Restoration of lithosphere-scale wrenching from integrated structural and tomographic data (Hercynian belt of western France)

C. Gumiaux Géosciences Rennes UMR 6118 Centre National de la Recherche Scientifique, Campus de Beaulieu, 35042 Rennes cedex, France
S. Judenherc Ecole et Observatoire des Sciences de la Terre, UMR 7516 Centre National de la Recherche Scientifique, 5 Rue René Descartes, 67084 Strasbourg cedex, France
J.-P. Brun
D. Gapais Géosciences Rennes UMR 6118 Centre National de la Recherche Scientifique, Campus de Beaulieu, 35042 Rennes cedex, France
M. Granet Ecole et Observatoire des Sciences de la Terre, UMR 7516 Centre National de la Recherche Scientifique, 5 Rue René Descartes, 67084 Strasbourg cedex, France
G. Poupinet Laboratoire de Géophysique interne et de Tectonophysique, UMR 5559 Centre National de la Recherche Scientifique, 1381 Rue de la Piscine, 38041 Grenoble cedex, France

ABSTRACT

Tomographic images of the mantle below the Hercynian belt of Brittany display strong anomalies of P-wave traveltimes that likely represent variations in composition, and whose trends change above and below 130 km. A quantitative strain analysis of surface geological structures has shown that the crust in the area was affected by regional-scale distributed simple shear. The change of trends of tomographic anomalies below and above 130 km is largely removed by extending the simple shear model down to 130 km. From this, we infer lithospheric-scale wrenching, and therefore deep-seated horizontal decoupling, possibly at the lithosphere-asthenosphere boundary. Simple shear restoration further provides arguments for the occurrence of a steeply dipping slab. Geological data support its interpretation as a remnant of oceanic lithosphere subducted prior to the Hercynian collision. Beyond regional implications, the study underlines the interest of combining geology and tomography for the understanding of lithosphere deformation.

Keywords: Hercynian lithosphere, mantle deformation, seismic tomography, shear belt, central Brittany.

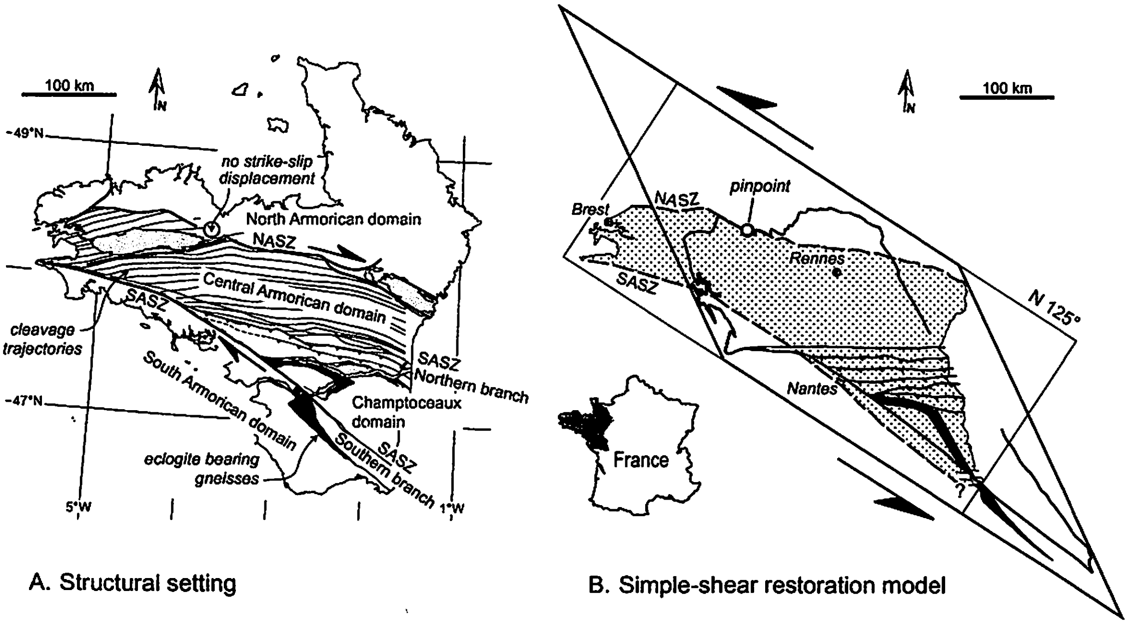
INTRODUCTION

Lithosphere deformation in orogenic belts is generally only constrained by the record of crustal layers, as information on the lithospheric mantle is generally lacking or scarce. However, progress of lithosphere tomography offers new tools to describe heterogeneities and structures in the lithospheric mantle, as tomographic images contain information about the mineralogy, mineral anisotropy, and/or the thermal state (e.g., Sobolev et al., 1996; Poupinet et al., 2003).

In old orogenic belts, like the Hercynian belt of western Europe where subduction and collisional events are older than 300 Ma, the occurrence of large differences in P-wave traveltimes can likely reflect variations in mineralogical composition and/or anisotropy. We use here teleseismic P waves recently recorded across the Hercynian belt of Brittany (Judenherc et al., 2002, 2003). Anomalies observed on mantle tomographic images, calculated down to 200 km, are analyzed in light of regional-scale strike-slip deformation that affects the overlying crust.

REGIONAL GEOLOGY

The Hercynian belt of Brittany shows three major dextral wrench shear zones that separate different tectonic domains (Fig. 1A). North of the North Armorican shear zone, the North Armorican domain shows rather limited Hercynian ductile deformations. South of the North



A. Structural setting

B. Simple-shear restoration model

Figure 1. A: Structural setting of Hercynian belt of Brittany. Central Armorican domain is bounded by northern branch of South Armorican shear zone (SASZ) and by North Armorican shear zone (NASZ). Point of no strike-slip displacement is located on North Armorican shear zone. Thin lines represent cleavage trajectories developed during regional-scale dextral shearing. B: Restoration of regional deformation by sinistral simple shear. Modified after Gumiaux et al. (2004).

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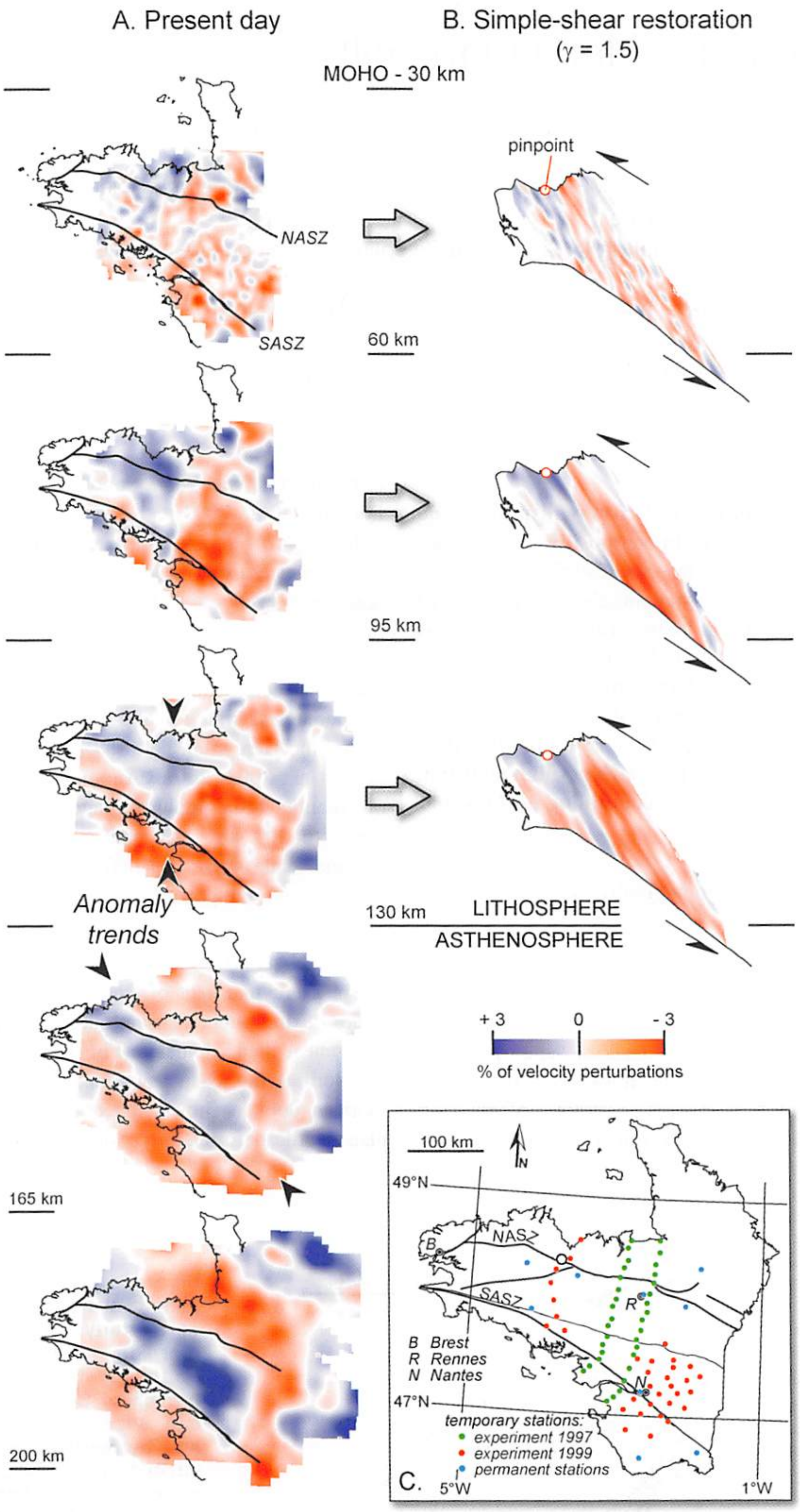

Figure 2. Tomographic images of lithospheric mantle (A) before and (B) after simple shear restoration, using model of Figure 1B. Inset shows positions of seismic stations. SASZ—South Armorican shear zone; NASZ—North Armorican shear zone.

Armorican shear zone, the Central Armorican domain represents the upper crust during the whole Hercynian evolution and corresponds to a regional-scale strike-slip shear belt of Carboniferous age (Gapais and Le Corre, 1980). The eastern part of the Champtoceaux domain consists of upper-crustal rocks; it is underlain to the west by high-pressure metamorphic units exhumed in early Carboniferous (Pennsylvanian) time (Bosse et al., 2000). The South Armorican domain is marked by high-temperature metamorphic units strongly affected by synconvergence extension (Gapais et al., 1993). The South Armorican shear zone, a major dextral strike-slip fault of Carboniferous age (Jégouzo, 1980), juxtaposes the Central and South Armorican domains to the west, and the South Armorican and Champtoceaux domains to the east.

STRIKE-SLIP SHEAR BELT OF CENTRAL BRITTANY: KINEMATICS AND RESTORATION MODEL

In the Central Armorican domain, low-grade metasedimentary rocks of Late Proterozoic to Devonian age are affected by east-striking upright folds with a subvertical slaty cleavage and a subhorizontal stretching lineation, resulting from dextral wrenching of Carboniferous age (Gapais and Le Corre, 1980). In the area south of Rennes (Fig. 1B), a mathematical removal of ductile strains (Percevault and Cobbold, 1982) has argued for bulk dextral simple shear along an overall N125°-striking shear direction, parallel to the southern branch of the South Armorican shear zone. A geostatistical analysis of cleavage directions has further shown that the simple shear model could be extended to the whole Central Armorican domain (Gumiaux et al., 2004). Considering the cleavage as a principal strain plane, the best fit-mean γ value is $\sim$1.5 (Gumiaux et al., 2004). North of Central Brittany, along the North Armorican shear zone, dextral strike-slip displacements increase both westward and eastward from a central point of nearly no displacement (Gumiaux et al., 2004). Deformation throughout the Central Armorican domain can therefore be restored by applying a sinistral simple shear (γ = 1.5) in a N125° direction, with a pinpoint located on the North Armorican shear zone (Fig. 1B).

The Champtoceaux domain consists of mica schists and strongly deformed eclogite-bearing gneisses (Ballèvre et al., 1987; Bosse et al., 2000). After their exhumation in early Carboniferous (Pennsylvanian) time (Bosse et al., 2000), these units were affected by dextral shearing, which produced an antiformal structure (Fig. 1A) with a steeply dipping axial plane and a steeply eastward plunging axis. As demonstrated by deep seismic profiling (Bitri et al., 2003), the Champtoceaux domain is thrust over the southern part of the Central Armorican domain. Both dextral strike-slip and northward thrusting postdate the exhumation of the high-pressure rocks. Restoration of Carboniferous deformations in the Champtoceaux domain was therefore achieved by removing displacements along the north-verging thrusts and by sinistral simple shear parallel to the South Armorican shear zone (Fig. 1B). The restoration yields a preshearing northwest trend of the eclogite-bearing units (Fig. 1B). This restored trend matches that of eclogite-

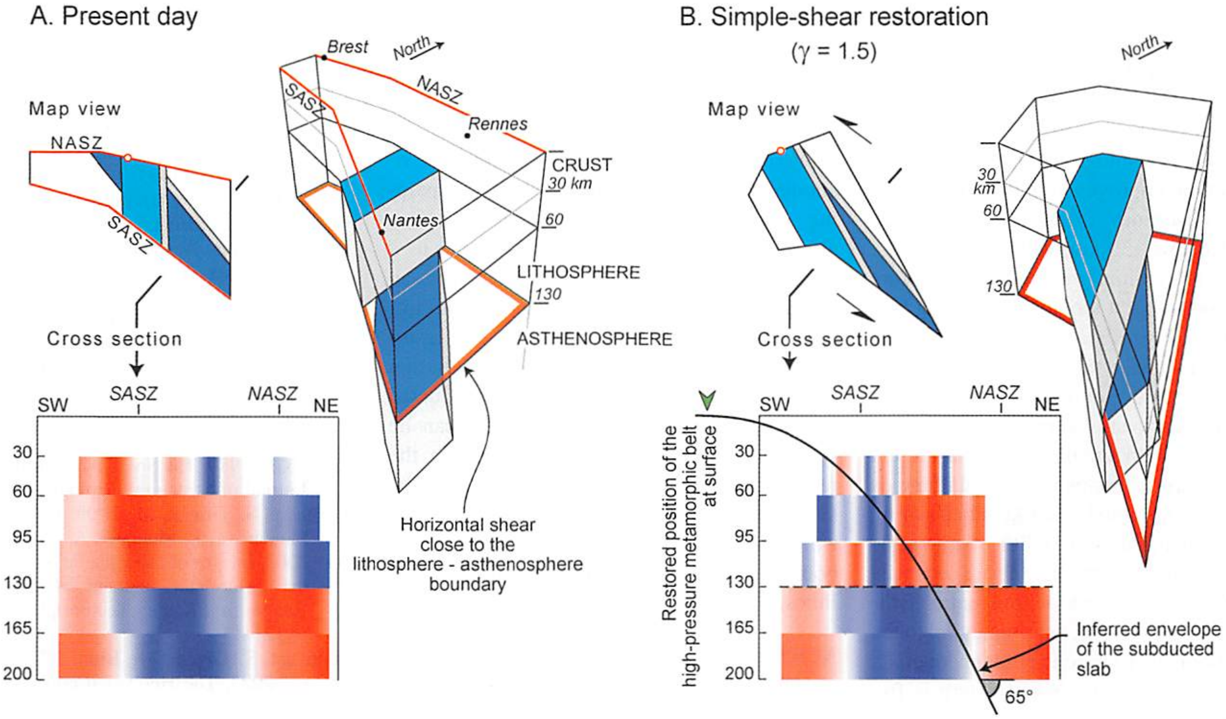

Figure 3. Three-dimensional diagrams, map views, and cross sections showing relative position of fast P-wave anomalies above and below 130 km before and after simple-shear restoration.

bearing rocks exposed along the southern branch of the South Armorican shear zone farther southeast (Fig. 1).

TOMOGRAPHIC DATA

In 1997 and 1999, two seismic experiments were performed in the region in order to image the three-dimensional velocity variations and the seismic anisotropy at depth (Fig. 2A). In addition to some permanent stations, networks were set up in order to cover the major tectonic features of the Armorican massif. The temporary arrays, together with the available permanent stations, form a dense two-dimensional network of 80 stations that allowed us to generate a velocity model for the crust and the mantle down to 200 km. The tomographic images of the Armorican massif, presented in Figure 2A as planar sections and in Figure 3A as a cross section, result from a high-quality data set of 5215 P-wave delay times from 230 teleseismic events with epicentral distances of >30° (Judenherc et al., 2002, 2003). A three-dimensional ray-tracing technique was used as a part of an iterative inversion process intended to consider the nonlinearity of the tomographic problem. The overall accuracy of the P-wave arrival times obtained by waveform matching is ~±0.05 s. The inversion reduces the variance of the residuals by 69%. The reliability of the three-dimensional model has been checked from the formal resolution matrix rather than from synthetic data calculations (Judenherc et al., 2002). The analysis of both the diagonal and the nondiagonal terms of this matrix showed that the velocity model was accurate.

Below 60 km, images display strong perturbations of P-wave traveltimes (to 6%). All available geological, geochronological, and geophysical data demonstrate that no strong tectonic or volcanic event occurred in the studied area since Triassic time. Therefore, no thermal perturbation younger than 250 Ma can be invoked. Furthermore, thermal anomalies associated with the Hercynian orogeny (ca. 300 Ma) have had time to equilibrate. In order to check a possible bias on the three-dimensional velocity structure by seismic anisotropy (Sobolev et al., 1999), Judenherc et al. (2003) tested the influence of the anisotropic structure and ray geometries. The inversion of synthetic data sets obtained from anisotropic models showed that the bias was related to the change of the anisotropy pattern rather than to the geometry of structures. According to Judenherc et al. (2003), even if an anisotropic bias exists, it is a second-order effect in the velocity pattern, <1%. Consistently, Judenherc et al. (2002, 2003) attributed the differences in P-wave traveltime as basically reflecting variations in chemical composition and mineralogy. Between the South Armorican shear zone and the North Armorican shear zone, the two main shear zones bounding the shear belt of central Brittany (Fig. 1), "fast-blue" and "slow-red" anomalies define two oblique trends, roughly north above 130 km and northwest below that depth (Fig. 2).

RESTORATION OF TOMOGRAPHIC IMAGES

The change in orientation of P-wave traveltime anomalies, observed above and below 130 km (Fig. 2A) could correspond to the lithosphere-asthenosphere boundary during Hercynian time. Considering that the strike-slip deformation observed in the crust could have affected the whole lithosphere, the north-trending anomaly observed in the lithosphere (above 130 km) could result from a shear-induced rotation of an initial northwest-southeast orientation, as observed in the underlying asthenosphere. We consequently applied the restoration model elaborated for the crust (Fig. 1B) to the three uppermost tomographic images (Fig. 2B).

For the shear strain $\gamma = 1.5$ calculated for the crust, the north trend is rotated at a low angle (~10°) to the direction of anomalies observed below 130 km (Fig. 3). To bring into parallelism the two anomaly trends above and below 130 km, the γ value should have been ~2.0. The difference from the expected γ value could mean that the total shear value calculated for the crust has been underestimated. However, the quality, density, and consistency of available structural data are such that an underestimation of $\gamma = 0.5$ seems unreasonable. The angular discrepancy could instead result from a downward increase in the amount of strike-slip shear. Such an increase in shear could, for example, arise if partial decoupling occurred between the upper crust and the lower ductile crust. Another hypothesis is that images of anomalies in the lithospheric mantle are altered by the occurrence of localized second-order shear zones. In favor of this is that fast anomalies appear thinner above 130 km than below (see Fig. 2).

Despite the remaining angular discrepancy, the restoration improves significantly the directional consistency of the fast anomalies above and below 130 km, which supports the hypothesis of an initially unique source before Carboniferous dextral strike-slip shearing (see cross section, Fig. 3B). The restored picture displays an anomaly trending northwest and dipping ~65° to the northeast. According to the three-dimensional interpretative sketches of Figure 3, a horizontal shear zone around the lithosphere-asthenosphere boundary is necessary to accommodate strike-slip shearing in the lithosphere. In favor of lithosphere-scale shearing is that anisotropic fabrics deduced from SKS fast directions below central Brittany trend ~N125°–130°, nearly parallel to the South Armorican shear zone (Judenherc et al., 2003). Such mantle anisotropy pattern is frequently observed along strike-slip zones (Silver, 1996; Little et al., 2002).

ORIGIN OF THE FAST ANOMALIES

The eclogite belt exposed in the Champtoceaux and Vendée areas underlines the limit between the southern metamorphic zones and northern upper-crustal domains (Fig. 1). The eclogites, which have backarc affinities (Ballèvre et al., 2002), are thus the best candidates for representing the surface trace of a subduction zone. Their preshearing northwest trend was slightly oblique with respect to the regional shear direction, as demonstrated by their folding during Carboniferous wrenching (Fig. 1). After restoration, the mantle body imaged by tomography appears to be subparallel to the restored eclogite belt (Brun et al., 2002) (cf. Figs. 1B and 3). From these features, we interpret the tomographic anomalies as likely imaging a remnant of oceanic lithosphere subducted toward the northeast, probably in a backarc context, prior to the main collisional event. However, geometric correlations between surface and depth data cannot be directly made because the Champtoceaux units were subsequently displaced eastward by at least 300 km during collision (Brun et al., 2002).

CONCLUSIONS

A regional-scale model for restoration of Carboniferous strike-slip shear that affects the crust of the Hercynian belt of Brittany has been applied to mantle tomographic images. It is shown that the mean shear value of $\gamma = 1.5$, calculated for the crust, rotates the P-wave velocity anomalies observed in the lithospheric mantle close to the direction of anomalies observed below 130 km. A remaining obliquity of ~10° between anomalies above and below 130 km could be due to a downward increase of the shear value or to an alteration of the lithosphere tomographic images by second-order shear zones. The restoration suggests a steeply dipping slab that could correspond to a remnant of subducted lithosphere whose surface equivalent can be found in the eclogitic units observed in the region. According to this interpretation, the slab must have been cut by a horizontal shear zone close to the lithosphere-asthenosphere boundary during strike-slip shear of the whole lithosphere.

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