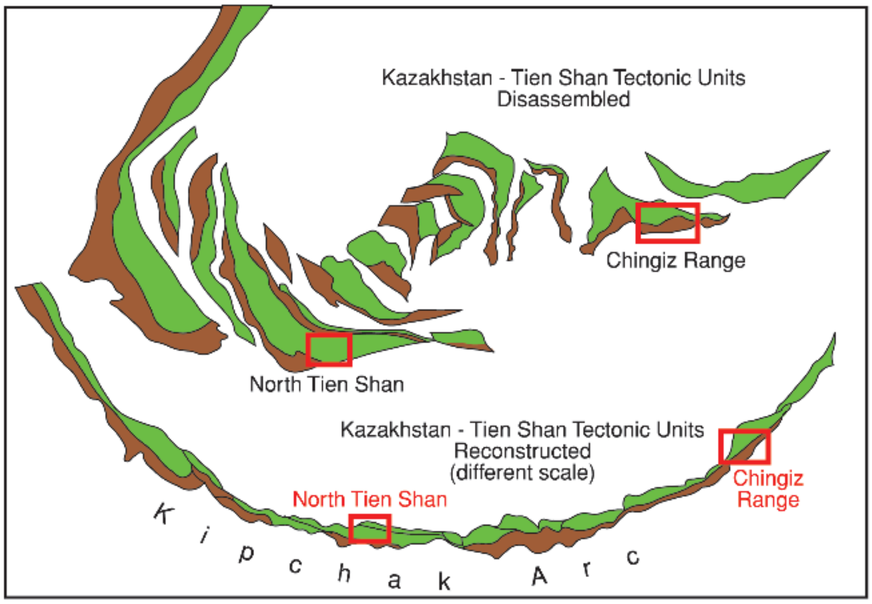

Figure 4. Disassembled tectonic units from the Kazakhstan–Tien Shan orocline and their reconstruction into the early Paleozoic Kipchak Arc according to Şengör and Natal'in (2004; reproduced with permission of the authors and the publisher and copyright holder, W.W. Norton and Co., ©2004). The Kipchak Arc became sheared and buckled during the late Paleozoic into the present-day oroclinal fault-riddled structure. Paleomagnetic sampling areas are labeled and indicated by the red boxes.

The most likely time span for oroclinal bending is late Carboniferous–Early Permian.

It appears that oroclinal bending in this area penetrated deeply, given that we are dealing with thick crustal arc segments with abundant subduction-related plutonic rocks. The arc segments appear to have amalgamated in collisions of crustal dimensions and not within a thin-skinned fold and thrust belt. The model of Şengör and Natal'in (2004) is very interesting in this respect (Fig. 4) and portrays the buckling, shearing and oroclinal bending of an originally very long Kipchak Arc that connected the independently drifting Paleozoic Siberia and Baltica continents in Ordovician times. The areas surrounding the locations of the Chingiz Range and the North Tien Shan evolved into the flanks of the horseshoe-shaped early and middle Paleozoic belts of Figure 3 during the Devonian, Carboniferous, and Early Permian, according to Şengör and Natal'in (2004). Collectively, this allows the interpretation that the rotations of the Kazakhstan Orocline are thick-skinned and involved ribbon continents, which are long strips of continental crust that can bend or buckle more easily than more equidimensional crustal blocks.

The term *ribbon continent* was used by Johnston (2001) to describe the long, originally fairly linear strip of continental crust that deformed into what he called "the great Alaskan terrane wreck." A depiction of this deformation can be gleaned from Figure 5. A similar ribbon-shaped continent that accreted to Asia in the Mesozoic is represented by Cimmeria (Şengör, 1987), and one can imagine that Paleozoic microcontinents such as Avalonia and Armorica may have been ribbon continents as well (Tait et al., 1994; Mac Niocaill et al., 1997). Rotations characterize all these accreting microcontinents and island-arc segments.

The amalgamation of the Baltic, Siberian, and Tarim cratons, the West and East Avalonia microcontinents, the Variscan belt in and around the Ibero-Armorican Arc, and the Ural-Mongol Belt (which includes Kazakhstan)

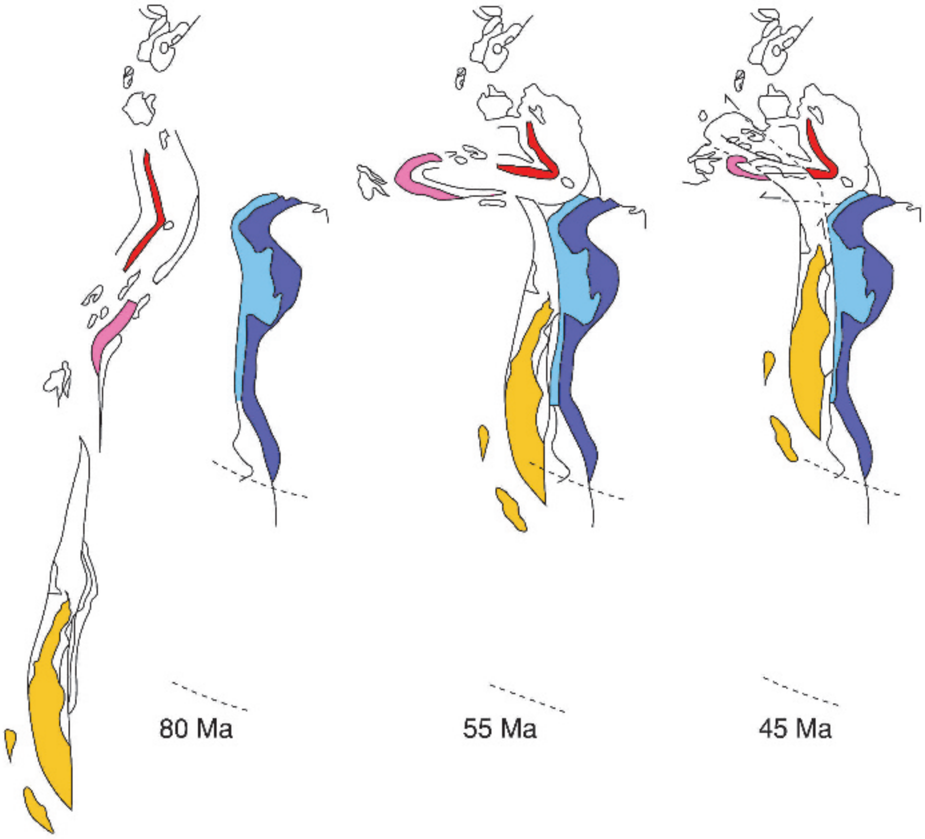

Figure 5. Evolutionary scenario of a ribbon continent that buckled and accreted to the northwest margin of North America during the early Tertiary in what the author called the "Great Alaskan Terrane Wreck" (reproduced with permission of S.T. Johnston, and the publisher and copyright holder, Elsevier, ©2001). The stable (unchanging) North American margin is represented by the different blue colors and the dashed lines represent the future Mexico–United States and United States–Canada borders.

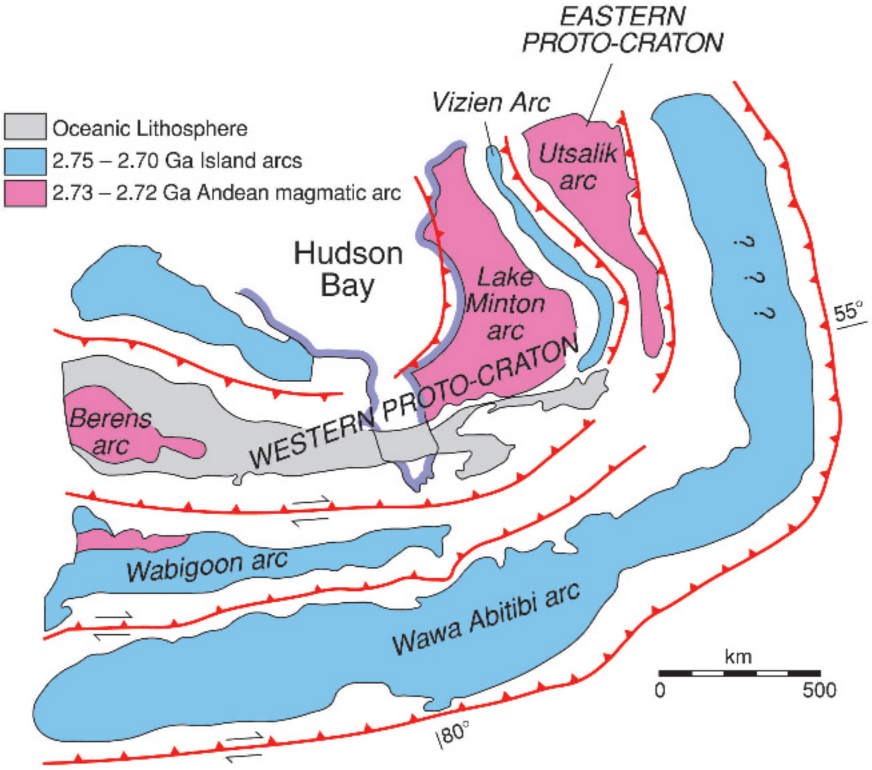

Figure 6. Schematic representation of the Superior Province at ca. 2.7 Ga during continental arc magmatism at the eastern and southern margins and assembly of island arc terranes into the Superior craton in statu nascendi. Modified from Percival et al. (1994) and reproduced with permission of the author.

represents Paleozoic growth of Eurasia. Similar events occurred in the Mesozoic, as the Cimmeria ribbon, and the China and Indochina blocks accreted onto the older nuclei. This pattern of cratonization and continental growth can be recognized in other continental elements as well. A good example exists in northeastern Africa and Arabia, where multiple island-arc and ophiolitic fragments amalgamated during the Pan-African orogeny (Windley, 1995, p. 244–248).

Models for the genesis and evolution of the Archean greenstone-gneiss belts are probably as numerous as there are authors discussing them, but some suggest that continental growth by accretion of ribbon continents may have already occurred in the Archean (e.g., Percival et al., 1994). Figure 6 displays the island arcs and Andean-type magmatic arcs that are, according to these authors, thought to have developed in a time span of ~50 m.y. The long linear ribbon-like strips were then telescoped in a collision process involving subduction of the intervening oceanic crustal segments. This, in my opinion, strongly resembles the situation described above for Eurasia in Phanerozoic times. Percival and colleagues (1994) did not discuss oroclinal bending, and there is to my knowledge no discussion of this in the promising paleomagnetic studies of the greenstones either (Tasillo-Hirt et al., 1982; Geissman et al., 1983), so perhaps this is something to be pursued in future paleomagnetic studies.

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