The transform fault – a golden calf of Plate Tectonics. Critique of the concept and alternative view on 'ridge transforms' (Case study Nr. 3)[1]

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Abstract. The hypothesis of Plate Tectonics created a multiplicity of concepts, among them *transform faulting*, which are disputable. It is shown that scientists are at strife in classifying faults with horizontal displacement since the term *transform fault* has been created half a century ago by Wilson (1965). In the view of the author the term should be restricted to faults that are genetically linked to ocean ridges, transecting them at various angles and materializing the shear component of oceanic spreading.

Introduction

The concept of transform faulting was introduced by Wilson (1965) and gained large acceptance in the geological community especially in regard of global kinematics because it proved to be "very successful in the geometrical considerations of plate tectonics" (Freund, 1974). Nevertheless, it seems to the present author that transform faults were loosely defined from the very beginning. Therefore it is not surprising that suggestions have been repeatedly made that the terms *transform* and *transcurrent* should be considered synonymous. Besides, the ever growing number of plates "identified" on the Earth's surface brought about also a proliferation of imaginary subduction zones as well as transform faults. It is the goal of this paper to throw some light upon the misuses of this concept and to present a new approach to the problem based on a simple but, I think, sound mechanical principle.

Ambiguous distinction between transform and transcurrent faults

According to Wilson (1965), transform faults are vertical shear dislocations of the lithosphere that link mobile structures like orogens or ocean ridges and end abruptly at these features where the shearing movement is 'transformed' into compressional or extensional movements, respectively.

One important criterion that distinguishes in the eyes of Wilson a transform from a transcurrent fault is the motion direction along ridge offsets which in the former case is opposite to, while in the latter – concordant with, that required to produce the offset (**Fig. 1**). To defend this viewpoint Wilson is, however, compelled to postulate that the offsets are only apparent: "The offset is merely a reflection of the shape of the initial break between continental blocks." Accordingly, the step-like aspect of a ridge trace would be a primary feature, inherited from the continental-rift stage.

[1] An enlarged version of this paper was presented under the title "Uses and misuses of the concept of transform faulting" at the International Conference << Problems of the Expanding Earth>> held at Wroclaw and Sosnowka, 14-17th November 1994. For this online presentation the paper was shortened and partially revised. With one exception, newer data were considered and referenced only in footnotes.

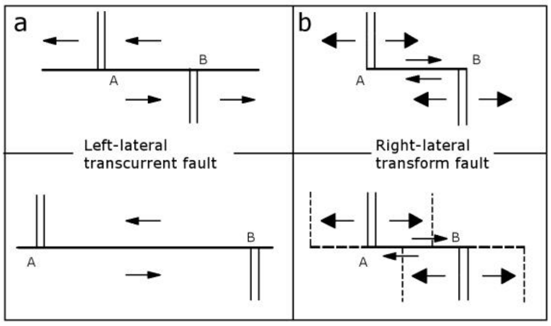

Figure 1. Two idealized stages in the evolution of a transcurrent (a) and a transform fault (b) transecting a ridge. The mechanisms are clearly distinct (Redrawn from Bleahu, 1983)

Soon after publication Wilson's paper became a corner-stone of the newly evolving Plate Tectonics Theory and transform faults an essential part in plate-tectonics reconstructions. According to this theory transform faults are subvertical, trans-lithospheric plate-bounding faults, whereas transcurrent faults are "only" intra-plate features (Freund, 1974; Sylvester, 1988, Lemiszki and Brown, 1988). However, this distinction turned out to be highly subjective. To stress on the confusion that exists in assigning the faults to the two "classes", it is sufficient to mention that some of the best studied faults, like the Great Glen or the North Anatolian Fault are considered transform faults by some authors (Lemiszki and Brown, 1988; Sengör, 1979), but transcurrent faults by others (Reading, 1980; Woodcock, 1986). Moreover, Freund (1974) had to admit that even "typical" transform faults like the San Andreas or the Dead Sea 'Rift' show most of the distinctive features of transcurrent faults.

Major inconsistencies were already inherent in Wilson's original views by the equalization of faults segmenting oceanic ridges with faults crossing continents or continental margins.

Another inconsistency of Wilson's refers to the temporal relationship between the transform fault and the ridge. On the one hand it is claimed that the transform faults are pre-figured by lines of weakness (**Fig. 2A**) that predate the tension gashes later evolving into rift zones (**Fig. 2B**). On the other, it is stated that transform faults "adjust the rift to the shape of the adjacent coasts". However, if one considers the spatial position of the transform faults to be preset, it is hardly imaginable how such an adjustment could be effected. This assumption is the more astonishing as Wilson suggested only some paragraphs before that the configuration of the coasts does actually represent the mirror image of the rift itself (**Fig. 2C**).

The confusion that appeared with the launch of the concept of transform faulting is at least twofold. First, entirely different faults, such as 'ridge transforms' [2]and 'plate-boundary transforms' were grouped together. On the other hand, faults characterized by clearly similar features are thought to belong to different "classes" , sometimes only due to the fact that some terminate at both ends at a major crustal feature (like ridges, trenches, orogens or another 'transform'), while others do not. The alleged primordial "pinning" of a fault at both ends in order to be addressed as a 'transform' is perhaps one of the most illustrative examples of hidden plate-"mobilistic" fixism, particularly if

[2] Wilson (1965) defines a *transform* as "a junction where one feature changes into another". However, in recent literature the term *transform* is equivalent to transform fault. It is in this latter sense that it is used in this article.

viewed in the context of the actually proven propagation in time and space of other major structural elements, namely the mid-oceanic ridges.

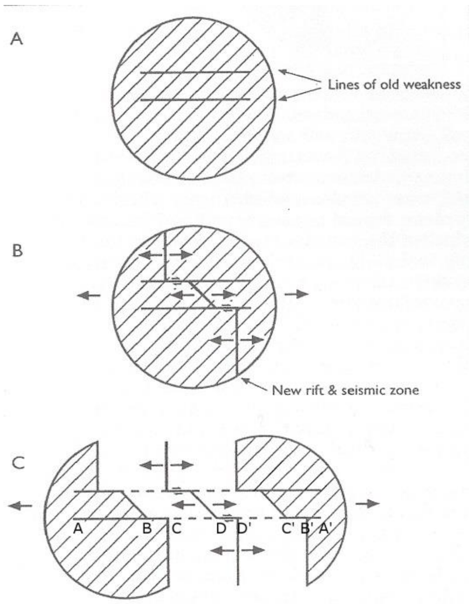

Figure 2. Evolution from splitting of continental crust to oceanic spreading, according to Wilson. A. Lines of weakness in the continental crust predetermining the position of future 'transforms'; B. The Rift stage; C. Oceanic spreading preserves the "inherited" offsets of the ridge segments (Redrawn from Wilson, 1965)

According to Sylvester (1988), the transform faults are of three types, 'ridge transforms', 'plate-boundary transforms' and 'trench-linked strike-slip faults', respectively. This classification is essentially based on that previously presented by Woodcock (1986), but differs from it by assuming 'trench-linked strike-slip faults' as "true transforms", not as transcurrent faults. Nevertheless Sylvester cautiously maintains the descriptive term of Woodcock, instead of speaking of 'trench-linked transforms'. In my view, there are no fundamental differences between faults like the San Andreas ('plate-boundary transform'), the Semangko ('trench-linked strike-slip fault'), or the North Anatolian Fault ('indent-linked' transcurrent fault), that in usual plate-tectonic classifications belong to different drawers not even of the same chest! Such approaches seem to me extremely dangerous not because they attempt to classify faults with horizontal displacement, but because they are biased by ruling geotectonic paradigms, obviously ignoring the reality.

Ridge 'transforms'

According to Freund (1974), the criteria to be considered in order to delimit between transform and transcurrent faults should be: physiographic expression, sense of displacement, relationship with associated structures as well as generation and generation site. However, the great majority of features which have been ascribed by Freund to the 'transform' class as a whole are in fact only features of 'ridge transforms'. It is for this reason that Freund met with great difficulties in including the San Andreas Fault and similar others into the above mentioned class. To me it appears that the unique criterion to be taken into consideration when classifying faults with horizontal displacement should be the evidence whether they evolve or not independently of ocean ridges. The most important feature of 'ridge transforms' is, as it was already observed by Wilson (1965), the "confusing" fact that the *detectable* sense of displacement along them is contrary to that required to offset the ridge. It should be mentioned anyway, that the stair-step geometry of oceanic ridges in plan view cannot be an inherited feature as Wilson surmised. The sinuous but generally continuous aspect of the East African rift system seen as a forthcoming oceanic ridge could be taken as evidence in this respect (**Fig. 3**). The lineaments considered by Chorowicz (1983) to transect the rift cannot be regarded as nascent 'ridge transforms'. They might eventually be considered as 'false transforms', as the real 'ridge transforms' seem to be generated concurrently with the spreading.

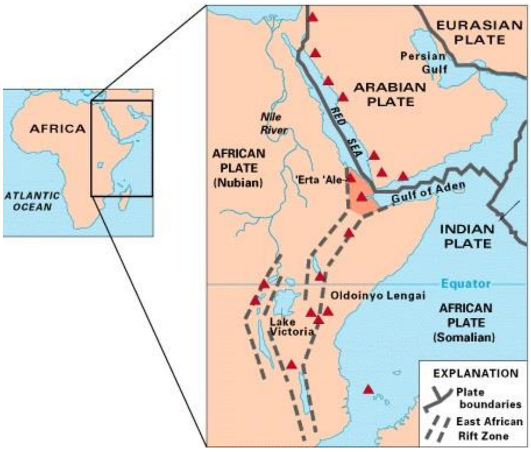

Figure 3. The East African Rift. No important faults ("lines of weakness") crosscut the ridge. No stair-step features, similar to those presented by the ridges of the Indian Ocean are remarked (From Wikipedia)

We shall now try to throw some light on the nature of 'ridge transforms' and the reason of their initiation, a problem which, according to Freund (1974), has not been answered yet.

Oceanic spreading ridges are unanimously accepted as tensional features of the Earth's crust or of the lithosphere as a whole. However, by no means should these structures be understood as being hundred per cent tensional. 100% crustal extension does not require creation of 'transforms' except for the case that there are large variations in the spreading rate from one segment of the ridge to the neighboring one. Graphically this situation that does not even claim the offset of the ridge is represented in Figure 4. Anyhow, the normal situations are not – or at least – not only of this type.

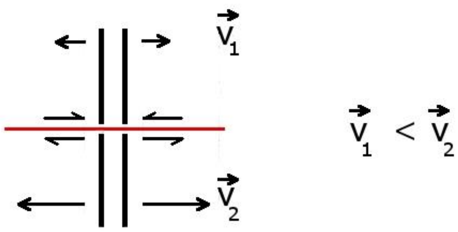

Figure 4. Spreading in a 100 per cent tensional regime may generate ‚transforms' but they do not offset the ridge

From a purely mechanical point of view we may describe ridge spreading as extension in response to the activity of a pair of equal, antiparallel forces. If these forces are also collinear, i.e. if their vectors coincide with the straight lines connecting their working points (Fig. 5A), we may assume to have 100% tension. In all other cases, however, where the angle ϑ between this line and the vectors of the two forces is different from zero ($0^0 \neq \vartheta \leq 90^0$) each force comprises a normal (F_N) and a shear component (F_S), implying that spreading must be oblique. The greater the angle ϑ, the greater the ratio between F_S and F_N, because

$$F_S/F_N \sim \text{tg}\ \vartheta.$$

In accord with this growing ratio we may distinguish between tensional regimes with a simple shear component (Fig. 5B), transtensive regimes (Fig. 5C) and – at least theoretically – purely transcurrent regimes (Fig. 5D).

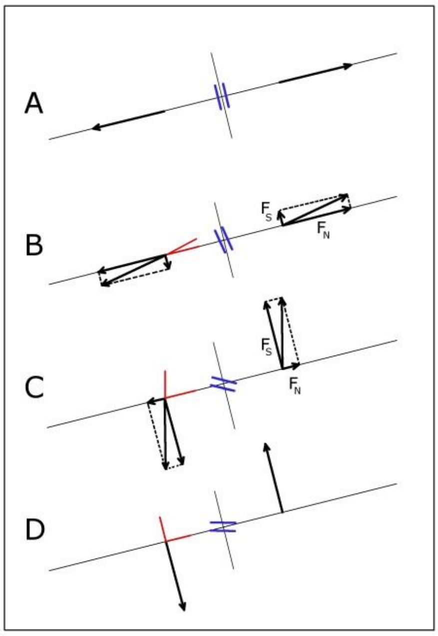

Figure 5.Regimes from 100 per cent extensional (A) to 100 per cent transcurrent (D), due to the increasing F_S/F_N ratio (see text for details). Tensional gashes or rifts are represented in blue; the angle θ is shown in red.

The situation in Figure 5A, without a shearing component, does not imply rotations. On the contrary, situations shown in Figures 5B, 5C and 5D imply growing amounts of rotation with increasing F_S, as suggested by the orientations of appendant tension gashes or rift segments. In practice, however, the immanent cohesive forces within the “rigid” lithosphere are resisting the rotation, a situation that must generate internal stresses expected to be finally resolved by shear failure of the weakest zone, i.e. the oceanic ridge. In accordance with this requirement, I suggest that the ridge ‘transforms’ are in fact materializing the shearing component of the spreading, thus being the expression as well as the measure of the “impure” character of crustal extension.

Let us now call into mind the Riedel experiment (Riedel, 1929), well-known to researchers dealing with simple shear (Fig. 6). As stated by Tchalenko (1970), simultaneous with the Riedel shears (R) or even earlier the conjugate Riedel shears (R’) occur. Due to the large angle which they form with the general direction of movement R’ shears soon become passive and distorted into an S-shape owing to the rotational strain component. Characteristic of the conjugate Riedel shears is the fact that the displacement – if there is any – is in the reverse sense as compared to displacements along the Riedel shears.

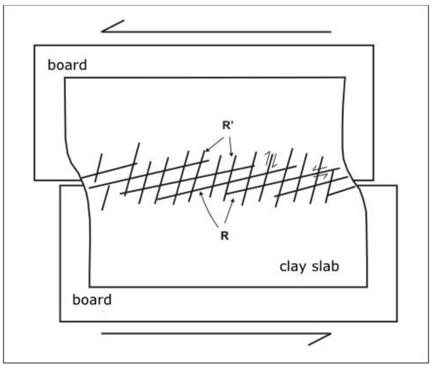

Figure 6. Two types of Riedel shears (R and R‘) revealed by the Riedel experiment (Redrawn from Tchalenko, 1970)

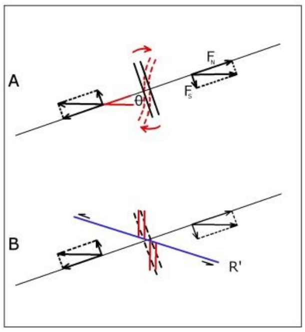

Figure 7. Generation of a ‚transform‘ / R’ shear due to „impure“ extension

I have mentioned R' shears because in many cases – where the tensional regime has an important shear component – the ridge 'transforms' apparently accomplish the role of R' shears. To demonstrate my assertion I shall refer to the situation in the Red Sea – Gulf of Aden where the plate kinematics is fairly well understood.

It is generally assumed that in the Gulf rifting began earlier than in the Red Sea, most probably during the Oligocene[3]. Oceanic spreading evidenced by magnetic anomalies was initiated about 10 Ma ago (Abbate et al., 1988)[4], being, however, clearly earlier than the spreading in the Red Sea, where the oldest basalts have been assigned an age of no more than 2 or 3 Ma[5]. I hypothesize that during the opening stage the regime in the Gulf of Aden was near to hundred per cent tensional (situation *a* in Fig.5). The separation and northward displacement of Arabia from the African block are supported by the simultaneous activity of the Dead Sea 'Rift', oriented almost N-S, with a sinistral sense of displacement. Initiation of spreading in the Red Sea, implying an eastern relative displacement of Arabia, must have imparted an important component of dextral shear to the tensional regime in the Gulf. According to the interpretation proposed herein, the materialization of this shear component is given by the narrowly spaced 'transforms' of NE-SW orientation that produce the advanced segmentation of the central section of the Sheba Ridge[6]. Their direction and the sinistral offset of the ridge segments become understandable if we admit that these 'transforms' fulfil the same task as do the conjugate Riedel shears in the evolution of a simple shear (Fig. 6). Due to the fact that extension still rules over shearing Riedel shears do not occur. The mechanism of conjugate Riedel-shear development in a tensional regime with a dextral shear component is illustrated in Figure 7 and is based on the consideration that rotation (Fig. 7A) is mainly "resolved" by shear failure (Fig. 7B) and simultaneous displacement along the shear surfaces in the opposite sense as compared to the sense of motion of the system as a whole. In accordance with the hypothesis proposed, the situation in the central portion of the Sheba Ridge would approximately correspond to that presented in Figure 8.

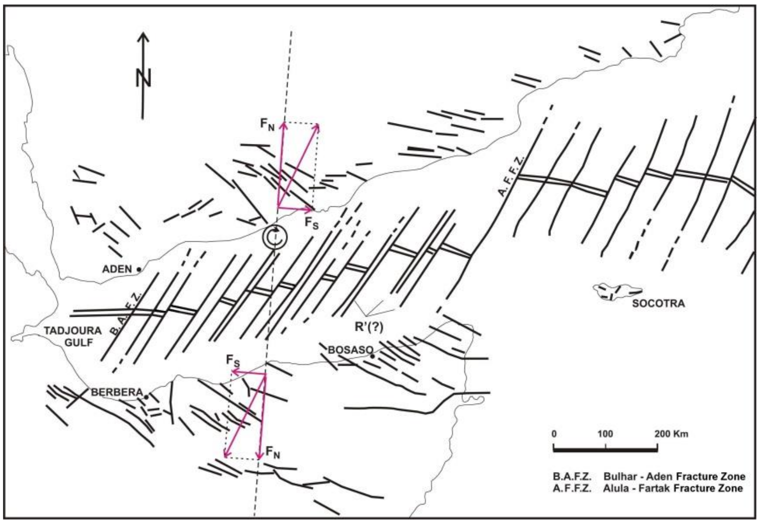

Figure 8. The segmentation of the Sheba Ridge by the NE-SW-oriented system of transform faults. The parallelogram of forces for the Aden section of the ridge is figured in red. Note that the Bulhar-Aden Fracture Zone corresponds to the Shukra El Sheikh Transform of recent authors. Adapted from Abbate et al., 1988).

[3] According to Fournier et al. (2010) and Leroy et al. (2011) rifting started about the same time in both the Gulf and the Red Sea, being "poorly dated around Oligocene" (Fournier et al., 2010).
[4] Newer data (Fournier et al., 2010; Leroy et al., 2011) are concordant in assuming that oceanic spreading in the Gulf of Aden began 20.0 - 17.5 Ma ago (Early Miocene) and propagated westward.
[5] Fourier et al. (2010) fix the onset of seafloor spreading in the southern part of the Red Sea at 5-4 Ma ago.
[6] Aden Ridge, according to Hébert & Deplus (2001), Leroy et al. (2011), a.o.

Additional evidence in favor of the presented hypothesis comes from the Southwestern Indian Ridge (SWIR). It is obvious that, at least since the Cenozoic, spreading along the SWIR must have gained a strong dextral shear component, a situation in perfect agreement with the sinistral sense of offset of the ridge along the pertinent ‘transforms’/R’shears. As a matter of fact, the bathymetry of the SWIR does not even show a clearly definable ridge (Fig. 9). Besides, the narrow stripes of Cenozoic oceanic crust along the ridge, compared to the broad ones along the Southeast Indian Ridge (SEIR) (Fig. 10),

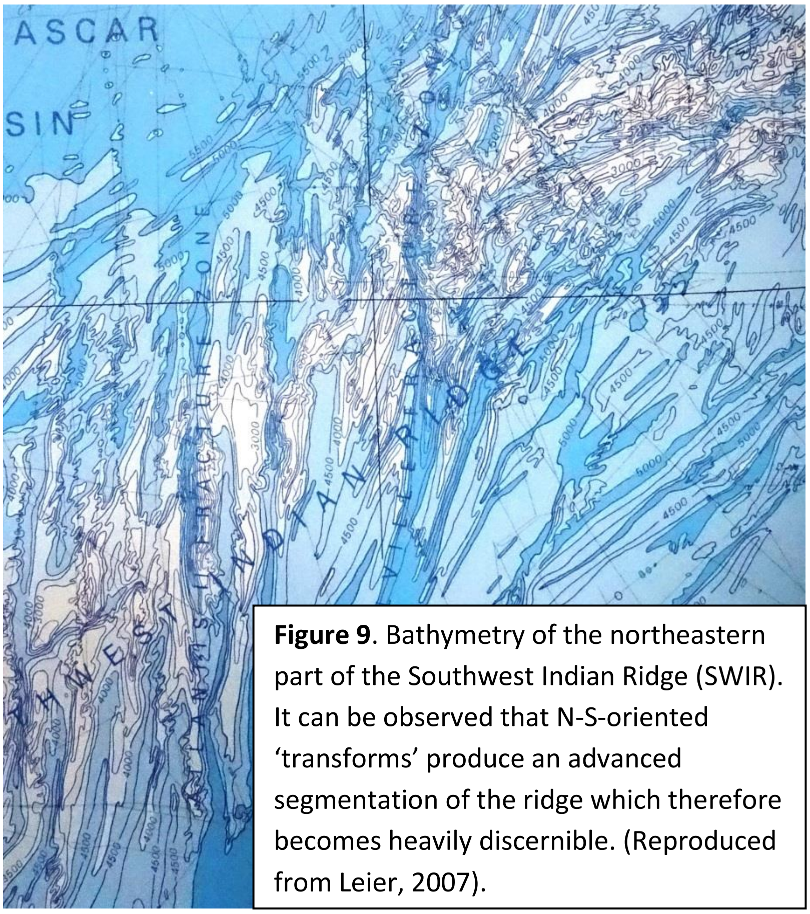

Figure 9. Bathymetry of the northeastern part of the Southwest Indian Ridge (SWIR). It can be observed that N-S-oriented ‘transforms’ produce an advanced segmentation of the ridge which therefore becomes heavily discernible. (Reproduced from Leier, 2007).

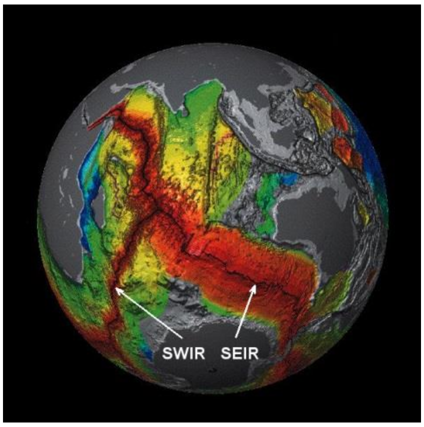

Figure 10. The great difference in the expansion rates between the SEIR and the SWIR, as attested by the width of Cenozoic oceanic crust (in red), is interpreted as a result of the extremely different shear components within the tensional regime of the ridges (Modified after Wikipedia).

are better explained by assuming consistently different degrees of shearing along these two ridges than by different (ultra-slow versus intermediate) expansion rates[7]. It seems clear that extremely low expansion rates are not primarily due to some peculiar mantle characteristics like a reduced “mantle

[7] Moreover the ‘push’ exerted by the faster spreading SEIR on the SWIR may be the main cause for the initiation of the dextral shearing along the SWIR.

productivity” as is commonly assumed by plate tectonics reasoning, but due to intense shearing which greatly impedes spreading. Furthermore one may logically reason that the more important the shear component, the greater the density of the ’transforms’ along the pertinent ridge (compare, e.g. the situation in the Gulf of Aden and along the SWIR with that of the Southeast Indian or the Carlsberg Ridge). I shall go further by assuming that an even greater shear component ($F_S >> F_N$) than at the SWIR is typical of the Gulf of California and, at the extreme end, of all “classical” geosynclines. According to Ingersoll (1988), the Gulf of California is “a primarily transtentional feature, although it shares many characteristics with the Red Sea”. The presence both in geosynclinal (orogenic) systems and in structures like de SWIR of diapirically driven upper mantle peridotites[8] should be taken as compelling evidence that geological structures form a continuum from purely extensional to transtensional to purely transcurrent irrespective of their site of occurrence.

In order to find a plausible explanation of the “confusing” fact evidenced by Wilson (1965), i.e. that the *measurable* sense of displacement along ridge ‘transforms’ is the reverse of that required by the ridge offset, we must, above all, make sure that the offset is actually due to the evolution of the ridge itself. A quite simple observation proves this.

The ridge segments from the central Sheba Ridge (Aden Ridge) are offset in a stair-step manner by 15-35[9] kilometers along the delimiting ‘transforms’. The oldest oceanic crust in this sector is about 16 Ma old. On the other hand, the Red Sea ‘Rift’, only 4-5 Ma old[10], is likewise segmented by ‘transforms’ but their offsets are very small, of the order of hundreds of meters, exceptionally up to 6 km (Juteau et al., 1983). Besides, the dextral sense of the offsets fits well with the sinistral shear component of the system imposed by the activity of the Dead Sea ‘Rift’. Thus, if – as seems obvious – older ridges show relatively large offsets along “their” ‘transforms’ while the youngest oceanic rift on Earth is only affected by ‘incipient transforms’, an elementary logic tells us that the offsets cannot be an inherited feature, but “grow” simultaneously with the ridge itself. This means that along each ridge ‘transform’ we have to admit motion in two senses. On the one hand is the motion that produces the offset of the ridge. It probably takes place at greater time intervals, but then at high velocities. On the other hand is the more or less continuous – but very slow – motion exclusively due to the accretion process and manifest by the reverse displacement within the ‘transform’ section flanked by the ridge segments. Being continuous at the geological scale, this motion does not escape from seismic surveying, which is not the case with the motions effectively displacing the ridge. In analogy with the time-limited activity of conjugate Riedel shears along a strike-slip fault, we may even suppose that the offset is created during an early evolutionary stage, after which the system stabilizes dynamically creating the false impression that the offset predates the rifting. This does not mean that there are no faults older than the rifting. In the Gulf of Aden the Alula-Fartak fault may be of this type. On the other hand, the western (Tadjoura) sector of the ridge, which is of nearly the same age as the Red Sea ‘Rift’, is straight, without any apparent offsets or ‘transforms’[11]. The young age of this ridge segment and the proximity of the Afar hotspot which contributes to a lowering of crustal rigidity may be the reason why in this sector ‘transforms’ did not form up to the present.

[8] Mantle peridotites occurring along the SWIR or other ultra-slow spreading ridges are considered to be a consequence of this type of spreading (see synopses of, e.g., Snow & Edmonds, 2007; Searle, 2013), which, according to my hypothesis, is only a side effect of intense shearing.
[9] 14-47 km, according to Shinjo et al. (2015).
[10] See footnote nr.3
[11] However, en echelon basins (Hébert et al., 2001) that share the direction of the ridge segments from the eastern part of the Aden ridge are possibly anticipating the generation of ‘transforms’ across their margins.

In support of the assumption regarding the dualism of ridge 'transforms' the following observation made in the FAMOUS area from the Central Atlantic should be mentioned. As pointed out by Bleahu (1983) leaning on studies published by MacDonald and Luyendyk (1977) and Ramberg et al. (1977), the micro-earthquakes that probably define the motion produced by the accretion process are aligned along a line perpendicular to the actual spreading axis. This line forms, however, an acute angle of 17^0 with the morphological trace of the 'transforms' which may well correspond to the direction of the initial R' failure. For this particular region of the Mid-Atlantic Ridge the right-lateral stepping of the ridge would thus be indicative of a left-lateral shear component.

Conclusions

Though the original paper was presented more than 20 years ago, its fundamental proposition in regard of transform faults remains an alternative to be tested. In opposition to conventional plate-tectonic interpretations according to which there are fundamental geometrical as well as mechanical differences between transform and transcurrent faults, I show that a clear distinction cannot be made, when 'ridge transforms' are left aside. Indeed, it is asserted that probably most 'ridge transforms' are different from other strike-slip faults. They integrate well in the kinematic framework of oceanic ridges if we regard them as conjugate Riedel (R') shears that materialize the shear component in "impure" tensional regimes. In accord with this point of view the concept created by Wilson 50 years ago thus changes its significance: transform faults do not transform a type of stress or a structure created by it (extensional, compressional or strike-slip) into another one, as Wilson propounded, but transform/relieve the rotational motion inherent to "impure"(oblique) spreading into shear motion.

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Saarbrücken, 25.09.2015

Revised: 27.04.2019