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# Forward modeling of non-steady-state deformations and the 'minimum strain path': Reply

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We appreciate D. Jiang's interest and discussion on our article on non-steady-state deformations and the 'minimum strain path' (Fossen and Tikoff, 1997). While we clearly do not share his general negativism about the article, his discussion is quite useful in clarifying some of the main issues.

The main point of our article was to model non-steady-state finite strain accumulation in a straightforward and understandable way or, as stated in the original article, to show that "non-steady-state deformation paths can be theoretically modeled if certain deformation parameters, such as strain or offset, are specified" (Fossen and Tikoff, 1997, p. 987). Exploration of non-steady deformations through theoretical modeling is important because we really do not know how to approach such deformations in most cases, forcing structural analysts to rely on the assumption of steady-state deformation. Any realistic idea or model that can increase our understanding of how flow parameters may vary with time in different tectonic setting may therefore be very important.

## BOUNDARY CONDITIONS AND TYPE OF OFFSET

The problem with modeling non-steady finite strain accumulation is that one must assume some boundary conditions, such as our 'minimum strain path' or the 'transpression' boundary conditions of Dutton (1997). Jiang in his Discussion is completely correct in saying that our 'minimum strain path' is based on an offset (or displacement), which he labels $U$ (see his fig. 1). The reason we choose this offset should be obvious from Fig. 1. The alternative measure of shear zone displacement, $\delta$, does not work for coaxial deformations. Yet, coaxial deformations do cause relative displacement of material particles (see, for example, fig. 4 in Fossen and Tikoff, 1997). To emphasize why $U$ may be a better (and more common) measurement of offset in many cases, we refer to Fig. 1, which illustrates an internally deformed thrust nappe with a deformed basal part above an undeformed basement. The nappe has collapsed by coaxial deformation under the influence of gravity and its base is also influenced by non-coaxial deformation during nappe transport: i.e. the classical situation envisaged by Ramberg (1981), Merle (1986), and many others. Few people would disagree that the relevant displacement is $U$, not $\delta$ in this and similar examples (see also figs 4c & d and 7d in Fossen and Tikoff, 1997). The effect of an undeformed side-wall (basement) is not considered in Jiang's fig. 1, which only describes the special case of a sub-simple shear zone with side walls that absorb exactly the same amount of coaxial deformation as the sub-simple shear zone, but are unaffected by any simple shear. This important point allows us to emphasize the significance of boundary conditions once more; if at least one side wall is undeformed, the non-steady-state minimum strain path as outlined in our article is a reasonable strain model. If, on the other hand, both side walls are deformed, other measures of displacement may be more relevant (such as Jiang's $\delta$), and the results in our original article may not be quantitatively applicable. In general, we freely admit that we do not know whether $U$ is the most relevant variable to quantify the effect of adding coaxial and non-coaxial components of deformation.

## COMPARING $U$ AND $\delta$

We also wish to emphasize certain aspects of $\delta$ as a measure of offset in shear zones. First, $\delta$ is generally maximized by a combination of pure and simple shear (sub-simple shearing). Therefore, whether $U$ or $\delta$ is used, a simple shearing path does *not* lead to the least amount of accumulated finite strain for a given offset.

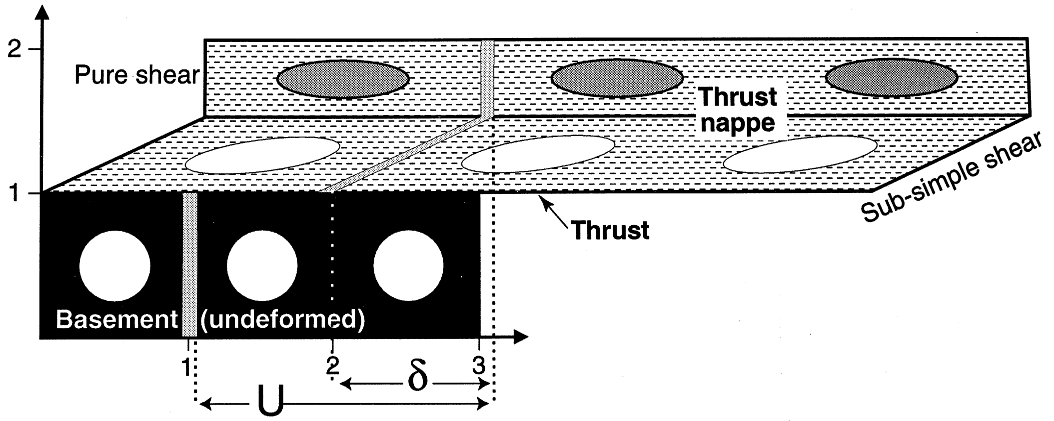

Fig. 1. The situation where a thrust nappe is deformed by pure shear in the upper part and sub-simple shear in its lower part above an undeformed basement. The two measures of displacement, $U$ and $\delta$, are indicated. Clearly, in this case $U$ is a better measure of the offset across the section. Modified version of fig. 7(c) in our original paper (Fossen and Tikoff, 1997).

This fact is very useful for making assumptions about maximum transport based on finite strain, such as in thrust systems. In contrast to the statement by Jiang, we contend that if the offset of the tectonic system is prescribed, then a minimum strain path will accumulate strain more slowly than a similar offset for a simple shear deformation. What matters is which external variables are fixed (or independent). Second, if a deformation maximizes $\delta$ at each increment of a progressive deformation, it must, similar to $U$, follow a non-steady-state path. Thus, the pure shear component of the sub-simple shearing deformation would increase with increasing deformation, regardless of whether $\delta$ or $U$ is chosen. This effect is shown quantitatively for non-steady-state deformations in Figs 2 and 3, where also the difference between the $U$- and $\delta$-specified minimum strain paths are displayed. In general, the $\delta$-prescribed path rapidly approaches a $W_K$-value of about 0.7, whereas the $U$-specified minimum strain path soon requires significantly more of a pure shear component. Clearly, this effect has important consequences for the development of fabrics in the rock during the deformation history. In both cases, non-coaxial fabrics are expected to be replaced by lower-$W_k$ fabrics and eventually overprinted by almost coaxial fabrics if $U$ is specified. Although the results of the different displacement paths show important qualitative similarities, the differences highlight the importance of relating the type of displacement to the geologic setting.

## THE MINIMUM WORK PATH

As clearly stated in our original article, our 'minimum strain path' was an attempt to use displacement and strain as parameters to construct a non-steady-state deformation. In this context, we made a clear distinction between our 'kinematic' minimum strain path and Nadai's 'dynamic' minimum work path (Nadai, 1963). However, energetic processes can be described kinematically, such as the minimum work path (Nadai, 1963). Further, the principle of energy dissipation may

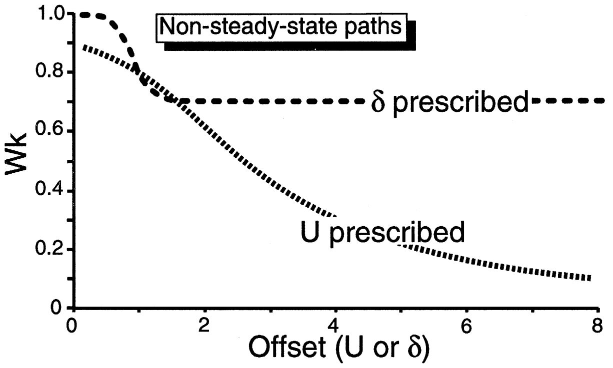

Fig. 2. The effect of specifying $U$ or $\delta$ (different measures of displacement; see Fig. 1) on kinematic vorticity during progressive non-steady-state deformation if strain is minimized. The two minimum strain path curves indicate the change in $W_K$ during deformation. See text for discussion.

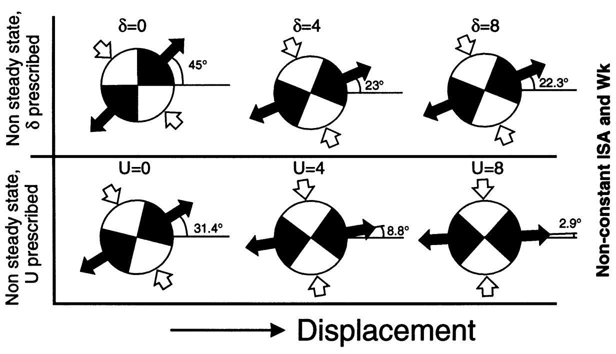

Fig. 3. Illustration of the difference between the orientation of infinitesimal strain axes during progressive non-steady sub-simple shear for the minimum strain paths shown in Fig. 2. The largest infinitesimal stretching axis initiates with an angle of 45° to the shear plane and decreases toward 22° as offset increases if $\delta$ is specified. If $U$ is prescribed, the largest infinitesimal stretching axis is lowered from 31.4° toward sub-parallelism with the shear plane.

not be strictly applicable to tectonic settings (Bird and Yuen, 1979; Molnar, 1992).

Jiang in his Discussion may ultimately be correct that deformations will not follow a minimum strain path. But, we remain unconvinced by his argument and do not accept the notion that deformation can not be controlled by the boundary conditions and displacements imposed on the system.

## CONCLUSION

The main point of our article was to model non-steady-state deformation in a two-dimensional setting in a straightforward manner. This type of modeling is critical, if we are ever to obtain information about non-steady-state deformation of naturally deformed rock. We believe that this type of information is ultimately accessible.

The subsequent discussion and reply concern our choice—the minimum strain path—for demonstrating non-steady-state accumulation of finite strain. Our minimum strain path is a geometric curiosity in the same sense that transpression is a geometric curiosity: A set of boundary conditions that leads to a pattern of finite strain. The question remains, is it useful? In our view, any type of deformation path that helps elucidate the connection between finite strain and displacement is useful and worth exploring. Ultimately, many deformations are characterized by a simultaneous combination of simple shear and pure shear, such as spreading nappes. Trying to understand their behavior, with as few assumptions as possible, seems a reasonable approach.

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