# Seismic reflections from subvertical diabase dikes in an Archean terrane: Comment and Reply

## COMMENT

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The demonstration by Zaleski et al. (1997) that bright subhorizontal reflectors apparently at 1–3 km depth are actually sideswipe from dikes trending subparallel to the seismic line is salutary. They have provided a valuable warning of the possible dangers of over-enthusiastic geological interpretation of two-dimensional seismic reflection profiles over crystalline terrane.

However, their claim to have published the first data set in which reflections are "unambiguously correlated with dikes" is unfounded. Seismic reflection observations were made as long ago as 1969 of some of the well-known Tertiary (Paleocene) tholeiitic dikes of northwest Britain inferred from geophysical methods. The Loch Ewe dike in the North Minch west of Scotland is the best documented example (McQuillin et al., 1979, fig. 7/22; Chesher et al., 1983). It is about 500 m wide, with its top about 1 km below sea level, and it shows up prominently as a reflected refraction event on all the seismic reflection sections that cross it. It dies out to the southeast at the mainland coastline and does not reach the surface anywhere (Ofoegbu and Bott, 1985). The Loch Ewe dike and others of the same swarm were also noted (although not explicitly discussed) on the well-known BIRPS deep seismic profiles from offshore northwest Scotland (Brewer and Smythe, 1986; Klemperer and Hobbs, 1991). Members of the swarm can be traced to the southeast off the eastern coast of England, where they are identified on industry multichannel seismic reflection lines, correlating with aeromagnetic anomalies (Kirton and Donato, 1985; Brown et al., 1994).

I have compiled geophysical evidence for the Late Carboniferous quartz dolerite dike swarm of northern Britain (Smythe, 1994; Smythe et al., 1995). Aeromagnetic data in the North Sea show that onshore dike anomalies can be traced up to 200 km east from the United Kingdom coast. Individual dikes, which are generally up to 30 m wide onshore, attain widths of well over 1 km offshore. Thus they are at least as wide as any known dikes. This swarm is probably as extensive and voluminous as the well-known and better-exposed Paleocene tholeiitic swarm of northwest Britain. The easterly extensions offshore of dikes at Dunbar are seen on industry multichannel seismic reflection sections, coincident with the location of the positive linear magnetic anomalies. The dikes are revealed by prominent diffraction patterns, which are probably reflected refractions (Day and Edwards, 1983). The closely spaced Dunbar dike sub-group has a cumulative width of 2–3 km over its length of 200 km, which makes it as large, volumetrically, as any intracontinental dike discovered to date. In comparison, the Great Abitibi dike on the Canadian Shield is 600 km long and 250 m wide (Ernst et al., 1987). The Great Dyke of Nova Scotia (also known as the Shelburne dike) is up to 200 km long, and 60–180 m wide (Papezik and Barr, 1981). Gravity modeling of the Great Dyke of Zimbabwe shows that it is bell shaped, with the main feeder about 1 km wide (Podmore and Wilson, 1987). This dike is 550 km long.

What can we learn from this? First, many more ultrawide dikes may be discovered if we look for them. We can reprocess existing seismic reflection data to enhance reflected refractions, and thereby identify dikes, rather than to filter them out, as is normally the aim in conventional processing (e.g., Larner et al., 1983; Tsai, 1984, 1985). Second, such reprocessing methods may prove to be fruitful on data shot over oceanic crust, to enhance and possibly image the dikes of oceanic layer 2. Third, those of us interested in seismic imaging of the crystalline upper crust should employ three-dimensional (3-D) methods to avoid the pitfall of misleading out-of-plane reflections such as those demonstrated by Zaleski et al. (1997). This is especially important where the primary aim of the survey is to image sub-horizontal reflections at deep crustal boreholes where igneous intrusives or extrusives are known to be present; obviously, such sills and basalts are usually fed by dikes. As a minimum precaution, intersecting 2-D lines must be surveyed, as over the Swedish Siljan Ring structure (Juhlin, 1990). A better strategy is to augment a 2-D profile with some limited 3-D coverage, as was done at the Kola (Russia) SG-3 superdeep well (Smythe et al., 1994). But the best strategy is to obtain full 3-D seismic coverage, as was done at the German KTB superdeep well (Harjes et al., 1997). In conclusion, the future of crystalline crustal seismic reflection profiling lies in using some kind of 3-D method, as is already routine in hydrocarbon exploration and production.

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## REPLY

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We thank Dr. Smythe for his Comment providing additional illustrations that dikes produce significant seismic events, in both land- and marine-based seismic reflection surveys, ranging in scope from our detailed high-resolution survey to regional surveys designed to image lithospheric thicknesses. However, in many of the examples given, the seismic evidence for dikes is based on secondary features, such as disturbance of reflective sedimentary horizons by dike emplacement (McQuillin et al., 1979; Kirton and Donato, 1985; Ofoegbu and Bott, 1985), channel features interpreted as the result of dewatering, diagenetic volume-loss and graben formation near dike contacts (Brown et al., 1994), and sedimentary drapes over extrusive material at the top of a dike or over the dike itself (Brown et al., 1994). Brown et al. (1994) combined secondary features with modeling of seismic interval velocities and identified dikes as zones of anomalous apparent uplift and high velocity. In other examples, dikes are associated with diffraction patterns (McQuillin et al., 1979), rather than with coherent reflections. Smythe (1994, p. 23) suggested that the diffraction patterns are "probably reflected refractions," and from his reference to Day and Edwards (1983), we infer that he envisaged a geometry and mechanism analogous to that of our modeling studies. Our contribution lies in unambiguously correlating several subvertical dikes with their associated reflected refractions, and in providing a predictive model that demonstrates the relationship between the map-view position and trend of dikes, and the position and apparent dip of the reflected refraction in the seismic profile.

We were able to recognize the systematic relationships and to devise the model from the results of a 2-D seismic reflection survey because of the excellent constraints on the surface position and possible subsurface geometry of lithological units, including dikes. The constraints were based on geological mapping, interpretation of high-resolution aeromagnetic data, structural analysis, and down-plunge projection, integrated with determinations of acoustic rock properties and 3-D forward-modeling of the seismic expression of predicted reflective interfaces. Although we agree with Smythe that full 3-D seismic coverage may provide optimal control on the position and origin of seismic events, and we have conducted 3-D surveys ourselves for this purpose (Adam et al., 1997; Eaton et al., 1997; Milkereit et al., 1997), the monetary and environmental costs for land-based 3-D surveys can be prohibitive, and nonscientific factors, such as existing road networks, are an important consideration. Hence, in many investigations of the crystalline crust, 2-D seismic methods will continue to be a practical tool for reconnaissance surveys, and any model that can enhance the interpretation of 2-D data and assist in the identification of off-line reflections will be useful. At least for crystalline upper crust, the tools and techniques of the field and structural geologist can go a long way toward augmenting the interpretation of 2-D seismic data.

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# Early Paleozoic paleogeography of Laurentia and western Gondwana: Evidence from tectonic subsidence analysis: Comment and Reply

## COMMENT

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Williams (1997) used tectonic subsidence curves to constrain paleogeographic interpretations of the early Paleozoic. Despite our differing interpretations of the geographic relations of Laurentia and Gondwana during this time, we are united in finding Williams's contribution flawed in methodology, factually incorrect, and thereby presenting unsubstantiated and misleading claims.

The basis of the methodology (Williams, 1995, p. 79) is that there are "a limited number of distinct tectonic subsidence curves, each of which is representative of a different tectonic style." Thus, it is claimed that study of these curves may "provide constraints on some paleogeographic reconstructions" (Williams, 1997, p. 747). Tectonic subsidence analysis is a valuable approach to timing of rift-drift transition. It does not, however, otherwise furnish data directly on the time-space relations of continents. All six of his tectonic settings for subsidence curve types are represented, for example, in basins formed during the Mesozoic-Cenozoic history of subduction along the Andean margin of South America. Thus, the presence or absence of basins with certain types of subsidence curves along a continental margin need have no bearing whatsoever on ocean width.

With regard to factual errors, one very important example is the statement that the tectonic subsidence curve for the Cambrian-Ordovician strata of the critical Precordilleran terrane of northwest Argentina "does not show any significant response, either in the form of a major unconformity or of a foreland basin, to the docking onto Gondwana in the Ordovician that is predicted by both the wide- and narrow-ocean paleogeographic models" (Williams, 1997, p. 748). Actually, the Middle-Upper Ordovician strata of the Precordillera show not only a major unconformity at the time of docking, but also a change in flexural behavior coeval with the sedimentation of black shales that initiate the collisional clastic wedge (e.g., Astini et al., 1995, 1996). Williams does note a major change from carbonate- to clastic-dominated successions. This interval of increased gradient in the subsidence curve was related to the collision-induced flexural subsidence in a peripheral foreland context (Thomas and Astini, 1996). Collision-induced flexure started in middle to late Arenig times, whereas the basaltic pillow lavas in the west were extruded during postcollisional extension in the Caradoc and have an E-MORB signature rather than being "arc-related" (for review see Dalziel, 1997).

We have several problems with the paleogeographic scenario presented by Williams in his recent paper (William, 1997, Fig. 2), and the earlier contribution on which it is based (Williams, 1995, Fig. 14): the totally unsubstantiated placement of the Patagonian "terrane" outboard of Peru and Chile in late Precambrian times; the location of Baltica in tropical latitudes at the Cambrian-Ordovician boundary; and the location of West Antarctica ("east Antarctica" in Williams, 1997, Fig. 3) in the Cape embayment. Most egregious to us, however, is the statement (Williams, 1997, p. 749) that derivation of the Precordilleran terrane from the vicinity of the Ouachita embayment (Dalziel et al., 1994; Astini et al., 1995; Thomas and Astini, 1996; Dalziel, 1997) can be explained by "a