Wrench faults down to the asthenosphere: Geological and geophysical evidence and thermo-mechanical effects

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Abstract:
We review a set of geological and geophysical observations that strongly support a coherent deformation of the entire lithosphere in major intracontinental wrench faults. Tectonic studies of wrench faults eroded down to the middle to lower crust show that, even in cases in which the lower to middle crust is partially melted, strain remains localized (although less efficiently) in transcurrent shear zones. Seismic profiling as well as seismic tomography and magnetotelluric soundings provide strong argument in favor of major wrench faults crosscutting the Moho and deforming the upper mantle. Pn velocity anisotropy, shear-wave splitting and electric conductivity anisotropy measurements over major wrench faults and in transpressional domains support that a wrench fault fabric exists over most or even the entire lithosphere thickness. These seismic and electrical anisotropies are generated by a crystallographic preferred orientation of olivine and pyroxenes developed in the mantle during the fault activity, which is frozen in the lithospheric mantle when the deformation stops. The preservation of such a "wrench fault-type" fabric within the upper mantle may have major effects on the subsequent tectono-thermal behavior of continents, because olivine is mechanically and thermally anisotropic. Indeed, the association of numerical models and laboratory data on textured mantle rocks strongly suggests that the orogenic continental lithosphere is an anisotropic medium with regards to its stiffness and to heat diffusion. This anisotropy may explain the frequent reactivation, at the continents scale, of ancient lithospheric-scale wrench faults and transpressional belts during subsequent tectonic events.

Introduction:
Horizontal displacements in transcurrent faults represent one of the fundamental modes of accommodation of deformation in the crust. It is quite obvious that transcurrent faults generated at transform plate boundaries, like the San Andreas Fault in California or the Alpine fault in New Zealand crosscut the entire lithosphere. It is however less clear whether intracontinental strike-slip fault systems generated in active margins or in collisional domains are only crustal structures or are rooted in the upper mantle. The penetration of a "wrench-fault type" tectonic fabric (i.e., a vertical flow plane associated with a horizontal flow direction) deep into the upper mantle may have major geodynamic implications, since it would generate an anisotropy of the mechanical and thermal properties of the lithospheric mantle and, hence, modify the large-scale rheological behavior of continental plates during subsequent tectonic events (Tommasi et al., 2001; Tommasi & Vauchez, 2001).

Assuming that major, i.e., continental-scale, strike-slip faults observed today at the surface continue down to the base of the lithosphere implies a strong mechanical coupling between the various rheological layers of the lithosphere. This raises the question of the mechanical properties of the hot middle to lower crust. Strain localization should remain efficient enough to allow the development of strike-slip faults zones at this level. In addition, rheological contrasts between the lower crust and the upper mantle should remain moderate; otherwise the lower crust would behave as a horizontal decoupling level in which upper crustal wrench faults would root. These issues have been already addressed in a large number of studies on the rheological stratification of the continental lithosphere (e.g., Meissner et al., 2002;
Molnar, 1988; Ranalli & Murphy, 1987; Vauchez et al., 1997), but experimental data on the rheology of lower crustal materials is so limited that these studies are not conclusive.

In this paper, in order to evaluate how deep a coherent "transcurrent fabric" may penetrate, we analyze direct observations from surface geology, which are of course restricted to the crust, and indirect information from geophysics and geochemistry that gives a hint on the crust/mantle coupling. We consider evidence from active and fossil tectonic domains and discuss observations from both individual shear zones and broad transpressive domains. The review of this broad dataset suggests that major wrench faults do crosscut the entire lithosphere. This leads us to discuss the effect of these lithospheric-scale wrench faults on the thermo-mechanical evolution of continental plates.

**Transcurrent shear zones and strain localization in a hot middle to lower crust**

If major transcurrent faults were rooted into the crust, the wrench deformation in the upper crust must be decoupled from the mantle flow. Decoupling between crustal and mantle deformations is supposed to be favored in the middle to lower crust (especially in regions displaying high geothermal gradients) by the low stiffness of crustal material at high homologous temperature (T/Tm, with Tm = melting temperature). It would be marked by rooting of the strike-slip faults into this low stiffness layer, and therefore by a listric shape of the fault in order to accommodate the transition from a vertical to a horizontal flow plane.

In this section, we examine a set of continental-scale transcurrent faults eroded to increasingly deeper levels from the middle to the lower crust. In all these cases, during transcurrent deformation, the crustal levels exposed today were submitted to high temperatures and even partial melting. These levels represent former low viscosity layers into which crustal-scale strike-slip faults might have rooted.

![Figure 1: The high-temperature Borborema shear zone system of Northeastern Brazil (Vauchez et al., 1995). (a) Sketch map showing the complex pattern of transcurrent faults formed during the Neoproterozoic orogeny: (1) Neoproterozoic granitoids, (2) Mid- and Late Proterozoic sedimentary basins, (3) Mesozoic sedimentary basins, (4) Neoproterozoic high-temperature shear zones, and (5) Neoproterozoic low-temperature shear zones. (b) and (c) are two Landsat images showing segments of two major high-temperature wrench faults: the Patos and the West Pernambuco shear zones, respectively. Gray lines in (b) mark the shear zone limits.](image-url)
In northeastern Brazil, the Neoproterozoic province of Borborema displays a complex network of wrench faults (Figure 1) that are several hundred kilometers long and up to 30 km wide (e.g., Vauchez et al., 1995). Satellite images highlight a clear textural contrast between the shear zones and the country rock. This contrast is mostly due to the transition from a predominant low-angle metamorphic foliation outside the shear zones to a steeply dipping mylonitic foliation within the shear zones. At the satellite image scale, the boundaries of the fault zones appear usually rather sharp, although in the field a continuous transition from the external flat-lying foliation to the internal steeply dipping foliation (half "flower-structure") is observed where no subsequent reactivation concealed the original relationships. Mylonites outcropping in the shear zones were formed at depths of 16-18 km (P ≤ 500 MPa) and at high temperature (>650°C).

Under these conditions, the protoliths of the mylonites (metasediments, pre-kinematic intrusives, felsic gneisses from the basement) were partially melted and the resulting rock is indeed a migmatitic mylonite. At these temperature conditions, felsic rocks are expected to display low viscosity, which will be further decreased by partial melting. Nevertheless, even when the degree of melting is rather high, the foliation in the shear zones remains consistently steeply dipping and bears a shallow-dipping stretching lineation (Figure 2). Shear-sense indicators developed in the partially melted mylonites consistently support dextral wrenching (Figure 3). Evidence of downward decrease of the foliation dip, suggesting rooting of the faults, has never been reported. On the contrary, a large volume of mantle-derived magmas, especially diorites, was emplaced as syn- or late-kinematic dikes (Figure 4) and/or elongated plutons within the shear zones (Neves et al., 2000; Vauchez et al., 1995); this strongly suggests that the faults were connected to a partially melted upper mantle.

The Neoproterozoic Mozambique belt in Madagascar and East Africa is also characterized by the development of a large network of wrench faults (Figure 5) at ca. 530-500 Ma (Martelat et al., 2000). The present-day level of exposure shows rocks that were 20 to 30 km deep during the deformation [0.5 to 1.1 GPa; Martelat, 2000 #4157; Pili, 1997 #3960]. At these depths, deformation took place at temperatures >750°C. The major shear zones in this domain are typically several hundred kilometers long and up to 40 km wide. Numerous minor ductile wrench faults formed under similar P-T conditions are also documented. The tectonic fabric in the shear

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**Figure 2:** High-temperature vertical foliation (S) and horizontal mineral stretching lineation (L) in a mylonite from the Borborema shear zone system. Deformation in this felsic mylonite occurred at T>600°C. Location on Fig.1a. Scale bar is 0.5m.

**Figure 3:** Migmatitic mylonite from the West Pernambuco shear zone (see location on Figure 1a). Downward view. Intense shearing occurred along a subvertical foliation in a partially melted crust. White layers are leucocratic neosome. Arrows indicate dextral shear.

**Figure 4:** Diorite dikes injected in a porphyritic granodiorite emplaced in the Pernambuco shear zone (location on figure 1a). Dikes were emplaced within the transcurrent shear zone and deformed before complete solidification. No evidence of solid-state deformation has been observed.
zones is typical of ductile strike-slip faults: the foliation is steeply dipping, the mineral-stretching lineation is sub-horizontal and consistent shear-sense criteria are observed. Outside the shear zones, the granulites that form the country-rock display a low-angle foliation and the fabric is metamorphic-migmatitic rather than mylonitic.

According to Martelat et al. (2000), the deformation regime in the southern Mozambique belt was transpressional and the deformation was partitioned; transcurrent shearing was localized within the vertical shear zones and large-scale folding accommodated transverse shortening. Through a regional scale investigation of the C- and O-isotopes compositions of carbonates from marbles and metabasites, Pili et al. (1997b) have shown that CO$_2$ in the major wrench faults of the network has a mantle origin. This suggests that these major faults were connected to the mantle. On the other hand, in minor shear zones and in metamorphic rocks outside the shear zones, CO$_2$ has a crustal isotopic signature. In the same region, Pili et al. (1997a) documented a systematic association of a short wavelength positive gravity anomaly to major strike-slip shear zones that also supports a deep rooting of the major wrench faults of the Mozambique belt. This anomaly was interpreted as due to a shallower crust-mantle boundary beneath the faults. Such an upward deflection of the Moho might result from thinning of the crust in response to the intense stretching associated with simple shear in the fault zones (Pili et al., 1997a).

In NE-Brazil as well as in the Madagascar Neoproterozoic belts, strain localization in transcurrent shear zones is observed even at crustal levels where synkinematic temperatures were high enough to induce partial melting. The width of the fault zones is extremely large (several tens of kilometers) compared to typical widths of shear zones developed under lower temperature conditions (cm to hundred m). This points out that, at these high temperatures, strain localization was less efficient and strain was distributed over a larger volume of rocks than it is usually observed in upper crustal shear zones. Rocks within the shear zones display a high-temperature mylonitic fabric largely due to dislocation creep assisted by very effective diffusional processes (in particular grain boundary migration), and consistent shear criteria. In addition, petrological and geochemical observations strongly suggest that fluids percolated from the mantle into the crust along these major shear zones, and therefore that the faults were continuous through the upper mantle.

"Moho" faults vs. lithospheric faults

The observations presented above strongly support that major transcurrent faults do not root in some intracrustal decoupling level, but rather crosscut the entire crust and are, in some way, connected to the upper mantle. These observations are however not sufficient to evaluate whether those faults are rooted at the crust-mantle interface or penetrate deeply into the upper mantle. Clear evidence supporting that major wrench faults crosscut the Moho and penetrate deeply into the upper mantle is nevertheless obtained by combining various
techniques of geophysical exploration of the lithosphere. Evidence may be subdivided in two groups. Seismic profiling, magnetotelluric soundings, and seismic tomography have imaged "Moho faults" (Diaconescu et al., 1997), i.e., discontinuities crosscutting the Moho beneath several wrench faults observed at the surface. On the other hand, electric conductivity anisotropy evidenced in magnetotelluric soundings, azimuthal anisotropy of Pn velocities, and S-waves splitting are directly related to the tectonic fabric of the upper mantle and support that the lithospheric mantle was deformed in major wrench faults.

Electric conductivity anisotropy in the upper mantle is interpreted as due to a preferred orientation of graphite films elongated along the foliation (Mareschal et al., 1995) or to an anisotropic electrical conductivity in a "wet" mantle due to the anisotropy of H² diffusion in the olivine crystal (Mackwell & Kohlstedt, 1990; Simpson, 2001). In both cases, a "wrench-fault type fabric" (i.e., a steeply-dipping flow plane, or foliation, containing a subhorizontal flow direction, or lineation) within the mantle would generate a higher conductivity parallel to the trace of the wrench fault observed at the surface.

Seismic anisotropy in the upper mantle, which may be characterized by measurement of an azimuthal anisotropy of Pn velocities or by the splitting of teleseismic S-waves, results from the lattice preferred orientation (LPO) of rock-forming minerals during high-temperature deformation by dislocation creep. Wrench-faulting within the lithospheric mantle would generate a LPO of olivine, the dominant mineral phase in mantle peridotites, characterized by a concentration of [100] axes close to the lineation (i.e., subhorizontal) and of [010] axes normal to the foliation plane [Figure 6; Tommasi, 1999 #3215]. Olivine is elastically anisotropic. Thus if deformation produces coherent olivine LPOs at the scale of tens of km in the upper mantle, it also results in anisotropic seismic properties (Mainprice & Silver, 1993; Nicolas & Christensen, 1987; Silver et al., 1999). P-waves that propagate either parallel to the maximum of [100] or [010] axes of olivine in the mantle are respectively the fastest and the slowest. On the other hand, S-waves propagating through a deformed upper mantle split into two quasi-S waves polarized in orthogonal planes; the fastest one is polarized in a plane containing both the maximum concentration of olivine [100] axis and the propagation direction. The delay time between the arrivals of the two split waves is proportional to both the length of wave propagation path within the deformed layer and the propagation direction relative to the structural fabric; the largest S-waves splitting is observed for waves that propagate at low angles to the maximum of [001] axis. A wrench-fault fabric in the mantle would therefore be evidenced (Figure 6) by a fast propagation of P-waves (in particular, horizontally propagating Pn waves) parallel to the fault and a polarization of the fast split S-wave in a plane containing both the direction of propagation of the wave and the lineation, i.e., parallel to the fault direction for waves having an almost vertical incidence (such as SKS, SKKS, PKS...). It is also in this case that the birefringence will be the largest, leading to relatively large time lags between the arrivals of the fast and slow split S-waves. Indeed, SKS splitting data above transform boundaries, such as the Caribbean or the Alpine fault in New Zealand, systematically display fast shear waves polarized parallel to the transform direction and delay times significantly larger than 1s, which imply that the entire lithosphere deformed in a strike-slip regime (Klosko et al., 1999; Russo et al., 1996).

These techniques "probe" the upper mantle fabric with different spatial resolutions and depth sensitivities. Magnetotelluric

Figure 6: Cartoon illustrating the concept of lithospheric fault, in which crustal fault zones broaden downward and tend to coalesce forming a broad shear zone that cuts across the entire lithospheric mantle. It displays the tectonic fabric associated with the fault within the crust and the mantle, the crystallographic fabric of olivine expected to develop in the mantle section of such a fault zone (oriented in the structural framework of the fault: X=lineation and Z=normal to the foliation), and the splitting of a polarized incoming shear wave that propagates across a lithospheric mantle displaying a "wrench fault type" fabric. A seismic station locate above such a lithospheric shear zone will record a fast shear wave polarized parallel to the shear zone trend (X direction) and strong delay times (>1s).
soundings using a large spectrum of measurement frequencies allow an evaluation of the electrical conductivity anisotropy from the crust to the asthenospheric mantle. However, MT data depend on both anisotropy and heterogeneity of electrical conductivity, and reliable anisotropy determinations may only be obtained when high-quality, long-period MT transfer functions are available and lateral conductivity gradients are small (Simpson, 2001). Pn waves sample the uppermost mantle (3–5 km beneath the Moho), but the measured velocities depend on both the anisotropy and the heterogeneity (in temperature and composition) along the wave path. Teleseismic S-waves splitting provides reliable evidence of seismic anisotropy with a very good spatial resolution (ca. 50 km), but these measurements integrate all anisotropic contributions along the wave path (which is roughly vertical from the core-mantle boundary to the surface for the most commonly used SKS waves). Their association should therefore allow us to better constrain the structural fabric of the upper mantle. Indeed, comparison of electric conductivity anisotropy determined by magnetotelluric soundings and S-waves splitting measurements shows that the direction of largest conductivity and the fast split S-wave polarization plane are often almost parallel (Barruol et al., 1997b; Simpson, 2001; Wannamaker et al., 1996) or make a slight, but consistent angle (Mareshal et al., 1995). Ji et al. (1996) interpreted this slight obliquity as representing the obliquity between the foliation and the shear plane in shear zones.

To investigate how deep a "wrench fault fabric" may penetrate into the upper mantle, we analyze geophysical data for several ancient or active wrench faults and transpressional belts. In each case, transcurrent displacement, either in a single fault or in a broader domain of transpressional deformation, is supported by surface geology.

**Transcurrent shear zones**

Recently, Pollitz et al. (Pollitz et al., 2000; Pollitz et al., 2001) using a combination of GPS and synthetic aperture radar (InSAR) data, have shown that the deformation in the years following the 1992-Landers and 1999-Hector Mine major earthquakes in the Mojave desert (California-USA) was about 3 times greater than before the earthquakes. This interseismic velocity field supports a right lateral displacement parallel to the San Andreas transform fault system (Figure 7). According to these authors, the visco-elastic relaxation of the lower crust and upper mantle was the dominant postseismic process; this requires that the lower crust acted as a coherent stress guide coupling the upper crust with the upper mantle (Pollitz et al., 2001).

**Figure 7:** (a) Structural sketch displaying the active faults in California. (b) Shear-wave splitting in western California from Hartog et al. (2001). Anisotropy beneath the westernmost stations, i.e., those above the San Andreas Fault system, results from the superposition of two anisotropic layers. The upper layer, which corresponds to the lithospheric mantle, is characterized by a polarization of the fast shear wave (black bars) in a plane parallel to the San Andreas Fault system and a delay time close to or even higher than 1 s. The easternmost stations display a simpler anisotropy pattern (gray bars) that may be accounted for by a single anisotropic layer with a roughly E-W flow direction. A similar flow direction is inferred for the lower anisotropic layer (gray bars) in the westernmost California. (c) Horizontal velocity field showing the contemporary interseismic deformation across southern California (relative to a group of GPS and VLBI stations on the stable North American Plate). Geodetic data include Global Positioning System (GPS), Very Long Baseline Interferometry (VLBI), and Electro-optical Distance Measurement (EDM) obtained by the Crustal Deformation Working Group of the Southern California Earthquake Center during the past three decades. Error ellipses are regions of 95% confidence. Release 2, 1998, available at: http://www.scecdc.scec.org:3128/group_e/release_v2
These conclusions are consistent with those drawn from the analysis of the seismic anisotropy measured across the San Andreas Fault system slightly north of the Landers and Hector Mine earthquakes area (Hartog & Schwartz, 2001; Ozalaybey & Savage, 1995; Silver & Savage, 1994). The shear waves splitting parameters retrieved from a large number of records consistently suggest two layers of anisotropy within the upper mantle (Figure 7). The upper layer, which corresponds to the lithospheric mantle, is characterized by a polarization of the fast split shear wave parallel to the San Andreas Fault system. This suggests that the lithospheric mantle has a tectonic fabric consistent with the crustal fabric, i.e., a steeply dipping foliation bearing a subhorizontal lineation. Both geodetic and seismologic observations therefore converge toward a coherent deformation of the entire lithosphere.

The Himalayan orogen provides some of the best examples of active wrench faults in an intracontinental setting. These faults have accommodated large lateral displacements associated with the India-Asia collision (e.g., Tapponnier et al., 1986). The main faults of the system have been mapped over hundreds of kilometers and are commonly several kilometers wide. The Red River fault, for instance, was recognized over 1000 km from Tibet to the Gulf of Tonkin. Pham et al. (1995) have performed a 70 km long magnetotelluric profile across the Red River fault system in North Vietnam (Yen Bai region). In this area, the Red River system is formed by three parallel transcurrent faults, a few tens of kilometers apart (Tapponnier et al., 1990). This MT survey (Figure 8) shows that: 1) each fault is characterized by a high conductivity zone down to the uppermost mantle, 2) the Sông Hồng fault, the main branch of the Red River fault system, separates two lithospheric domains presenting contrasted electrical properties, and 3) a large conductivity anisotropy is observed in both the crust and the uppermost mantle; the direction of highest conductivity is consistently parallel to the strike of the faults. This anisotropy is consistent with a steeply dipping foliation within the uppermost mantle as well as in the entire crust.

In Tibet, seismic anisotropy measurements have been performed above and in the vicinity of two other well-known major wrench faults, the Altyn Tagh and the Kunlun faults. These faults, several hundreds of kilometers long (1800 km for the Altyn Tagh fault), have accommodated several hundreds km of lateral escape during the India-Eurasia collision (e.g., Tapponnier et al., 1986). Wittlinger et al. (1998) have performed a seismic tomography study of an area where the Altyn Tagh fault juxtaposes Precambrian basement with the Qailam sedimentary basin. This tomography shows a southeastern domain characterized by low-velocity perturbations in contrast with a northwestern domain where high-velocity
perturbations dominate. The limit between these domains is marked by a low-velocity anomaly located just beneath the Altyn Tagh fault (Figure 9a). From these results Wittlinger et al. (1998) have suggested that the Altyn Tagh fault in the mantle is ca. 40 km wide and is continuous down to a depth of 140 km at least. In addition, shear-wave splitting measurements above the Altyn Tagh fault (Herquel et al., 1999) show fast split shear waves polarized in a plane parallel to the trend of the fault and delay times between the fast and slow S-waves arrivals of ca. 1s. Such delay times require a thickness of anisotropic mantle of ca. 100 km, in agreement with the values of fault penetration inferred from seismic tomography (Figure 9b). Shear-wave splitting measurement above and across the Kunlun fault (Herquel et al., 1999; McNamara et al., 1994) have reached similar results. Approaching the Kunlun fault zone the orientation of the fast S-wave polarization plane progressively rotates into parallelism with the trend of the fault, suggesting a shear strain gradient and an upper mantle fabric similar to that in the crust. The 2s of delay time measured above the Kunlun fault requires a thickness of anisotropic material >200 km, assuming a steeply dipping flow plane and a subhorizontal flow direction, thus larger than the lithosphere thickness. This suggests that the asthenosphere fabric also contributes to the recorded anisotropy and deforms somewhat coherently with the lithosphere.

Similar observations also characterize ancient wrench faults whose fabric was frozen into the lithospheric mantle at the end of the orogenic evolution. The Great Glen – Walls Boundary fault (GGWBF) is a major wrench fault that belongs to a more complex fault array developed in the northern segment of the Caledonian belt between 428 and 390 Ma (e.g., Stewart et al., 1999). Two segments of the initial fault are exposed: the Great Glen fault in Scotland and the Walls Boundary fault in the Shetland Islands. Paleomagnetic reconstructions suggest that several hundred kilometers of sinistral strike-slip displacement

![Figure 9: Mantle structure beneath the Altyn Tagh and Kunlun active faults in Tibet. (A) Cross section displaying the main geological structures and the P-wave velocity structure across the Altyn Tagh fault system (Wittlinger et al., 1996). Light gray and dark gray colors correspond to the crust and mantle, respectively. Lighter shades in both layers indicate domains of lower P-wave velocities. (B) Compilation of shear-wave splitting measurements across the Kunlun and Altyn Tagh faults from Herquel et al. (1999). Both faults are characterized by a fast split shear wave polarized parallel to the trend of the fault, contrasting significantly with the anisotropy pattern away from the faults.](image)

![Figure 10: Shear-wave splitting in northern UK from Helffrich (1995). Initials (e.g., MCD, LRW...) represent the name of the stations. APM is the Absolute Plate Motion in the hot-spot framework calculated using Morgan and Morgan's model (see, Barruol et al., 1997a). Thick gray line north of the Shetland Islands marks the location of the UNST deep seismic reflection profile displayed in Fig. 11.](image)
have been accommodated along this fault. Shear-wave splitting has been measured (Helffrich, 1995) at stations close to the GGWBF in Scotland (Figure 10; station MCD) and in the Shetland Islands (Figure 10; station LRW). In both stations, the fast split shear wave is polarized in a plane parallel to the trace of the fault and a delay time of 0.94 and 0.53 s is observed between the arrivals of the two SKS waves for MCD and LRW, respectively. The fast S-wave polarization direction close to the fault is significantly oblique to the fast polarization direction measured at other stations in the British Caledonides (Barruol et al., 1997a). Interestingly, several seismic profiles performed across the GGWBF, in Scotland as well as in the Shetland Islands (e.g., Klemperer & Hobbs, 1991; Klemperer et al., 1991; McGeary, 1989), show topography and a change in the seismic expression of the Moho tightly associated with the trace of the GGWBF at the surface (Figure 11). These features have been interpreted as due to the fault crosscutting the Moho and bounding two initially remote domains that show contrasted seismic responses. This interpretation is in good agreement with shear-wave splitting measurements. Altogether these results strongly suggest that the GGWBF, rather than being rooted in some crustal decoupling level (McBride, 1995), is a lithospheric fault that crosscuts the Moho and penetrates deeply into the upper mantle.

The well-known South Armorican Shear Zone (SASZ) in Brittany, France, is a major intracontinental transcurrent fault formed during the Hercynian orogeny. Surface geology evidence of strain localization and strike-slip displacement has been reported in a large number of papers (e.g., Berthé et al., 1979; Jegouzo, 1980). The fault is located north of the high-pressure domain that marks the trace of the suture between two collided continents. A seismic velocity model of the structure of the lithosphere down to 200km beneath Brittany has been obtained through a recent passive seismology experiment (Granet
et al., 2000; Judenherc, 2000). P-wave velocity perturbation models show a marked contrast between two domains (Figure 12): the northeastern domain is characterized by a positive velocity anomaly, whereas the southwestern domain displays negative anomalies. The limit between these two domains coincides with the trace of the SASZ and is observed down to the base of the lithosphere. In addition, the direction of fast propagation of Pn waves and the direction of the polarization plane of the fast split shear wave are consistently parallel to the trend of the SASZ. The delay time between the fast and slow split shear waves at stations close to the SASZ is consistently larger than 1s, also suggesting that the entire lithosphere displays a "wrench-fault type" fabric (Judenherc, 2000). These results are very consistent and altogether suggest that the South Armorican Shear Zone crosscuts the entire lithosphere.

Combined magnetotelluric (MT) and seismic anisotropy measurements (Figure 13) have been recently performed in the vicinity of the Proterozoic Great Slave Lake shear zone (GSLSZ; e.g., Hanmer et al. 1992), in northwestern Canada (Wu et al., 2002). This NE-SW trending dextral wrench fault is 25 km wide and its magnetic expression can be correlated over 1300 km. This study provided interesting insights on the lithospheric structures associated with this major wrench fault: 1) The fault is associated with a crustal-scale resistive zone which is coincident with a magnetic low, 2) The resistivity structure in the lower crust to upper mantle is approximately 2D with a geoelectric strike N60°E parallel to the large-scale trend of the GSLSZ, and 3) There is a close parallelism between the orientation the fast split shear wave polarization plane and the geoelectric strike retrieved from long-period MT measurements. This similarity of seismic and electric conductivity anisotropies suggests that they both have an origin related to the wrench fault fabric of the lithospheric mantle beneath the GSLSZ.

Transpressional orogenic domains

Often, orogenic domains as a whole have been submitted to a transpressional deformation characterized by the association of thrusting normal to the belt and lateral escape accommodated by transcurrent faulting parallel to the belt. Recently, Meissner et al. (2002) using Pn anisotropy measurements have shown that in such domains the uppermost (sub-Moho) mantle is characterized by a fast propagation of P-waves parallel to the trend of the belt, pointing to a flow fabric in the uppermost mantle dominated by the lateral escape of lithospheric blocks. Shear-wave splitting measurements in active and fossil orogenic areas also record orogen-parallel flow directions in the upper mantle (e.g., Savage, 1999; Silver et al., 1999; Vauchez & Nicolas, 1991). Fast shear waves are polarized parallel to the trend of the transpressional belts, even in domains where crustal deformation is essentially accommodated by thrusting, and delay times frequently ≥ 1s indicate that this "wrench fault type" flow fabric affects the entire lithospheric mantle.
Taiwan is currently deforming in response to the oblique convergence between the Philippines and the Eurasian plates. As a result, the crust displays evidence of a transpressive deformation and strain is partitioned between thrusting and wrench faulting normal and parallel to the belt, respectively (e.g., Huang et al., 2000; Lallemand et al., 2001). Shear-wave splitting measurements by Rau et al. (2000) display nevertheless a coherent pattern over the entire Taiwan Island (Figure 14). S-waves generated in the Benioff zone by local earthquakes that probe the mantle above the subduction zone, are split. The fast shear wave is polarized parallel to the tectonic grain and delay times are up to 2s. These observations suggest that the upper mantle beneath Taiwan has a homogeneous transcurrent/transpressional fabric due to northward tectonic escape, i.e., a transport direction parallel to the active orogen.

The Neoproterozoic Ribeira orogenic belt of Southeastern Brazil formed during the final amalgamation of Gondwana between 580 and 540 Ma (Egydio-Silva et al., 2002). The southern and central domains of the belt were subjected to an oblique convergence between the South American and African protocontinents (Figure 15a). This resulted in development of numerous dextral wrench faults, hundreds of kilometers long and up to 10 kilometers wide, oriented parallel or slightly oblique to the belt. In the central domain, the current level of erosion (17-20 km) shows mylonites that formed at high temperature (T>800°C) and continued to deform during a slow cooling down to ca. 740°C. Southward, the erosion level is more superficial and the shear zones are marked by mylonites formed under amphibolite facies metamorphic conditions (Vauchez et al., 1994). The wrench faults reworked a slightly older low-angle foliation due to thrusting toward the South American protocontinent. During the late orogenic stages, both orogen-normal thrusting and orogen-parallel wrench faulting occurred. As a whole, the southern-central Ribeira belt represents a transpressional orogenic segment about 100km wide and almost 1000 km long (Trompette, 1994). Shear-wave splitting measurements performed over the southern branch of the Ribeira belt (Heintz et al., 2000) have yielded a coherent pattern characterized by a polarization of the fast S-wave in a direction parallel to the orogenic grain (Figure 15b), suggesting that the bulk volume of lithosphere in the transpressional domain has a "wrench fault-type fabric". Larger delay times between the fast and slow shear waves arrivals (up to 2.5s) have usually been retrieved from data recorded above or close to the main shear zones, suggesting that strain was not homogeneously accommodated but was somewhat localized in the main shear zones.

Figure 14: Deep structure beneath the active Taiwan orogen. A: simplified map showing the geodynamic situation of the Taiwan orogen (from Lallemand et al., 2001). B: Shear-wave splitting measurements (Rau et al., 2000) using S waves from local earthquakes and teleseismic ScS.
The Pyrenees in Western Europe (Figure 16) formed during the Mesozoic due to displacement of Iberia relative to Eurasia. This motion, generated by the opening of the Atlantic ocean between North America and Iberia, was mainly accommodated along the North Pyrenean fault (e.g., Choukroune, 1992). At first, the deformation regime was transtensive and several pull-apart basins formed. Then, during the final stages of the evolution it became transpressive and finally compressive. Indeed, the North Pyrenean fault, i.e., the rupture between Iberia and Eurasia, reactivated an older, pervasive transpressive fabric formed during the late stages of the Hercynian orogeny (e.g., Bouchez & Gleizes, 1995; Vauchez & Barruol, 1996). Shear-wave splitting measurements performed across the Pyrenees and adjacent areas revealed a very consistent pattern of anisotropy (Barruol et al., 1998). The fast shear wave polarization plane is usually oriented parallel to the belt, and the delay between the fast and slow S-wave 

Figure 15: Lithospheric structure of the Neoproterozoic Ribeira transpressive belt. (a) Cartoon showing the geodynamic situation of the Ribeira-Araguad-West Congo orogen (light grey) at the end of the Gondwana assembly (580-540 Ma): (1) Archean and Mid-proterozoic eratic domains, (2) Neoproterozoic belts, (3) main wrench faults in the Ribeira belt, and (4) large-scale kinematics at the end of the Gondwana assembly. Shaded areas mark continental domains stabilized before 600 Ma. (b) Core shear waves splitting measurements in the central-southern Ribeira belt and the southern Brazilian belt (Heintz et al., 2000).

Figure 16: Shear-wave splitting in the Pyrenees and adjacent areas. (a) Sketch map of the main hercynian structural directions in the Pyrenees and adjacent regions. NPF is for the North Pyrenean Fault and SASZ for the South Armorican Shear Zone (see Figure 12). The relative position of Iberia relative to Europa is the current position. (b) Shear-wave splitting measurements in the Pyrenees (Barruol et al., 1998). At each location, the size of the circle is proportional to the delay time that is usually >1s and the line indicates the polarization of the fast split shear wave.
arrivals is larger than 1s, even beyond the Mesozoic Pyrenees belt. Pn anisotropy measurements (Judenherc et al., 1999) are in good agreement with S-wave splitting measurements; the fast propagation direction of Pn is also parallel to the Hercynian/Pyrenean tectonic fabric, suggesting that the entire lithosphere beneath the probed area has a coherent "wrench fault type" fabric.

The analysis of the seismic anisotropy data for the active orogen of Taiwan, the Neoproterozoic Ribeira belt and the Hercynian/Alpine Pyrenean belt leads to similar conclusions. S-waves splitting results are consistent with seismic anisotropy models in which the lithospheric mantle deforms by homogeneous transpression, instead of the partitioned mode displayed by the crust (Tommasi et al., 1999). However, the tectonic fabric of the mantle does not correspond to the classical transpression as defined by Sanderson and Marchini (1984, i.e., with a vertical stretching), but rather to lengthening-thinning shear (i.e., plane transpression, Tikoff & Fossen, 1999; Tommasi et al., 1999). This deformation regime involves simultaneous shortening normal and stretching parallel to the trend of the belt and results in a lateral escape of the lithospheric mantle. This may explain why observation of a seismic anisotropy coherent with orogenic-normal thrusting at the scale of the lithosphere is so scarce (e.g., Silver, 1996).

**Lithospheric wrench faults: Thermomechanical effects**

The various examples presented above converge toward a model of major wrench faults deeply rooted into the upper mantle. Especially seismic tomography and shear-wave splitting observations support that the fault fabric affects the entire lithosphere thickness. The width of the domain presenting a "wrench fault-type" fabric likely ranges between several tens of kilometers for a single fault to several hundreds of kilometers for a transpressional domain involving various transcurrent and thrust faults. Moreover, seismic anisotropy observations using long-period data such as SKS waves imply that the olivine lattice preferred orientation associated with this "wrench fault-type" fabric, characterized by horizontal [100] axes and vertical (010) planes, both parallel to the fault trace, is coherent at scales ≥ 50 km.

On the other hand, the olivine crystal does not only display an anisotropic elasticity, which leads to the observed seismic anisotropy. The plastic deformation and thermal diffusivities of olivine also are highly anisotropic (Bai et al., 1991; Chai et al., 1996; Durham & Goetze, 1977; Kobayashi, 1974). Thus if major wrench faults are characterized by a coherent olivine lattice preferred orientation that affects the entire lithosphere over domains several hundreds (or thousands in the case of a transpressional belt) of kilometers long and tens (or hundreds) of kilometers wide, these domains might also be the source of a large-scale mechanical and thermal anisotropy within the continental lithosphere that may influence the thermomechanical behavior of the plate during subsequent tectonic events.

**Strain-induced mechanical anisotropy of the continental lithosphere**

Experimental deformation of olivine single crystals under different orientations relative to its crystallographic lattice shows that olivine has only three independent slip systems and that these systems display significantly different strength or critical resolved shear stress (CRSS) values (Bai et al., 1991; Durham & Goetze, 1977). Under high-temperature conditions, the (010)[100] slip system displays the lowest critical resolved shear stress; this means that, compared to the other possible slip systems, for a given stress it is able to accommodate the largest slip rate, or, conversely, that it requires the lowest built-up resolved shear stress to accommodate a given strain rate. In other words, for deformation in the dislocation creep regime, which is expected to prevail in the lithospheric mantle in active areas, olivine displays an anisotropic viscosity.

In a lithospheric wrench fault, the weakest (010)[100] slip system is oriented parallel to the fault, i.e. the olivine crystals are preferentially oriented with the (010) plane
subvertical and the [100] axis horizontal, parallel to the shear direction. The question is whether the anisotropic mechanical behavior of the olivine single crystal combined with such a LPO coherent over large scales in the lithospheric mantle may result, at the scale of the lithospheric mantle, in an anisotropy of viscosity large enough to influence the deformation of the lithosphere during subsequent tectonic solicitations.

Tommasi and Vauchez (2001) used a polycrystal plasticity model to investigate the effect of a pervasive "wrench fault-type" fabric frozen in the lithospheric mantle on the continental breakup process. In this work, the deformation of an anisotropic continental lithosphere in response to an axi-symmetric tensional stress field produced by an upwelling mantle plume was evaluated by calculating the deformation of textured olivine polycrystals representative of the lithospheric mantle at different positions above a plume head (Figure 17). These models show that an LPO-induced mechanical anisotropy of the lithospheric mantle may result in directional softening, leading to heterogeneous deformation. Reactivation of the inherited crystallographic fabric, which is favored by tensional stresses oblique to its trend, is characterized by higher strain rates than other deformation regimes.

The reactivation of the pre-existing fabric also results in higher strain rates than those accommodated by an isotropic mantle in similar conditions. During continental rifting, this mechanical anisotropy may thus induce strain localization in domains where extensional stress is oblique (30-60°) to the pre-existing mantle fabric. The directional softening associated with olivine LPO frozen in the lithospheric mantle may also guide the propagation of the initial instability that will follow the pre-existing structural trend. The inherited mantle fabric also controls the deformation regime, imposing a strong strike-slip shear component to the deformation. An LPO-induced mechanical anisotropy may therefore explain both the systematic reactivation of ancient collisional belts during rifting (structural inheritance) and the onset of transtension within continental rifts.

**Figure 17.** Predicted deformation of a lithosphere displaying a wrench fault-type fabric above a mantle plume (Tommasi & Vauchez, 2001). (a) Strain rate (von Mises equivalent strain rate, normalized to the isotropic behavior) as a function of the orientation of the radial tensional stress relative to the [100] axis maximum of the preexisting LPO for points above the plume head periphery for three models with different initial LPOs. (b) Normal and shear components of the strain rate tensor (normalized by the von Mises equivalent strain rate displayed by an isotropic polycrystal) for the model in which the initial LPO is the model aggregate. The reference frame is defined relative to the pre-existing mantle fabric: X is parallel to the [100] axis maximum, i.e., parallel to the pre-existing structural trend, Y is normal to the pre-existing shear plane, and Z is vertical. Positive normal strain rates denote extension and negative ones, shortening. Gray region marks orientations that may trigger strain localization.
These results, obtained for a specific geodynamic case, can be extended to a more general situation. In major strike-slip faults and transcurrent/transpressional orogenic domains, the inherited fabric of the lithospheric mantle should induce a directional softening, with the consequence that this fabric should be preferentially reactivated. Development of new structures oblique to the preexisting shear zones should only be observed when the new tectonic solicitations (either distensive or compressive, Figure 18) are normal or parallel to the inherited foliation, i.e., when no shear stresses are applied parallel to the inherited fabric. In most cases, reactivation will occur through transtension or transpression, and the relative proportion of simple and pure shear depends on the obliquity of the stress axes relatively to the inherited fabric.

The crustal fabric in lithospheric-scale shear zones also contributes to this mechanical anisotropy. Indeed, localized deformation in the middle and lower crust gives rise to strong LPOs. Crustal minerals, in particular micas that are important phases in mylonites, display a still stronger mechanical anisotropy than olivine; their layered structure results in plastic deformation accommodated by glide on the (001) plane only. In addition, strength variations in polymineralic crustal rocks often gives rise to a mm- to cm-scale compositional layering parallel to the shear zone that, at a larger scale, also contributes to a directional weakening and reactivation of the shear zone. Finally, grain-size reduction associated with shearing in the upper/middle crust may result in an isotropic strain-softening within the shear zone; at these depths, the shear zone will thus act as a planar weak heterogeneity localizing the subsequent deformation.

Repeated reactivations of major transcurrent shear zones or domains during long periods of time and the necessity for the cause of this persistence to be in the lithospheric mantle have been recognized long ago (e.g., Watterson, 1975). Many examples of such reactivation in various geodynamic environments are available in the literature. Tommasi and Vauchez (2001) have already discussed those related to the reactivation of lithospheric-scale shear zone or transpressional belts during continental rifting. So we will focus on one of the best illustrations of the reactivation of a collisional wrench fault as a transform boundary: the development of the Newfoundland-Azores-Gibraltar transform plate boundary at the northern edge of the central Atlantic Ocean during the Early Mesozoic (Figure 19). The Newfoundland-Azores-Gibraltar fault zone formed a major
Figure 19: Fit of the Central and North Atlantic ocean showing that the initial rift in the central domain propagated parallel to the Hercynian orogen and that the Newfoundland-Azores-Gibraltar hercynian wrench fault was reactivated in the Mesozoic as a transform fault transferring extension from the Central Atlantic basin to the Thetys basin.

Hercynian dextral strike-slip fault zone that offsets the Appalachians orogenic front in Newfoundland (Keppie, 1989). During the final stages of the Appalachian-Variscan convergence, this fault accommodated the relative displacement between the Iberian and North African blocks. This fault subsequently played a major role on the Central Atlantic initial rifting, limiting one of the promontories of the North American stable margin. Indeed, the opening of the central Atlantic Ocean took place almost simultaneously from Florida to the Newfoundland-Azores-Gibraltor transform (the first Central Atlantic magnetic anomaly, M25 is identified along this entire segment (Owen, 1983)), but further northward propagation of the Central Atlantic leading to separation between Eurasia and North America did not occur until Late Cretaceous time. From mid-Jurassic to Late Cretaceous time, the Newfoundland-Azores-Gibraltar transform connected the Central Atlantic and the Thetys oceanic basins, accommodating the differential motion between Africa and Europe.

Thermal conductivity anisotropy

Heat transfer is a key process controlling the Earth's dynamics, since temperature is a major parameter controlling the rheological behavior of both crustal and mantle rocks. Thermal conductivity in both mantle and crust is usually assumed to be isotropic. Yet, experimental data shows that, at ambient conditions, the dominant mineral phases in the crust and upper mantle display a large anisotropy of thermal diffusivity. In olivine, for instance, heat conduction parallel to the [100] crystallographic axis is 1.5 times faster than parallel to the [010] axis (Chai et al., 1996). Quartz and micas, the main constituents of crustal mylonites also display a strongly anisotropic thermal conductivity, with the highest and lowest conductivities parallel to the [001] axis and within the (001) plane, respectively (Clauser & Huenges, 1995).

This thermal anisotropy is also observed at the rock scale. Recent studies combining petrophysical modeling and thermal diffusivity measurements on upper mantle rocks (Tommasi et al., 2001) show that a deformation-induced olivine LPO may result in a significant thermal diffusivity anisotropy in the uppermost mantle: heat transport parallel to the olivine [100] axes concentration (flow direction) is up to 30% faster than normal to the flow plane ([010] concentration). Moreover, in the studied temperature range (300 to 1250 °K), the thermal diffusivity anisotropy does not depend on temperature, suggesting it might be preserved even at higher temperatures corresponding to asthenospheric conditions. Seismic anisotropy data, like those presented in the previous sections, indicate that major wrench faults are characterized by a coherent olivine lattice preferred orientation that affects the entire lithosphere over domains several hundred (or thousand in the case of a transpressional belt) of kilometers long and tens (or hundreds) of kilometers wide. This "wrench fault type" fabric should therefore induce a large-scale thermal diffusivity anisotropy in the lithospheric mantle, characterized by faster heat conduction within
the shear zone parallel to the shear direction and slower conduction normal to the shear zone.

A similar thermal anisotropy should be present in the crustal section of a lithospheric shear zone. Laboratory measurements of thermal conductivity of gneisses drilled in the KTB borehole show up to 40% of anisotropy (Buntebarth, 1991). In these samples, which display mineralogical compositions (quartz, micas, andfeldspars) and microstructures similar to those of high-temperature mylonites in the Borborema, Ribeira, and Madagascar shear zones, heat conduction parallel to the foliation plane is on average 1.2 times faster than normal to it. A weaker anisotropy is observed within the foliation plane, with the highest conductivity measured parallel to the lineation. Comparison between measured thermal conductivities and those predicted by petrophysical modeling suggests that, similarly to the mechanical anisotropy, the major contributions to the gneisses thermal conductivity anisotropy stems from the strong LPO of micas and quartz (Siegesmund, 1994).

Existence of a large-scale, strain-induced thermal anisotropy in the upper mantle implies that the temperature distribution, rheology, and, hence, the upper mantle dynamics depend on its deformation history. Olivine orientations frozen in the continental lithosphere may modify plume-lithosphere interactions for instance. Enhanced thermal diffusivity along lithospheric-scale wrench zones, i.e., parallel to the olivine [100] preferred orientation, may lead to anisotropic heating of the lithosphere above a mantle plume, favoring the reactivation of these structures during continental break-up (Tommasi & Vauchez, 2001; Vauchez et al., 1999; Vauchez et al., 1998). Such a control of the pre-existing lithospheric structure on the propagation of a thermal anomaly may be inferred, for instance, from tomographic images of the East African rift in Kenya (Achauer & krispgroup, 1994). In these images, the low-velocity seismic anomalies display two main trends: a N-S trend, parallel to the surface expression of the East African rift, and a NW-SE trend following Neoproterozoic structures that were reactivated during the Mesozoic to give rise to the Anza rift.

**Conclusion**

**Geological and geophysical** observations in active and fossil orogenic belts converge to support that major wrench faults are rooted into the upper mantle. Huge transcurrent shear zones (several hundreds of kilometers long and a few tens of kilometers wide) in Brazil and Madagascar have been eroded down to levels where deformation was accommodated under high temperature conditions (650°C to >800°C) in partially melted rocks. It is remarkable that under these high-temperature and, hence, low-viscosity conditions, which were highly favorable to development of a decoupling level, no evidence of rooting of these shear zones has been observed; on contrary, strain was still localized in wide transcurrent shear zones. Seismic profiling, seismic tomography, Pn azimuthal anisotropy and magnetotelluric soundings also support that several major wrench faults crosscut the Moho discontinuity and penetrate the uppermost mantle. In addition, shear-wave splitting measurements and electric conductivity anisotropy above major strike-slip faults are in agreement with a "wrench fault type" mantle fabric coherent across most or even the totality of the lithosphere thickness. Indeed, transform fault boundaries as the San Andreas Fault, for which a connection with the mantle is required, display geophysical characteristics similar to those of the main intracontinental faults, either active or fossil. A similar conclusion is reached for transpressional orogenic domains deforming in response to oblique convergence/collision.

The existence of a "wrench fault-type" fabric into the continental mantle, besides inducing anisotropic elastic and electrical properties, may result in the development of a directional softening and an anisotropic conduction of heat in the continental mantle. These anisotropic properties probably influence the large-scale tectonic behavior of the continents. Reactivation of the inherited mantle fabric represents in most cases the most economic behavior in terms of energy.
Only in very specific situations (solicitation orthogonal or parallel to the ancient fabric), the pre-existing fabric of the lithospheric mantle will not be reactivated. Preferential propagation of continental break-up parallel to ancient orogenic belts as well as the systematic reactivation of major wrench faults likely result from both a directional softening and an anisotropic heat transfer due to wrench-type olivine-preferred orientations frozen in the continental mantle.

Finally, the work by Pollitz et al. (Pollitz et al., 2000; Pollitz et al., 2001) that suggests that the mantle beneath active wrench faults deform coherently with the crust and, in some way, determines the interseismic characteristics of the fault raises the question of the effect of the mechanical anisotropy of the lithospheric mantle on the dynamics of active faults. Characteristics of the fault like the slip rate, the stress building rate and therefore the magnitude and the recurrence of earthquakes could be affected by a lower stiffness of the mantle in a specific direction.

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