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Correction to "Extreme crustal thinning in the Bay of Biscay and the Western Pyrenees: From observations to modeling"

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Components: 2,235 words.

Index Terms: 8109 Continental tectonics: extensional: Tectonophysics; 8159 Rheology: crust and lithosphere: Tectonophysics; 0905 Continental structures: Exploration Geophysics; 0545 Modeling: Computational Geophysics; 1952 Modeling: Informatics; 4255 Numerical modeling: Oceanography: General; 4316 Physical modeling: Natural Hazards; 8031 Rheology: crust and lithosphere: Structural Geology; 8031 Rheology: crust and lithosphere: Corrections.

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[1] In the paper "Extreme crustal thinning in the Bay of Biscay and the Western Pyrenees: From observations to modeling," in order to give proper credit to the scientific contribution of Patricia Persaud, the author list has been changed to: Suzon Jammes,[1,2] Patricia Persaud,[3,4] Luc Lavier,[5,6] and Gianreto Manatschal.[7] The authors' affiliations are as follows: [1]*Institut de Physique du Globe de Strasbourg, EOST, Université de Strasbourg, Strasbourg, France;* [2]*Now at Department of Earth Science, University of Bergen, Allegaten 41, N-5007 Bergen, Norway (suzon.jammes@geo.uib.no);* [3]*Seismological Laboratory, California Institute of Technology, Pasadena, California, USA;* [4]*California State Polytechnic University, Pomona, California, USA;* [5]*Institute for Geophysics, Jackson School of Geosciences, University of Texas at Austin, Austin, Texas, USA;* [6]*Also at Department of Geological Sciences, Jackson School of Geosciences, University of Texas at Austin, Austin, Texas, USA;* [7]*Institut de Physique du Globe de Strasbourg, EOST, Université de Strasbourg, Strasbourg, France.*

[2] Section 4.1 "Modeling of Oblique Extension in 2.5 Dimensions" includes corrections and clarifications about the contribution of author Patricia Persaud to the work presented in the modeling section of the paper. It also includes multiple references to her thesis work [*Persaud*, 2004]. Section 4.1 reads as follow: "To check the validity of our geological assumptions and provide a continuous picture of the evolution of the rifted margin; in the limit of our understanding the physical processes driving deformation in the Earth's lithosphere, we ran 2D model experiments for the spontaneous development of structures similar to that observed in the Bay of Biscay and its vicinity. We use the code PARAVOZ developed by Yuri Podlatchikov and Alexei Poliakov [*Poliakov et al*., 1993]. This version is extended to account for energy conservation and particle phase and properties tracking to reduce phase boundary diffusion in between remeshings after large amounts of deformation [*Lavier and Buck*, 2002; *Lavier and Manatschal*, 2006]. To take into account the effect of the development of strike-slip structures, we solve the force balance out of the plane by calculating the forces resulting from the shear stresses in a plane perpendicular to the 2D model cross section. For each numerical time step, the modeling involves the quasi-static solution of the equation of motion for every grid point [*Cundall*, 1989]:

$$\frac{\partial \sigma_{ij}}{\partial x_j} - \rho g_i = 0 \quad (1)$$

where g_i is the acceleration due to gravity, ρ is the density, and σ_{ij} is the stress in each grid element with $i = x, y$, and z. We model strike-slip deformation in and out of the plane by calculating the force Fy resulting from the shear stresses applied in and out of the plane as [*Roy and Royden*, 2000]:

$$F_y = \frac{\partial \sigma_{yz}}{\partial z} + \frac{\partial \sigma_{yx}}{\partial x} \quad (2)$$

[3] We first use this formulation to establish the type of structure that the model will develop and we ran several experiments with small and large obliquity in a 10 km thick and 150 km wide layer [*Persaud*, 2004]. To model spontaneous accumulation of deformation on faults, we use an elasto-plastic constitutive update with a Mohr-Coulomb yield criterion. We assume that the yield stress of a brittle material is given by a linear Mohr envelope or Coulomb failure criterion. When that criterion is met, flow follows a rule for nonassociative plasticity. The cohesion and friction are reduced linearly with increasing strain after yielding [*Lavier et al*., 2000].

[4] Deformation in transtensional settings is commonly partitioned into strike-slip and tensional components [e.g., *Umhoefer and Dorsey*, 1997]. *Teyssier et al*. [1995] suggested that the angle between the rift margin and the direction of relative plate motion, θ, controls the efficiency of partitioning, with the transition between partitioned and nonpartitioned deformation occurring at $\theta = 20°$. These results were from analogue strain models of transpression, which in terms of strain, is the numerical inverse of transtension; therefore, these models may also apply in our case. Considering strain partitioning as the kinematic response of a deformation system to the applied boundary conditions [*Tikoff and Teyssier*, 1994], we test these predictions by examining how the style of deformation varies with obliquity with model setup similar to that of analogue models [*Persaud*, 2004].

[5] In the following analysis presented in *Persaud* [2004], the brittle crust is modeled as a single 10 km thick, 100 km wide, frictional and cohesional elastic-plastic material. We use two types of basal boundary conditions as end members, step or linear functions of velocity (Figure 6) [*Persaud*, 2004]. A step function of velocity represents one extreme form of basal shear, where shear is focused on a narrow fault zone and block like behavior is expected. A linear function of velocity is one representation of distributed shear, chosen for its simplicity [*Persaud*, 2004]. The basic model setup, parameterization and numerical resolution of the shear zone formation and weakening follow *Lavier et al*. [2000]. In all cases, a constant total plate velocity, $v_0 = 5$ cm.yr^{-1}, was applied to the sides of the models, which moved apart at different obliquities [*Persaud*, 2004]. Obliquity, r, is given as:

$$\mathrm{r} = \frac{v_y}{v_x + v_y} \quad (3)$$

where $v_x = v_0 \sin\theta$ is the extensional component of velocity and $\mathrm{v_y} = v_0 \cos\theta$ is the boundary condition. The relationship between r and θ is:

$$\tan\theta = \frac{1 - r}{r} \quad (4)$$

r is 0 for purely extensional and 1 for purely strike slip. The models in Figure 6 [*Persaud*, 2004] show a very wide range of structural styles, similar to that observed in rifts. As described in *Persaud* [2004], in the case of a step function like drag, by varying only the obliquity, we obtain localized rift structures ranging from half-graben (Figure 6a) to flower structures (Figure 6c) to single sag above a highly oblique fault (Figure 6e). These environments are similar to areas such as the Dead Sea Rift [*Rümpker et al*., 2003] or the East African Rifts [*Birt et al*., 1997]. In all models with step functions of basal velocity, deformation is localized on a single or few faults in the middle of the layer above the velocity discontinuity at 50 km (Figure 6, left). Low angle ($\theta < 45°$ dip) oblique-normal faults form at low values of obliquity, $\mathrm{r} < 0.35$ (Figure 6a), similar to the purely extensional cases of *Lavier et al*. [2000]. At higher obliquities, a single near-vertical fault forms in the center of the layer. This is accompanied by a set of conjugate normal faults if $\mathrm{r} < 0.9$. Slight normal offset on the near-vertical faults is evident in the topographic profiles (Figures 6c and 6e) even when normal faults coexist, indicating incomplete strain partitioning. For the cases with linear basal velocity boundary conditions, the deformation comprises a series of widely spaced half-graben with multiple oblique faults for a low obliquity (Figure 6b), and a series of sag basins separated by strike-slip faults accumulating normal offset for an intermediate obliquity (Figure 6d). Finally, for high obliquity, deformation is distributed over many strike-slip faults, each accumulating a small amount of normal offset (Figure 6f). When, at high obliquity, deformation becomes partitioned between normal faults and strike-slip faults, the blocks stuck between strike-slip and normal faults show differential rotation, forming structures typical in transtensional settings. Any of these styles of deformation can be encountered in settings of oblique divergence, or even in a single transtensional environment, e.g., the Gulf of California [*Persaud et al.*, 2003]. In all experiments with linear basal velocity boundary conditions, deformation is distributed across the entire width of the model (Figure 6, right). In these cases, multiple basins and oblique-normal faults form at low obliquities, $r = 0.25$ (Figure 6b). Starting at $r = 0.6$ ($\theta = 34°$), intrabasinal zones of steeply dipping faults develop, and strain is incompletely partitioned. We expect this from theory [*Tikoff and Teyssier*, 1994], but what we also see is a transition from shallower to steeper dips, with increasing obliquity and a closer spacing between faults as the strike-slip component increases [*Persaud*, 2004]. This was also noted in analog experiments on oblique convergence with solely basal boundary conditions [*Burbidge and Braun*, 1998]. The results for a linear drag function represent the same family of structures as in the case a step function drag. One can see that distributing the strain leads to a distribution of the partitioning over several structures or even a separation of highly oblique structures with steeply dipping fault zones and less oblique structures with shallower dipping faults [*Persaud*, 2004]. Whether distributed deformation in the lithosphere is due to viscous strengthening or elastic bending [*Buck and Lavier*, 2001], this phenomena should lead to the formation of multiple lower obliquity structures in highly oblique environments (Figures 6c and 6d). For the case of the Bay of Biscay and the Pyrenees addressed in this paper, the first phase of highly oblique deformation should, therefore, lead to the formation of multiple basins shaped as flower structures."

[6] The caption of Figure 6 should include the reference to Patricia Persaud's thesis work [*Persaud*, 2004] and should read: "Models of different structural styles that can be observed in oblique rift systems from *Persaud* [2004, Figure 2.5]. In these models, the obliquity 'r' is varied. On the left side, examples with a step function like drag, (a) half-graben; (c) flower structures; (e) single sag above a highly oblique fault. On the right side, in the case of a linear function, (b) widely spaced half-graben with multiple oblique faults; (d) series of sag basins separated by strike-slip faults accumulating normal offset; (f) deformation is distributed over many strike-slip faults, each accumulating a small amount of normal offset."

References

Birt, C. S., P. K. H. Maguire, M. A. Khan, H. Thybo, G. R. Keller, and J. Patel (1997), The influence of pre-existing structures on the evolution of the southern Kenya Rift Valley—Evidence from seismic and gravity studies, *Tectonophysics*, *278*, 211–242, doi:10.1016/S0040-1951(97) 00105-4.

Buck, W. R., and L. Lavier (2001), A tale of two kinds of normal fault: The importance of strain weakening in fault development, *Geol. Soc. Spec. Publ.*, *187*, 289–303.

Burbidge, D. R., and J. Braun (1998), Analogue models of obliquely convergent continental plate boundaries, *J. Geophys. Res.*, *103*, 15,221–15,237, doi:10.1029/98JB00751.

Cundall, P. A. (1989), Numerical experiments on localization in frictional materials, *Ing. Arch.*, *58*, 148–159, doi:10.1007/BF00538368.

Lavier, L., W. R. Buck, and A. N. B. Poliakov (2000), Factors controlling normal fault offset in an ideal brittle layer, *J. Geophys. Res.*, *105*, 23,431–23,442.

Lavier, L., and W. R. Buck (2002), Half graben versus large offset low-angle normal fault: Importance of keeping cool during normal faulting, *J. Geophys. Res.*, *107*(B6), 2122, doi:10.1029/2001JB000513.

Lavier, L., and G. Manatschal (2006), A mechanism to thin the continental lithosphere at magma-poor margins, *Nature*, *440*, 324–328, doi:10.1038/nature04608.

Persaud, P., J. M. Stock, M. S. Steckler, A. Martin-Barajas, J. B. Diebold, A. Gonzalez-Fernandez, and G. S. Mountain (2003), Active deformation and shallow structure of the Wagner, Consag, and Delfín Basins, northern Gulf of California, Mexico, *J. Geophys. Res.*, *108*(B7), 2355, doi: 10.1029/2002JB001937.

Persaud, P. (2004), Images of early continental breakup in and around the Gulf of California and the role of basal shear in producing wide plate boundaries, PhD thesis, Calif. Inst. of Technol., ProQuest, Ann Arbor, Mich.

Poliakov, A. N. B., Y. Podladchikov, and C. Talbot (1993), Initiation of salt diapirs with frictional overburdens-numerical experiments, *Tectonophysics*, *228*, 199–210, doi: 10.1016/ 0040-1951(93)90341-G.

Roy, M., and L. H. Royden (2000), Crustal rheology and faulting at strike-slip plate boundaries: 1. An analytic model, *J. Geophys. Res.*, *105*, 5583–5597, doi:10.1029/1999JB900339.

Rümpker, G., T. Ryberg, and G. Bock (2003), Boundary-layer mantle flow under the Dead Sea transform fault inferred from seismic anisotropy, *Nature*, *425*, 497–501.

Teyssier, C., B. Tikoff, and M. Markley (1995), Oblique plate motion and continental tectonics, *Geology*, *23*, 447–450, doi: 10.1130/0091-7613(1995)023<0447:OPMACT>2.3. CO;2.

Tikoff, B., and C. Teyssier (1994), Strain modeling of displacement-field partitioning in transpressional orogens, *J. Struct. Geol.*, *16*, 1575–1588, doi:10.1016/0191-8141 (94)90034-5.

Umhoefer, P. J., and R. J. Dorsey (1997), Translation of terranes: Lessons from central Baja California, Mexico, *Geology*, *25*, 1007–1010, doi/10.1130/0091-7613(1997) 025< 1007:TOTLFC>2.3.CO;2.