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# WHOLE-LITHOSPHERE NORMAL SIMPLE SHEAR: AN INTERPRETATION OF DEEP-REFLECTION PROFILES IN GREAT BRITAIN

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Abstract. Marine deep-seismic reflection profiles from the British Isles acquired by the British Institutions' Seismic Reflection Profiling Syndicate (BIRPS) provide some of the best images to date of the deep structure of a zone of intracontinental extension. Simple quantitative considerations of finite strain indicate that the reflection geometry on the eastern half of the MOIST profile is consistent with the concept that large, low-angle normal faults persist as single zones of displacement through the entire lithosphere. It is proposed that the lower crust absorbs displacement by the formation of a foliation parallel to the maximum elongation direction within finite-width normal shear zones. In contrast, both up-dip and down-dip in stronger or more brittle layers, the shear zones not only narrow, causing foliation to become aligned with their boundaries, but they also absorb strain via a foliation comprised of discrete, boundary-parallel slip surfaces. Such a geometry of through-going zones of displacement predicts non-alignment of lower crustal reflections with those in the mantle and upper crust within the same displacement zone. This model runs counter to current interpretations of deep reflection data that ascribe a more fundamental role to rheological stratification for the localization and development of zones of displacement in the lithosphere.

## Introduction

One of the most interesting and controversial aspects of research in continental tectonics is the nature of faults and shear zones at deep levels in the crust and mantle. While much is known about the kinematics of lithospheric strain in the upper 10 km of crust, it is poorly understood how major zones of displacement in the upper crust interact with deeper levels. Do large faults continue into the lower crust and mantle lithosphere as shear zones, or do they sole into decoupling horizons at various levels, controlled perhaps by changing rheology with depth [e.g. Sibson, 1983]? Recent deep-reflection data from the British Isles [Smythe et al., 1982; Brewer and Smythe, 1984; Brewer et al., 1983; Matthews and McGeary, 1984] provide some of the best seismic images to date of the deep structure of a zone of intracontinental extension. Some of these data are analyzed here in terms of the above question, and it is concluded that the data are consistent with either hypothesis. As such, they do not provide compelling evidence for the existence of decoupling horizons (as defined below) in the lithosphere.

## Decoupling and Displacement in the Lithosphere

A distinction is made here between the terms zone of displacement, a structure that accommodates motion between two fragments of lithosphere, and decoupling horizon, a zone of compensation that develops between tiers of lithosphere that accommodate approximately equal strains, but by contrasting mechanisms (Figure 1). Much of the new reflection data from rift zones, including COCORP data from the Nevada Basin and Range [Hauge et al., 1984; Hauser et al., 1984; Potter et al., 1984] as well as the BIRPS data show 1) a relatively non-reflective upper crust characterized by dipping reflections indicative of sediment-filled half-grabens; 2) a highly reflective lower crust with many short, discontinuous events; 3) a very flat, abrupt downward termination of these events at an appropriate depth to be the Moho; and 4) a relatively transparent upper mantle which locally displays long, continuous, discrete bands of dipping reflections. The fact that reflection geometry shows this gross stratification may be interpreted in conjunction with laboratory [e.g. Brace and Kohlstedt, 1980] and seismicity [e.g. Chen and Molnar, 1983] studies to infer that the upper crust deforms by localized shear in strong material, the lower crust by penetrative flow in weak material, and the upper mantle by localized shear in strong material that gradually weakens toward the base of the lithosphere [e.g. Smith and Bruhn, 1984]. It is thus very appealing to assume that for a given bulk strain of the

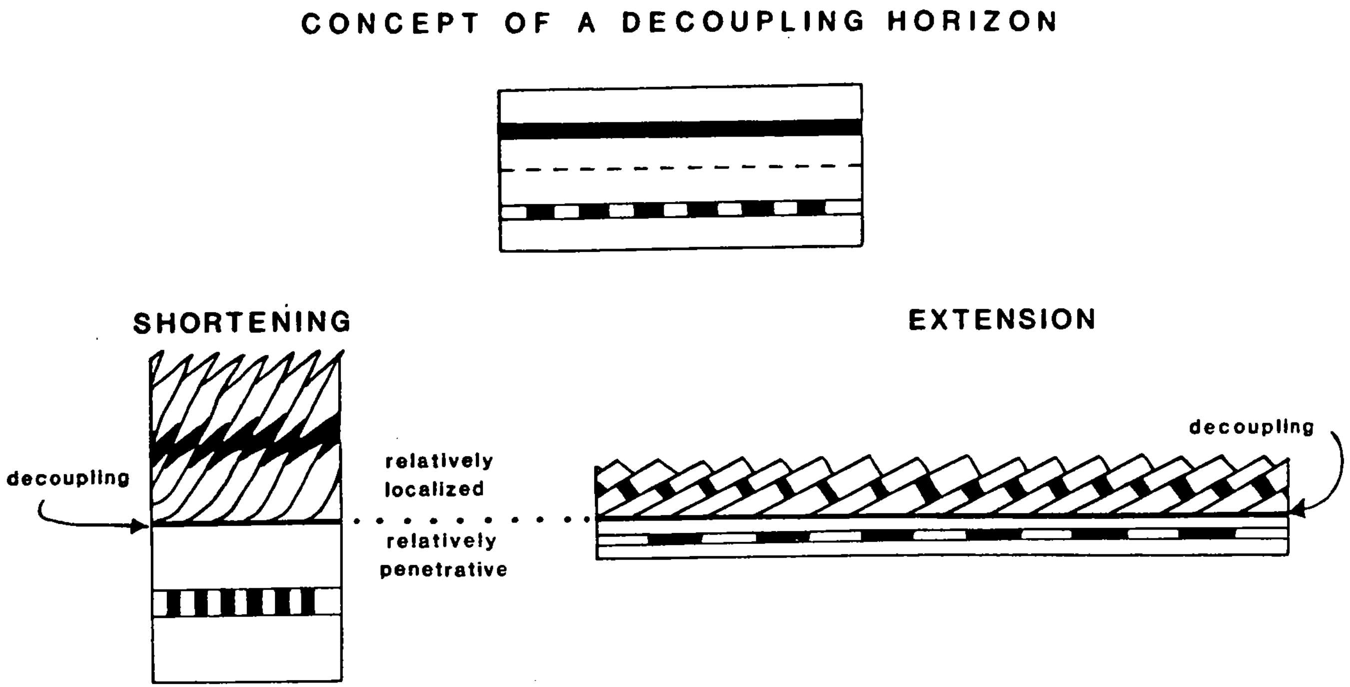


Fig. 1. Concept of a decoupling horizon.

lithosphere, these rheological tiers will respond differentially in some way, creating decoupling horizons between them.

As discussed elsewhere [Wernicke, 1985, Wernicke et al., 1985; Bartley and Wernicke, 1984], evidence from the Basin and Range is inadequate to demonstrate the existence of large-scale decoupling horizons in the upper and middle crust. It is now widely accepted that detachments (normal faults with large displacement that form at low-angle) in the Basin and Range form as single, relatively planar entities which pass from very high, brittle levels into upper greenschist and even lower amphibolite facies metamorphic conditions (ca. 500° C), regimes in which quartz and calcite experience dynamic recrystallization, and well below highly pressure-sensitive upper crustal rheologies [e.g. Davis et al., 1983; Bartley and Wernicke, 1984; Reynolds and Spencer, 1985].

Since detachments do transgress the upper crustal brittle-ductile transitions of quartzose rocks, it may be reasonable to suppose that they may do the same through other, deeper transitions [see Smith and Bruhn, 1984].

It is shown below that the reflection geometries on the MOIST profile and nearby profiles in Scotland are consistent with the concept that extension occurs via zones of displacement only, without the formation of decoupling horizons in the lithosphere. It is strongly emphasized that the demonstration of the consistency of MOIST with a displacement-zone hypothesis for the deep crust does not prove its validity, but it does show that the data do not require the existence of decoupling horizons. This point is important because crustal-scale displacement zones are proven entities, while the existence of decoupling horizons, at least as narrowly defined here, remains speculative.

## Model and Application

I will focus the discussion on the MOIST profile, which are some of the highest quality data available. On this line (Figure 2), the characteristic half-grabens are found in the upper crust, which except for the graben-bounding faults and basin fill, are relatively transparent compared with the lower crust. The assumed Moho on MOIST is a continuous, discrete band of reflections, rather than a lower limit to numerous short, discontinuous reflections found on many other BIRPS profiles and on lines from the western Basin and Range. Noteworthy on the MOIST line are: 1) a graben-bounding zone of displacement which extends more or less unbroken into the lower crust, and projects into a zone of mylonites on-land [Outer Isles thrust of Sibson, 1977]; and 2) a discrete band of dipping reflections in the upper mantle which both widens and flattens upward as it enters the lower crust [Flannan "thrust" of Smythe et al., 1982, and Brewer and Smythe, 1984].

In a previous report [Wernicke et al., 1985], it was argued that the Outer Isles and Flannan structures are normal zones of displacement which penetrate the Moho and may not sole into any decoupling horizons or zones of horizontal laminar flow. Other workers [Brewer and Smythe,

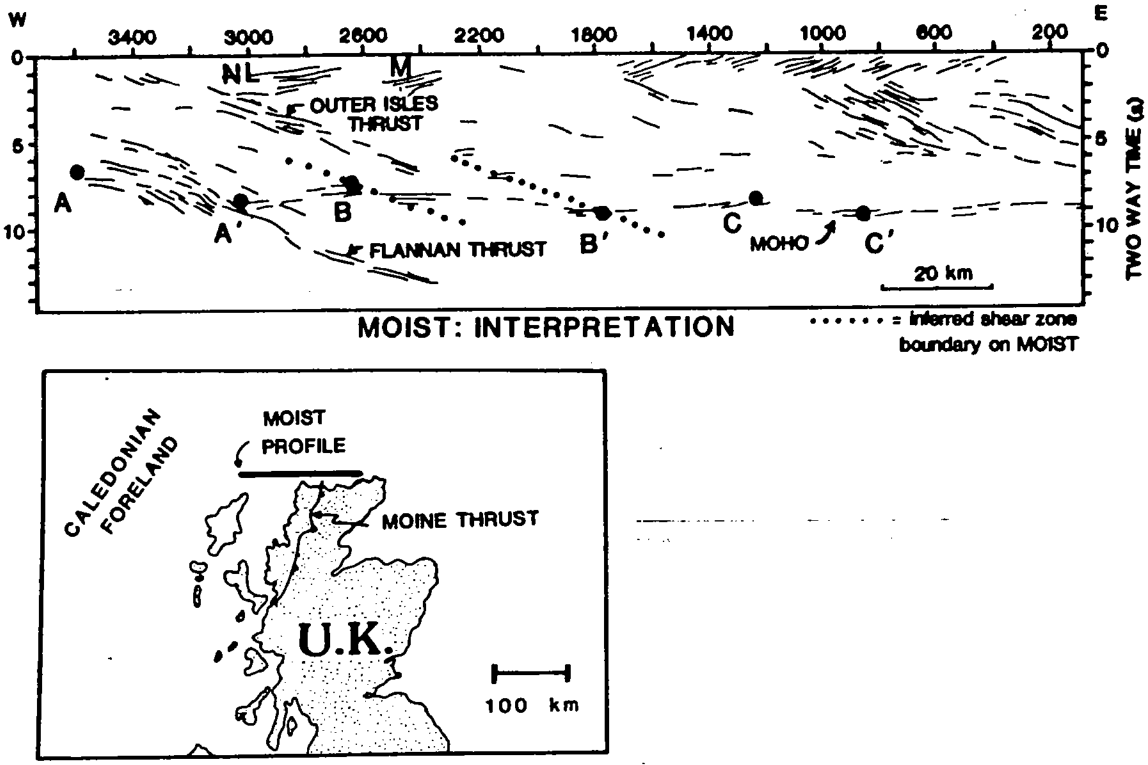


Fig. 2. Line drawing of the MOIST profile at 6.0 km/s [after Brewer and Smythe, 1984]. NL, North Lewis basin; M, Minch basin. Points B (7.5 s TWTT) and B' (9.0 s TWTT) define the proposed 1.5 s offset on the Moho caused by normal displacement on the Outer Isles "thrust". Points C-C' and D-D' bound other proposed normal offsets of the Moho, by the Flannan "thrust" and the fault bounding the Minch basin, respectively. Relief on the Moho is best seen by viewing the figure from one side with the eye about an inch above the page.

1984; Blundell et al., 1985; Smythe et al., 1982; Matthews and McGeary, 1984; Peddy, 1984] have commented on the fact that the total relief on the Moho (about 1.5 s two-way travel time) is only a fraction of the relief developed across the sedimentary half-grabens, and on this basis have rejected the interpretation that the Outer Isles structure displaces the Moho in a normal sense the same amount as the upper crustal half-graben fill.

It is clear from the reflection data presented in Brewer and Smythe [1984] that the Moho is comprised of long, east-dipping segments where the Flannan, Outer Isles, and next-higher graben-bounding structures project into it (segments AA', BB', and CC', respectively, on Figure 2). Peddy [1984] has analyzed MOIST and other lines nearby and concluded that the graben fill in the North Lewis and Minch basins (Figure 2) introduces pull-downs on the Moho which give rise to spurious offsets on time sections. However, her arguments do not change the geometry of the east-dipping segment between points B and B' on Figure 2, as one is at 7.5 s TWTT (two-way travel time) and the other is at 9.0 s TWTT, and neither point underlies thick graben fill. Thus, while the possible pull-down effects discussed by Peddy [1984] may slightly modify the shape of the east-dipping segment B-B', the total relief on the Moho (on the order of 5 km, assuming a lower crustal velocity of 6-7 km/s) could only be reduced by some sort of sideswipe effect, or marked lateral velocity changes in the crystalline rocks beneath the graben fill. The 5-10° west dip of the Moho to the west of point B on Figure 2 may flatten due to pull-down effects of the North Lewis basin, as suggested by Peddy [1984] based on analysis of the WINCH-1 line of Brewer et al. [1983]. Determining how much flatter this segment actually is depends upon a more detailed knowledge of the velocity structure of the North Lewis basin than is currently available. The flattening effect due to pull-down may also be partly reduced by migration. For example, in Blundell et al.'s [1985] model of MOIST, this segment of the Moho flattens from 8° on the time section to 4° on the depth section, rather than becoming absolutely horizontal as suggested by Peddy [1984].

It is shown below that the reflection geometry is quantitatively consistent with a model whereby the lithosphere extends along normal zones of displacement which have constant offset through the lithosphere. The model is contrasted with a decoupling-horizon model in Figure 3, showing how the rheology of the lithosphere could affect the

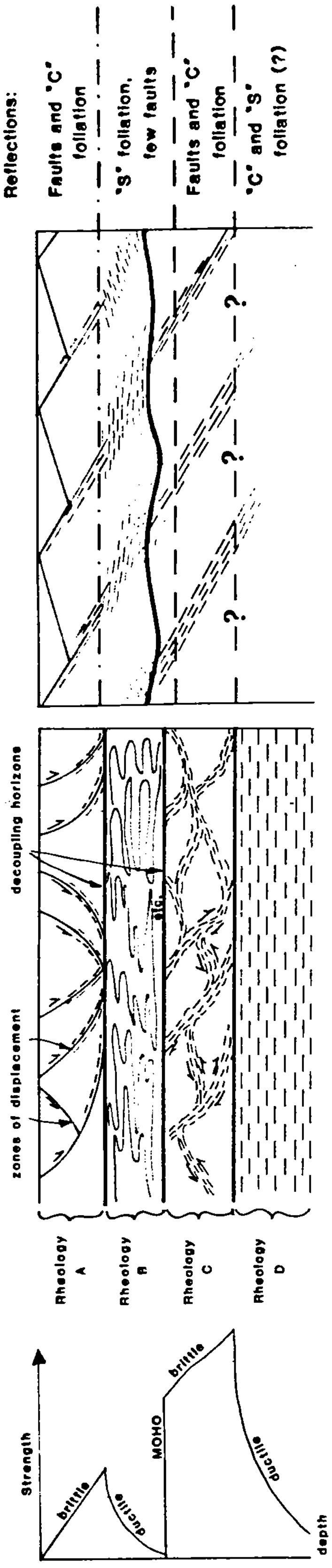


Fig. 3 Diagram contrasting a decoupling-horizon model with a displacement zone model for lithospheric extension.

nature of the shear zone with depth. Implicit in the model is the assumption that more ductile rheologies tend to widen the displacement zones, as well as decrease the tendency to form discrete offsets. In the parlance of "S-C mylonites" [Lister and Snoke, 1984], it is suggested that the displacement zones are comprised of discrete faults (C planes) in the upper crust, wide zones of S-C mylonite in the middle crust [cf. Sibson, 1983], but then in the lower crust the S foliation predominates. Brittle shear or the formation of S-C mylonites would then take over as the dominant mode in the upper mantle. The notion that wide, S-dominated shear zones occur in the lower crust is supported by the general preponderance of penetrative gneissosity and schistosity (i.e., S foliations) over mylonites with a strong C-plane fabric in very deeply eroded areas of continental crust.

Such a model resembles decoupling-horizon models only in the sense that penetrative subhorizontal foliation dominates over discrete shear in the deep crust, but contrasts with them in that 1) no decoupling horizons are present at any level; and 2) the strain path of the lower crustal rocks is characterized by progressively rotating non-coaxial laminar flow rather than simple coaxial flow. Thus, the transitions from dipping upper crustal and upper mantle reflections to "subhorizontal" lower crustal reflections may represent changing modes of accommodation within a continuous, dipping zone of displacement rather than a decoupling horizon. Key to the analysis below is the concept that foliation in ductile shear zones may develop at considerable angles to the shear zone boundary [Ramsay and Graham, 1970; Kligfield et al., 1984]. As such, a displacement zone that penetrates the lower crust would generally not be expressed on seismic profiles as bands of reflections parallel to those in the mantle and upper crust.

## Theoretical Considerations

To test the hypothesis that the Flannan and Outer Isles structures penetrate the lower crust as wide zones of progressive simple shear, it is necessary to quantitatively model a lithospheric zone of normal displacement in order to calculate 1) how initially flat, planar markers such as the Moho would be affected; and 2) how the orientation of foliation in lower crustal rocks would evolve.

The model developed here depends upon the following geometrical assumptions (Figure 4): 1) the extensional allochthons deform as a series of "megadominos" with limited rotation (since the displacement zones initiate at shallow angle) whose upper corners define a surface parallel to the geoid; 2) the displacement zones in the lower crust are zones of homogeneous progressive simple shear and have the same total offset across them as their more discrete counterparts

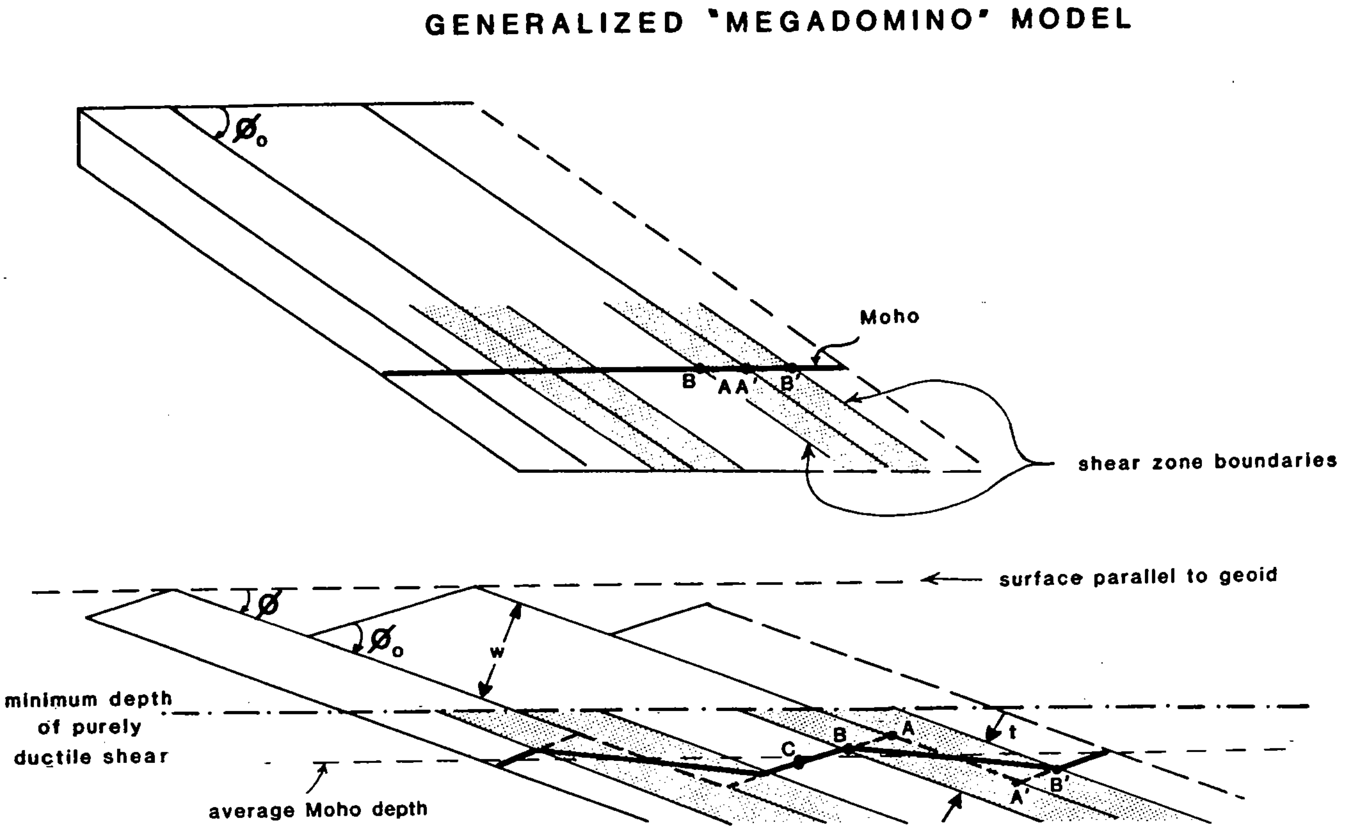


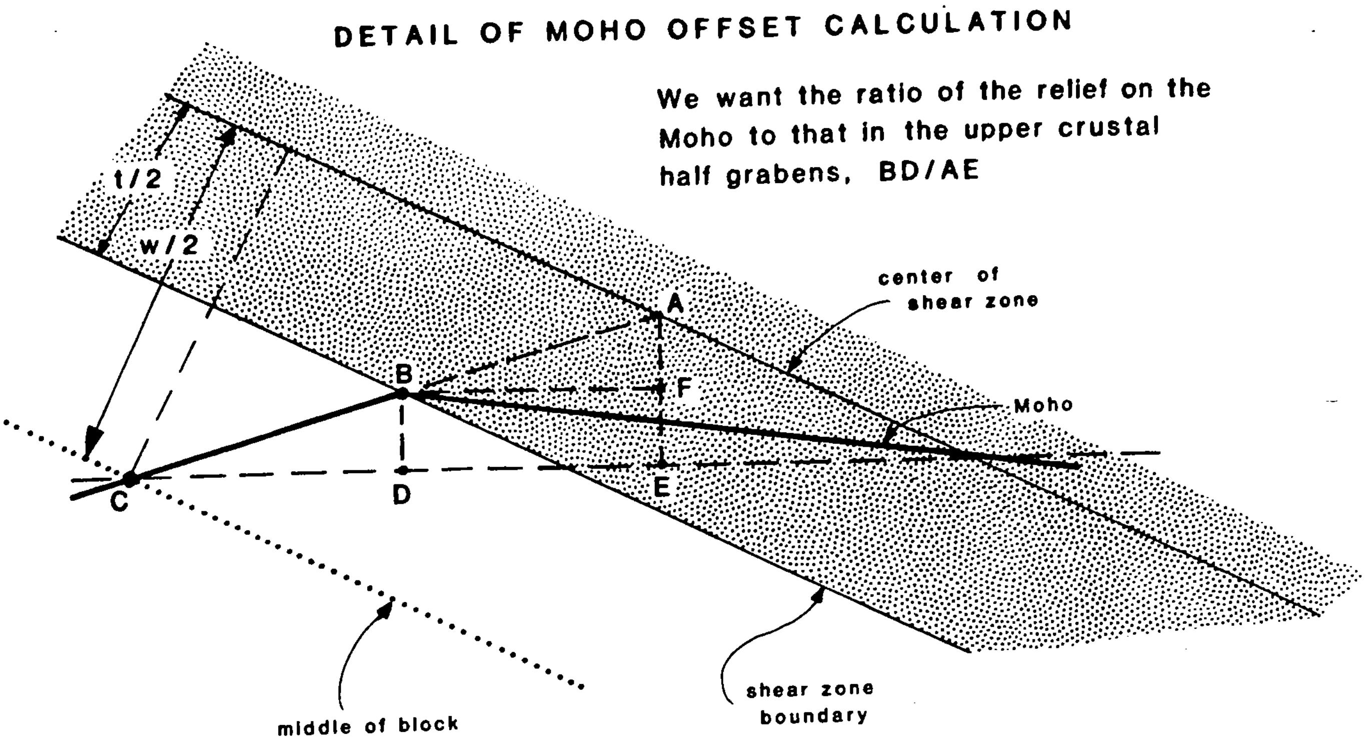
Fig. 4 Model of large-scale "dominos" whose bounding faults initiate at low angle. Points on this diagram are keyed to points on Figs. 5 and 6. $\phi_0$, initial dip of shear-zone boundaries; $\phi$, final dip of shear zone boundaries; w, width of block; t, width of lower crustal shear zone.

in the upper crust and upper mantle; 3) the foliation planes develop in the lower crust as a result of simple shear and contain the maximum elongation axis; and 4) all the blocks are of the same width. While these assumptions are not precisely duplicated by the half-graben geometry in Figure 2, they should give a reasonable first-order view of how the upper crustal geometry affects the lower crust and upper mantle if the model in Figure 4 is correct.

The geometrical problem is uniquely determined by specifying only two conditions: 1) the initial dip of the upper crustal fault and lower crustal shear zone boundaries, $\phi_o$; and 2) the ratio of the width of the lower crustal shear zones, t, to the width of the extending blocks, w, measured in a direction perpendicular to the shear zone boundaries (Figure 4). By specifying only t/w, we find from a simple proof using similar triangles that, for any amount of extension or $\phi_o$, the ratio of Moho relief to that in the upper crustal half-grabens and t/w sum to unity (Figure 5). Thus, for a perfectly discrete fault through the crust and upper mantle, the relief on the Moho is the same as that in the half grabens. If the shear zones are as wide as the blocks (t/w = 1), then there is no relief on the Moho. By specifying only t/w and $\phi$, the final dip of the displacement zones, we obtain the dip of the maximum elongation direction $\theta$ (the S foliation) in the lower crust (Figure 6). The derivations of these relationships are similar to, but less complicated than, those derived in Kligfield et al. [1984].

### Comparison of Theoretical Results with MOIST and WINCH

These theoretical results provide a simple explanation for why the Moho on the MOIST line has only a fraction of the relief of the upper crustal half-grabens. The deepest sediments in the North Lewis basin appear at about 3 s TWTT, or roughly 6 - 8 km depth in sediment [see velocity analysis of Blundell et al., 1985]. This much relief in the half-graben is slightly more than half that on the Moho (4.5 km assuming 6 km/s). These data predict that t/w should be slightly less than 1/2, according to the equation derived on Figure 5. This agrees well with Figure 2. The distance between the Outer Isles and Flannan structures is about 20 km on the 6



By similar triangles, $\frac{t}{w} = \frac{AB}{AC} = \frac{AF}{AE}$ ; but $BD = AE - AF$,

so $\frac{t}{w} = \frac{AE - BD}{AE}$ or $\boxed{\frac{BD}{AE} + \frac{t}{w} = 1}$

Fig. 5 Geometry showing the relief on a Moho displaced by a finite-width shear zone as compared to that of the upper crustal half-grabens. Points A, B and C are keyed to points on Figs. 4 and 6.

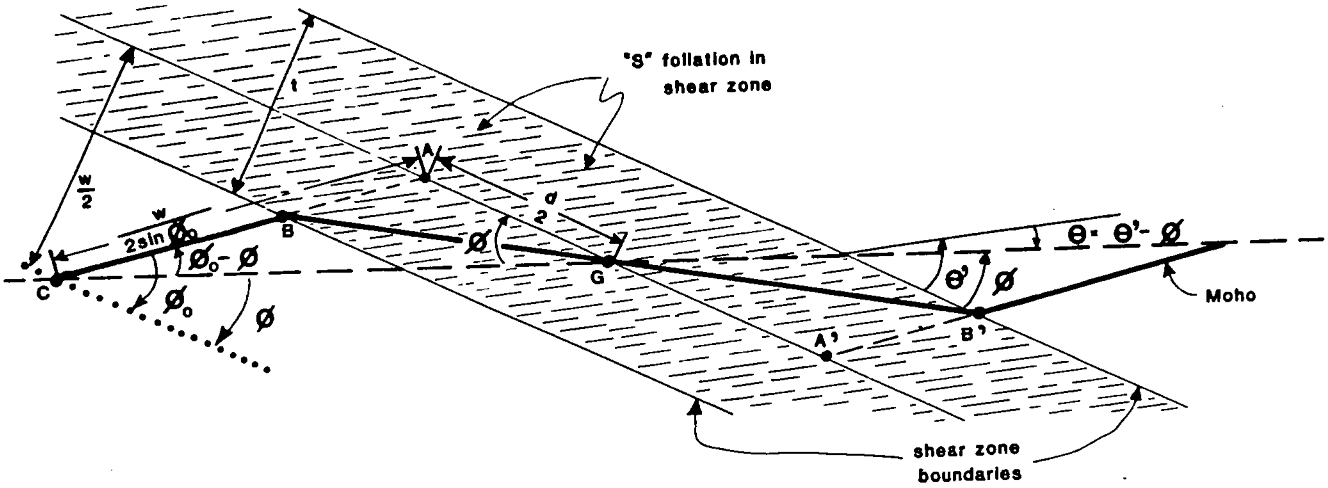
km/s time section, 21 km on Blundell et al.'s [1985] depth section, and 24 km on Peddy's [1984] depth section of WINCH-1. The width of the inferred shear zone on Figure 2 is about 10 km, and a similar width can be measured on the depth section of Blundell et al. [1985]; this parameter cannot be determined from Peddy's [1984] depth section, because it does not consider reflections as far east as those at point B on Figure 2]. It thus seems that within the uncertainties involved in depth conversion, the ratio t/w is about 1/2, in reasonable accord with the geometric model proposed here.

Other mechanisms, such as soling the normal faults into Moho-parallel simple or pure shear [e.g., Blundell et al., 1985], or "smoothing" the Moho through time by lateral flow (Brewer and Smythe, 1984) are also clearly plausible. One of the severest limitations in eliminating any of these mechanisms is that the velocity structure of the profile is only very poorly known. While the precise configuration of the reflectors may never be known, the analysis by Blundell et al. [1985] suggests there is little latitude in changing the basic geometry of the original time section in Brewer and Smythe [1984]. In particular, the upward flattening of the Flannan structure and the east-dipping segments of the Moho along deep projections of the Outer Isles and next-higher graben-bounding displacement zones are preserved. The dips of most reflections increase in Blundell et al.'s [1985] model, most notably the Flannan structure, which increases from 25° on the time section to 30-35° on their model. We wish to determine whether or not possible values of $\phi_0$, $\phi$, t/w, $\gamma$, and $\theta$ are internally consistent with the reflection data.

On the time section [Figure 2], $\phi$ for the Outer Isles structure is approximately 15-20° and the dip of the steepest sediments in the North Lewis basin is about 10-15°, giving a $\phi_0$ in the range of 25-35°. However, the model of Blundell et al. [1985] suggests that $\phi$ is actually 23° and the bottom of the graben fill dips 17°, suggesting a $\phi_0$ of 40°. The normal displacement on the Outer Isles structure is at least 20 km,

## DETAIL OF FOLIATION DIP CALCULATION

We wish to plot $\theta(\phi)$ contoured in $\gamma$ given $\left(\frac{t}{w}\right)$ and $\phi_0$.



Given: $\gamma = \frac{d}{t}$ and (1) $\tan 2\theta' = \frac{2}{\gamma}$ (Ramsay, 1980);

From Law of Sines on ACG, $\frac{w}{\sin\phi \sin\phi_0} = \frac{d}{\sin(\phi-\phi_0)}$

Thus $\left(\frac{w}{t}\right)\frac{\sin(\phi_0-\phi)}{\sin\phi_0 \sin\phi} = \gamma = \frac{2}{\tan 2\theta'}$

so $\theta = \frac{1}{2}\tan^{-1}\left[-2\left(\frac{t}{w}\right)\frac{\sin\phi\sin\phi_0}{\sin(\phi_0-\phi)}\right]$ and $\boxed{\theta = \frac{1}{2}\tan^{-1}\left[-2\left(\frac{t}{w}\right)\frac{\sin\phi_0\sin\phi}{\sin(\phi_0-\phi)}\right]-\phi}$

Taking (1), we also see that $\boxed{\phi = -\theta + \frac{1}{2}\tan^{-1}(-2/\gamma)}$

Fig. 6. (a) Geometry and calculation of the dip of foliation in a progressively rotating shear zone.

because this is the distance over which footwall basement is juxtaposed with the graben fill. The displacement could conceivably be on the order of 30 km or more.

The sigmoidal shape of the Moho where the Outer Isles structure projects to depth is consistent with a 20 km or greater offset. Assuming that t/w is on the order of 0.5, the approximate shear strain, $\gamma$, within the presumed lower crustal shear zone is 2. From Figure 6b, we note that a t/w of 1/2, $\gamma = 2$, $\phi_0 = 40^\circ$, and $\phi = 25^\circ$ are internally consistent with one another, and suggest foliation dips in the lower crust within $5^\circ$ of horizontal.

Some of the strongest reflections in the lower crust on MOIST occur where the Flannan structure projects into it. The reflections in the lower crust make an angle of about $15^\circ$ with the Flannan on Brewer and Smythe's [1984] time section, but this angle becomes about $30^\circ$ according to the model of Blundell et al. [1985]. Unfortunately, the total normal displacement on the Flannan structure is not well known, but the moderate east dip of the lower crustal reflections is certainly within the limits of the present model, because if we assume a migrated $\phi$ of $30^\circ$ for the Flannan, then with even moderate rotation (implying $\phi_0 = 40$-$45^\circ$) it is very difficult to get the foliation to dip opposite the shear zone. However, in the case where $\phi_0$ is low and the shear zones wide, opposite dips in lower crustal foliation would be possible even at very high strains ($\gamma > 10$).

### Conclusions

It is clear from this analysis that there are many degrees of freedom in interpreting the reflection data, and that the consistency of any model with the data does not constitute grounds

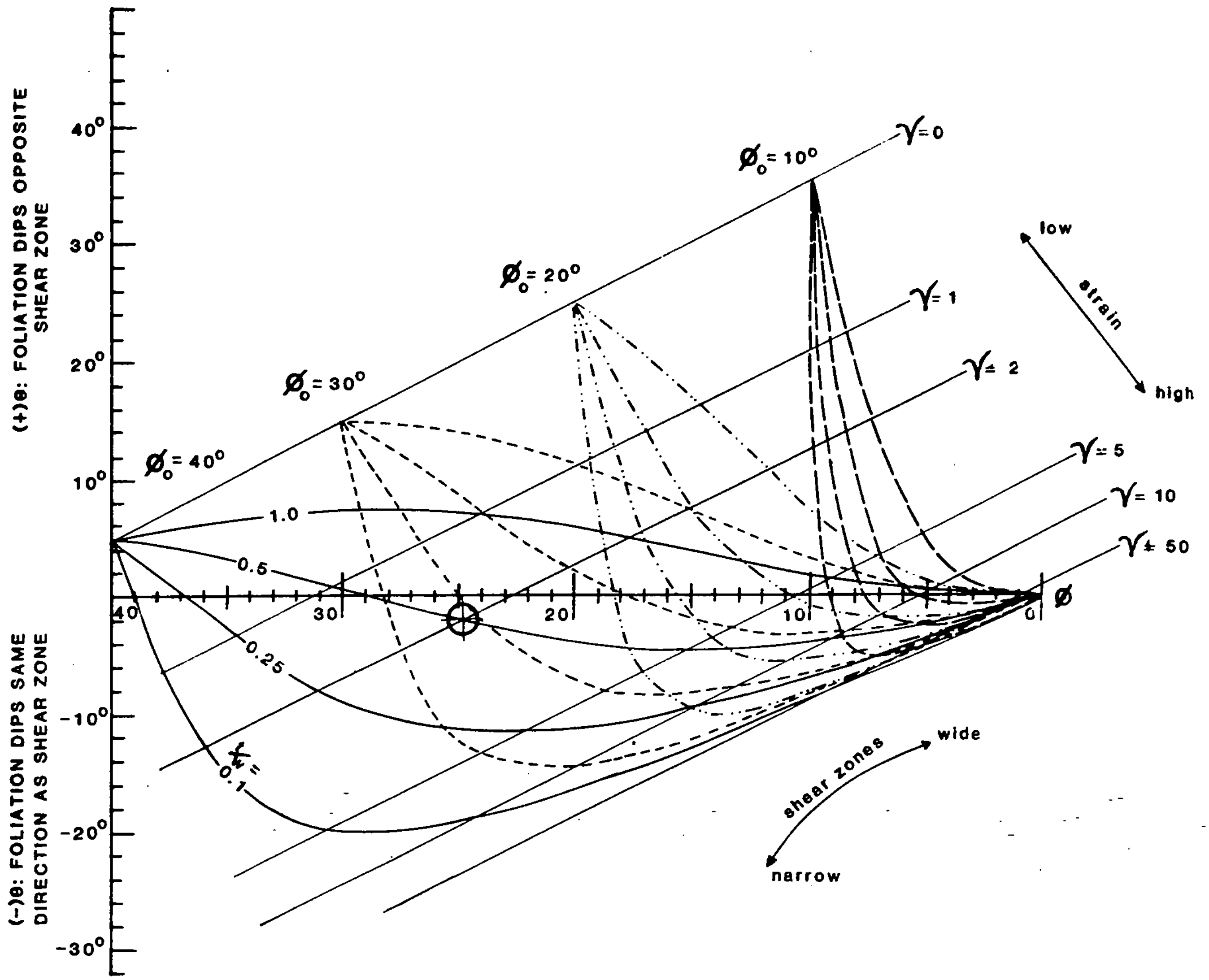


Fig. 6. (b) Graphical portrayal of the relationships between various parameters in (a). Circle with cross represents point discussed in text. Parameters not defined in Fig. 4. include: d, net displacement across shear zone; γ, shear strain within shear zone; θ', angle between foliation and shear zone boundary. Points A, A', B and B' are keyed to points on Fig. 4.

for ruling out other models. The purpose here is to introduce a more quantitative approach to thinking about lower crustal strain geometry that may eventually provide insight on how to test some of the many hypotheses about deep lithospheric extension.

One of the most attractive attributes of extending the lower crust on inclined shear zones is that it provides a mechanism for the development of shallow, variably dipping foliations. Although it is emphasized by many workers that the lower crust is dominated by many short, "subhorizontal" reflections, careful inspection of much of this data shows that the majority of these reflections actually dip, many of them as much as 20° or more [see, e.g., Brewer et al., 1983]. Upon migration, these dips will presumably increase. It is difficult to envision why a crust undergoing extension on the order of a factor of two or more by horizontal pure shear would preserve so many dipping reflections. The presence of pre-existing steep foliations presents major complications for both models, but the present one provides a means by which primary extensional foliation may have substantial dips, in either direction to the regional sense of shear (Figure 6b).

Deep reflection profiling by itself is clearly a tantalizing but very limited method for trying to unravel the nature of the lower crust. Significant progress in understanding the deep crust will most likely come out of attempting to test some of the many interpretations of deep reflection data by direct surface observation of deeply eroded continental crust, about which precious little is currently known. Considering that the phenomenal strides recently made in understanding continental extension processes are principally the result of detailed field studies in the Basin and Range province (similar to the early understanding of compressional structure gained from field studies in the Alps), it seems that only a combination of direct, hands-on geology and seismic studies will eventually lead to our most detailed understanding of lower crustal processes.

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