PSPredicting the Brittle-Ductile (B-D) Transition in Continental Crust Through Deep, Long Offset, Prestack Depth Migrated (PSDM), 2D Seismic Data*

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Abstract

Since 2001, GX Technology has acquired a number of long-offset (10 km), long-record (18-sec), 2D marine seismic surveys (the "SPAN™" surveys) over various passive margins and in some marginal seas (ION, 2009). The surveys are widely spaced and are located to image important geological features of regional crustal architecture that are beyond the scope of exploration-scale seismic surveys. The surveys are processed to PSDM datasets (Prestack Depth Migration, at least to 25 km but many to 40 km depth) using state of the art processing procedures for the supracrustal section and gravity and magnetic modeling to constrain stacking and migration velocities in the crystalline basement. As such, the SPAN surveys equal or surpass conventional exploration-seismic data, and far surpass the 1970s and '80s COCORP-vintage crustal imaging.

The interpretation of SPAN datasets is typically carried out in conventional wiggle-trace display and in various derivative displays in SMT's Kingdom Suite™ software before being delivered to clients. The "Average Energy" seismic attribute, in particular, tends to suppress a good deal of the small-scale noise in wiggle-trace displays in the crust and is commonly used as an auxiliary display for the mid- and lower-crustal level imaging and interpretation.

Kilometer-scale features are discernable both vertically and horizontally below the base of the sedimentary section in the migrated sections, including a variety of horizontal, dipping, and arcuate interfaces, and "noisy" as opposed to "transparent" zones in the data. In many cases several of these features are present in any one structural province, which serve to distinguish provinces from each other. Following

previous crustal seismic imaging studies, we are attempting to develop criteria to recognize their significance. One class of discontinuities, for example, includes interfaces that terminate at the top of “basement” and are interpreted to be older, un-reactivated faults within the crystalline basement. A particularly important class of features includes well defined faults that cut the sedimentary column and the sediment-basement interface (“acoustic basement”) but also are traceable into the underlying crystalline crust as dipping interfaces. This correspondence supports their identification as basin-formation-related, crustal-scale faults. We focus on these features in this study and their relationship to reflectivity zones in the crystalline crust.

Seismic Character of the Crust

Depth-processing minimizes velocity distortions in migrated sections so as to preserve true dip relationships. Fault systems in the class that ties to features in the supracrustal section are listric in form and commonly sole out into or merge with a fault flat at or near events or narrowly-defined intervals in zones of reflectivity contrast at the top of an acoustically transparent zone. That zone is usually at or near mid-crustal levels within the continental lithosphere, but may actually be deeper and approach Moho in some examples. Other events and zones of contrasting seismic character often lie between the Moho and the transparent zone. Above the transparent zone, the seismic character shows a variety of features assumed to relate to structure, lithology and fracture-related qualities of the crustal lithosphere. Figure 1 is a typical example of stretched continental crust, for the South Makassar Basin in Indonesia.

The Brittle-Ductile Transition

The observation that demonstrable supracrustal faults sole out near the top of transparent zones suggests the possibility that the brittle-ductile transition (B-D) in the continental crust *at the time of faulting* occurs there, for two reasons: (1) the B-D should be the level in the crust at which fault offsets are transformed into horizontal displacements as stretching or shortening is accomplished below the transition by ductile processes, and (2) crustal-scale faults should cross the boundary at low angles of dip and propagate or link upward at steeper angles in accordance with the ambient stress field.

We emphasize ‘at the time of faulting,’ because the onset of ductility at the B-D corresponds to the activation of crystal-plastic processes generally recognized to be thermally activated (Figure 2) and increasingly thought to be governed by temperature-dependent, cyclic hydration events in the crust (Yardley, 2009). “Dry” crystalline rock (i.e. that devoid of free water) has been known for some time to be strong at surprisingly high temperatures, suggesting that the crystalline crust under normal circumstances is relatively stable. On the other hand, silicate-dominated rocks are exceedingly weak in the presence of water. Free water is thought to be highly transient in crystalline crust at depths subject to metamorphic temperatures (>150° C, >~6 km), where it readily participates in retrograde metamorphic reactions and is stored in hydrous phases. Hence ductile deformation is probably only possible in the mid- to lower-crust at times when free water is either released from storage in hydrous minerals by dehydration (prograde) metamorphic reactions or when it infiltrates to appropriate depths along transient pathways from shallower sources. Activation of structures rooted or detached in mid- to lower-crustal levels is therefore a secular event, timed with water release in, or infiltration into the crust. Dry crust is probably constrained to detach at deeper levels in the lithosphere - at or near Moho - where strength is assumed to decrease (Figure 2) by reason of the ductility contrast between crustal and mantle lithologies.

Origin of Seismic Transparency

Not every seismically transparent zone is associated with fault detachments in the SPAN datasets, nor are detachment levels universally associated with transparent zones. Although it is tempting to attribute the transparency to homogenization of rock properties that are related to the B-D, the lack of a one-to-one correspondence with faults indicates that the transparency is likely related to several phenomena. The "transparent" seismic response zone simply indicates that any layering or fabric present is too thin to be resolved by the seismic frequency that is preserved at lower crustal levels. Intervals of healed fracture-related defects within discrete structural zones, stretching foliation, lithological homogeneity independent of the transition from brittle to ductile rheology, other high temperature effects on the acoustic impedance contrasts, or likely a combination of effects, may be involved.

In any case, the detachment within or at the top of the B-D transition is likely to be a thicker zone of ductile deformation than is the case for deformation at shallower (supra-crustal) levels, and similar in structure and fabric to mylonites (Sibson, 1977). This zone could be several hundred meters to kilometers in thickness, and thus within the range of seismic imaging. Hurich et al. (1985), for example, recorded a seismic reflection profile across the Kettle Dome in Washington State (USA) where mylonitic rocks are exposed in a metamorphic core complex that project to depth in a well known fault zone. They show how that fault zone is readily detected as a zone of enhanced and complex reflectivity extending down-dip from the outcrop. It follows therefore that if the detachment surface is in fact seismically visible, it may actually locate the B-D at the reflective top of transparent zones in data sets like Figure 1, rather than the transparent zone itself. The transparent zone would seemingly arise from other but potentially related acoustic sources.

Applications in Petroleum Industry

The petroleum industry has generally paid inadequate attention to crustal geology and relied instead on data from intra-basinal supracrustal rocks to develop concepts for basin evaluation, petroleum systems, and exploration. Observations from the SPAN datasets, however, indicate that there is geometric information *below* acoustic basement that may be of use to regional studies, and especially to the unraveling of details of basin evolution. In addition to the basin architecture at a gross scale, though, insofar as the B-D is thermally related, it offers basin-modeling studies much-needed constraints for the calibration of crustal temperature at specific stages in basin formation, either by directly constraining the temperature structure or, along with the depth to Moho, by providing constraints on stretching models. Discussion of the petrological control on the temperatures (T) that may be related to acoustic contrasts observed in the SPAN data is beyond the scope of this report, but seismic determination of B-D can fix the depth (z) and time (t) for basin-modeling studies.

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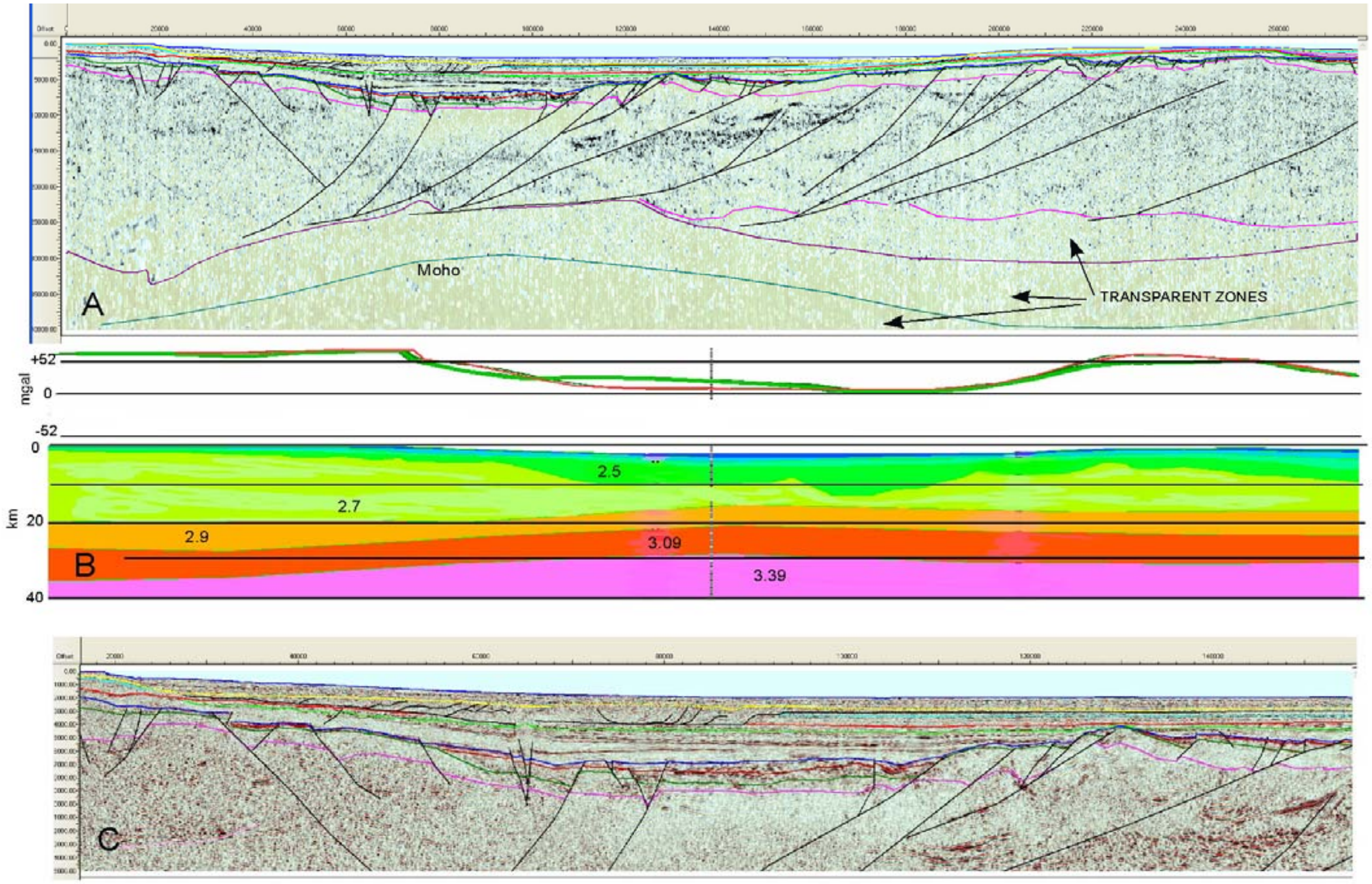

Figure 1. Line 4900 of the JavaSPAN dataset (ION, 2009) over the South Makassar Basin from NW (left) to SE (right). A) Average energy display of crustal scale section, to 40 km. Offset in m along top of line, depth in m along edge of section. Moho in green, mid-crustal reflectors in magenta and maroon, basement pink, supracrustal reflectors as described in ‘C’. Two transitions in “noisiness“ are apparent within the crust with intervening levels where faults that cut the sediment/basement interface root. One or both of these interfaces represent the brittle-ductile transition. B) Gravity model and density structure used to constrain seismic processing in the crystalline crust and its interpretation. Green line is observed, red modeled. C) Conventional wiggle trace display of the upper 15 km of the line showing crust-scale faults that form the Eocene basin architecture and some structure internal to the basement. A major gravity slide is shown in the section above the Oligocene and below the Pliocene, with detachment shown in black (faults). Stratigraphic horizons: yellow = Late Pliocene, bright blue = Late Miocene, red = Early Miocene, green = Early Oligocene, blue = Late Eocene, brown = mid Eocene, green = Early Eocene, pink = crystalline crust.

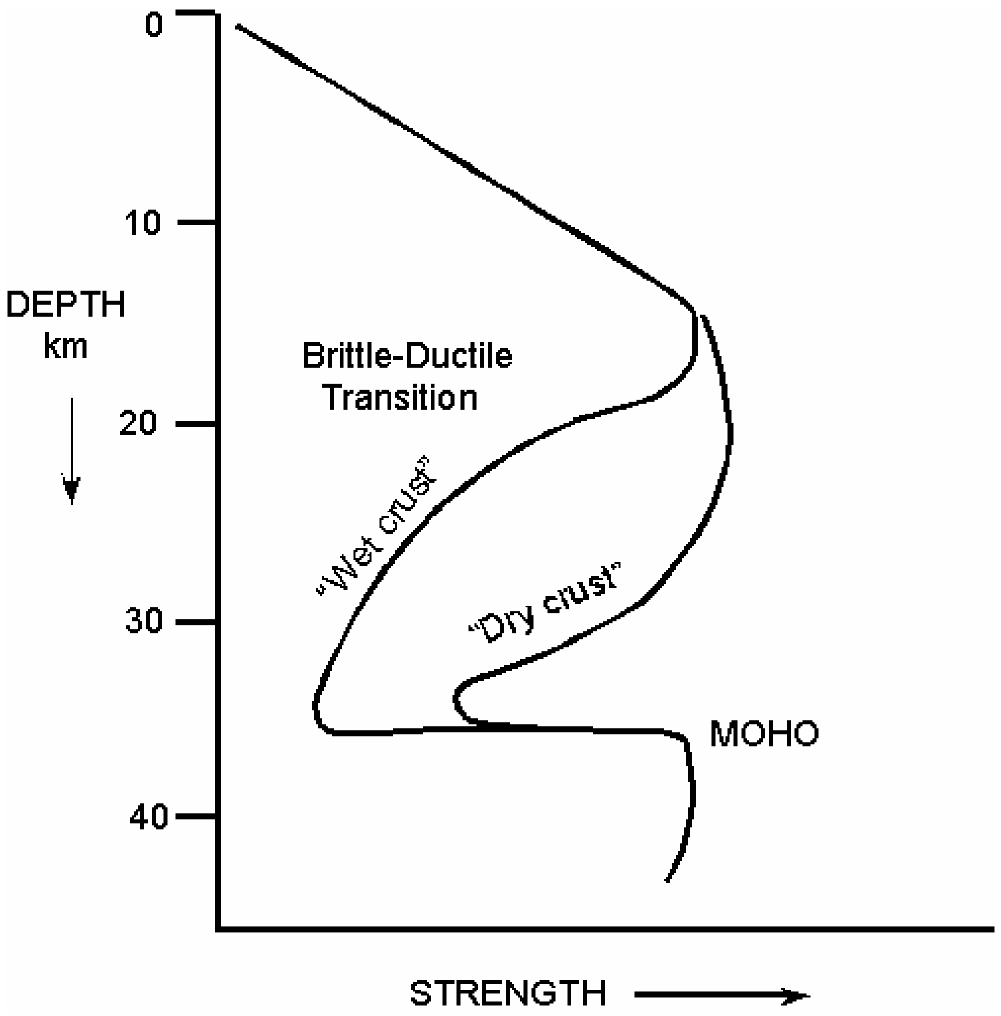

Figure 2. Generalized depth – strength profile for typical continental crust showing the strength reduction in situations where water is present to hydrolytically weakened crystalline rocks and where water is absent (the 'wet' and 'dry' conditions). Rheology in the upper crust is governed by fracture suppression, and thus increased strength, with increasing pressure as depth increases. Within and below the brittle-ductile transition, temperature increase promotes crystal-plastic processes that are aided by the presence of water. Dry crust maintains strength to near the MOHO discontinuity, where compositional changes to ultramafic rocks of the mantle again increase strength (adapted from Yardley, 2009, Figure 12).