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Has the Wyoming Craton lost its keel?

John Facer and Hilary Downes

School of Earth Sciences, Birkbeck, University of London, Malet Street, London WC1E 7HX, UK

1. Introduction

The mantle lithosphere beneath Archean cratons has two very distinctive features: (1) cratonic peridotites sampled by xenoliths all show major element (Ca, Al and Fe) depletion and high Mg # consistent with high (around 30 to 40%) basaltic melt extraction, and (2) most cratons are underlain by lithospheric keels up to 250 km thick. That these two features are related was suggested by Jordan (1978) who proposed that the deep roots beneath cratons are chemically stabilized by the buoyancy of the melt-depleted peridotites. The thick keels of ancient cratons may thus be the key to the formation and stabilization of the early continents.

There is much concerning the evolution of these Archean keels that is poorly understood, including what causes a craton to lose its keel. The keels beneath most cratons appear to have remained coupled to their crust since formation, protecting it from subduction and recycling. Some cratons, however, appear to have lost their keels including, it has been suggested, the Wyoming craton (Figure 1), one of the seven major Archean provinces making up the core of the North American craton, Laurentia. Our knowledge of the lithosphere under the Wyoming craton is based mainly on seismic studies and on evidence from xenoliths i.e., samples of the lithosphere which have been carried to the surface by magmatic eruptions. This poster reviews what we currently know about the keel of the Wyoming craton and identifies issues that still need to be resolved.

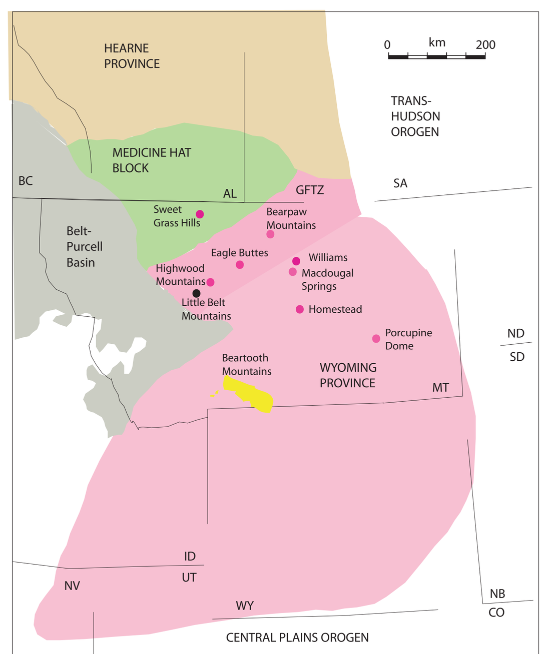

Figure 1. Generalised tectonic map of the Wyoming Province and contiguous terranes. Selected xenolith locations indicated by red dots. GFTZ = Great Falls Tectonic Zone. (Adapted fom Carlson *et al.*, 2004).

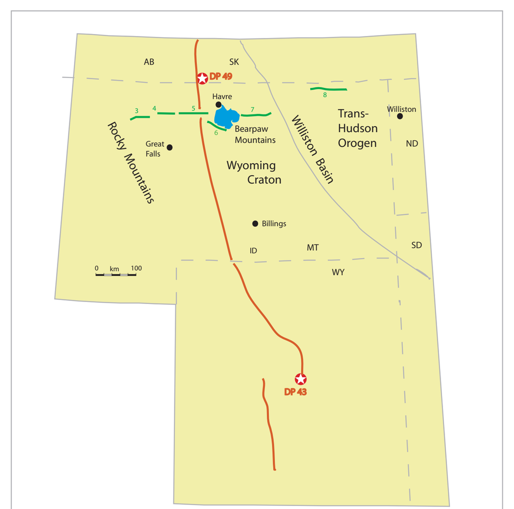

Figure 2. Sketch map showing approximate location of COCORP seismic lines 3-8 (green) and Lithoprobe Deep Probe north-south transect (red). DP 49 and DP 43 represent Deep Probe shot points shown in Figure 3. (Latham *et al.*, 1988; Gorman *et al.*, 2002).

2. What we know from seismic studies

Seismic tomography seems to suggest that there is no present-day lithospheric keel beneath the Wyoming craton (Van der Lee & Nolet, 1999). Seismic reflection and refraction studies have yet to resolve the lithosphere-asthenosphere boundary beneath the craton but they have raised questions concerning the lower continental crust. The 1986 COCORP seismic reflection survey across Montana found, on the eastern margin of the craton (line 8 in Figure 2), strong reflections at ~39-45 km which were taken as being a high velocity lower crustal layer of mafic material (Latham *et al.*, 1988). This layer was not found in any of the COCORP lines to the west. However, the Lithoprobe Deep Probe seismic refraction-wide-angle reflection experiment (the red line in Figure 2) subsequently revealed a thick (up to ~ 30 km) high velocity lower crustal layer (LCL) extending beneath the whole of the Wyoming craton and the adjacent Medicine Hat Block (Figure 3). The LCL is associated with anomalously high velocities (6.9-7.8 km/s) and has been interpreted by Gorman *et al.* (2002) as a thick layer of mafic underplating.

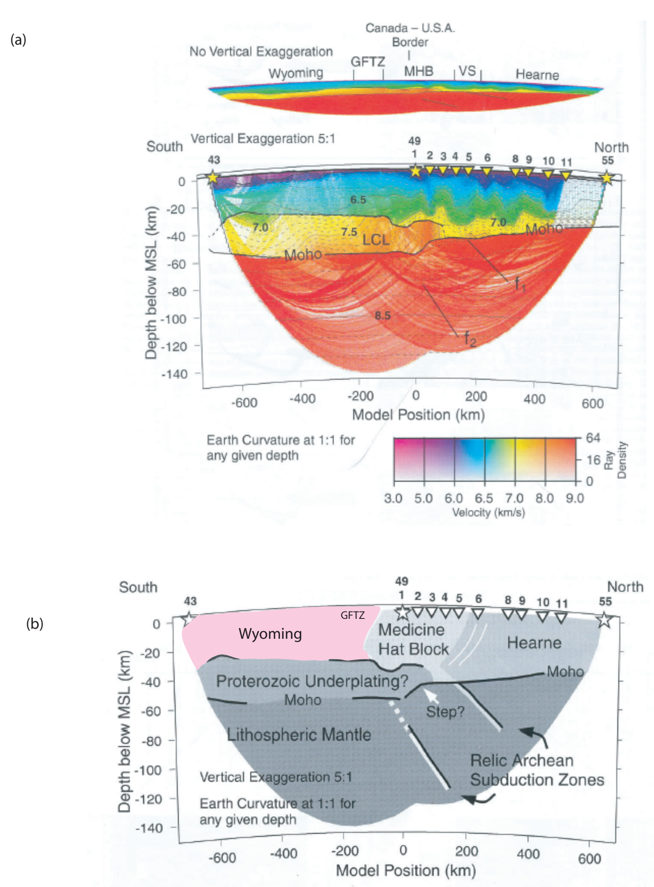

Figure 3. (a) Interpreted Deep Probe velocity model with velocities shown in colour. (b) Schematic structural interpretation of the velocity model in (a) with reflective boundaries indicated by solid black lines. Model position in km is indicated north (positive) and south (negative) of the Canada-USA border. Deep Probe (stars) and SAREX (triangles) shot points are shown. GFTZ = Great Falls Tectonic Zone; MHB = Medicine Hat Block; VS = Vulcan Suture (MHB-Hearne suture zone); LCL = lower crustal layer. MSL = mean sea level. (Gorman *et al.*, 2002).

3. What we know from xenolith studies

Zircons in lower crustal granulites from Sweet Grass Hills (Figure 1) were dated by Davis *et al*. (1995) as mid-Proterozoic (1.7-1.8 Ga) which led Gorman e*t al.* (2002) to conclude that the Wyoming craton has a Proterozoic lower crust beneath an Archean upper crust. They took this as implying that, if the Wyoming craton ever had an Archean keel, it must have been removed or modified substantially in some manner to make way for the Proterozoic LCL.

Delamination can cause lower crust and underlying mantle to be removed following a continent-continent collision if a density inversion develops between lower mafic crust (transformed by compression to eclogite) and underlying lithospheric mantle (Kay & Kay, 1991, 1993). But if the Wyoming lower crust had delaminated in the Proterozoic it would have taken the underlying lithospheric mantle with it and we know that this did not happen because mantle xenoliths with Archean ages (Figure 4) were erupted during the Eocene. These xenoliths tell us that Wyoming craton had a keel at least 150 km deep as recently as around 50 Ma.

Possibly the LCL represents a "failed delamination" where crustal thickening fell short of the critical amount of shortening needed to trigger delamination (Kay & Kay, 1993). A scenario of this kind involving the mid-Proterozoic collision between the Archean Dakota Block and the Wyoming craton is shown in Figure 5. However, with the volume of mafic underplating this would have involved, it is surprising that, apart from Little Belt Mountains, there seems to have been little volcanic activity in the area during the mid-Proterozoic (O'Neill & Lopez, 1988).

How sure are we that the LCL is Proterozoic? U-Pb SHRIMP dating of zircons from a felsic granulite from Bearpaw Mountains by Collerson *et al.* (1993) gave ages for the cores of 3.0-2.8 and 2.6-2.5 Ga and for the rims, 2.4-2.2 and 1.8-1.7 Ga, therefore, the ages from the Sweet Grass Hills granulites may not be representative of the whole of the LCL.

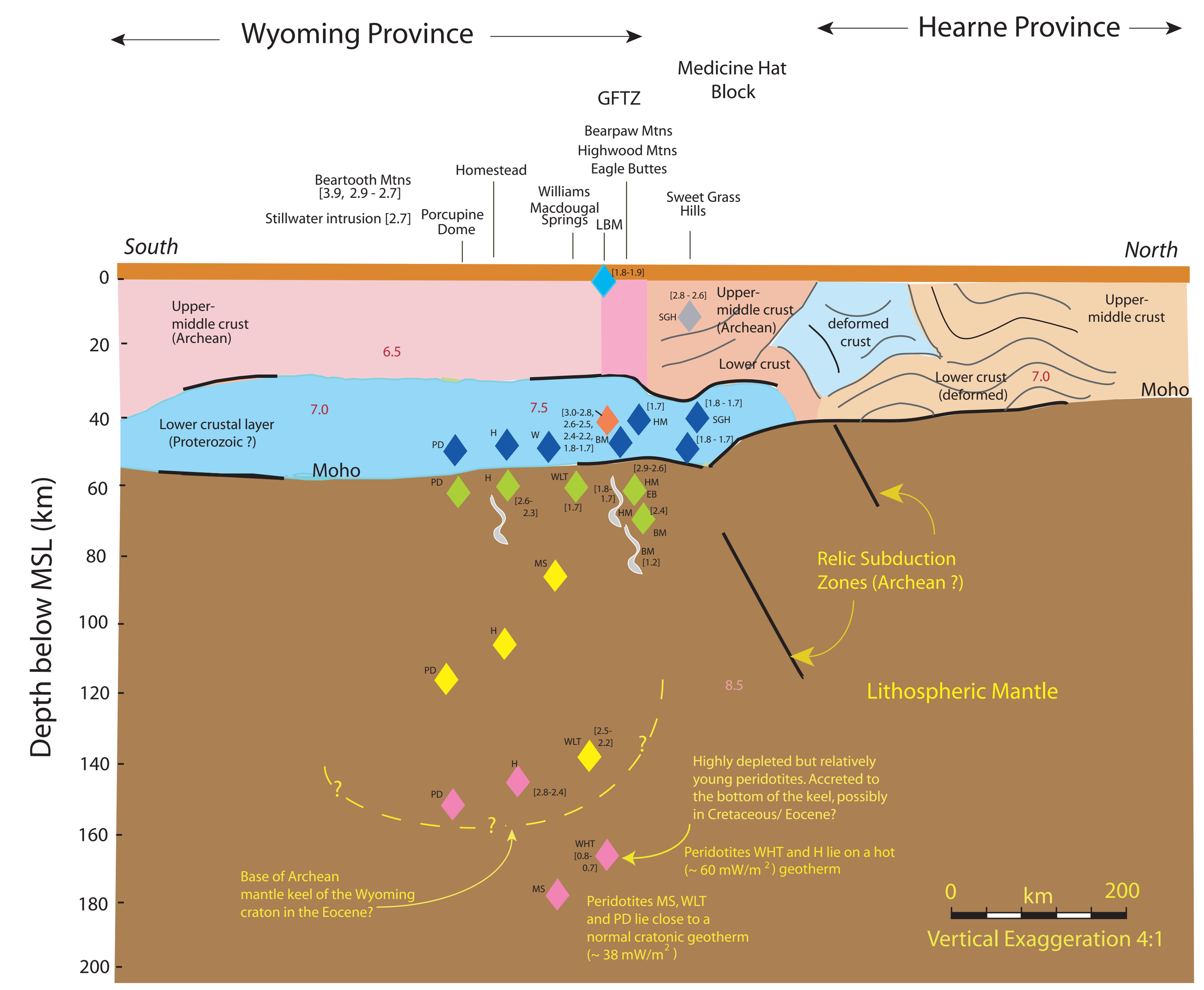

Figure 4. The structure of the lithosphere beneath the Wyoming craton in a north-south cross-section based on the interpreted velocity models of the Southern Alberta Refraction Experiment (SAREX) (Clowes *et al.*, 2002) and Lithoprobe Deep Probe (Gorman *et al.*, 2002); seismic velocities (km/s) shown in red. Xenolith locations: Sweet Grass Hills (SGH) (Irving *et al.*, 1997; Davis *et al.*, 1995); Highwood Mountains (HM) (Carlson & Irving, 1994, Rudnick *et al.*, 1999); Eagle Buttes (EB) (Carlson & Irvine, 1994); Bearpaw Mountains (BM) (Collerson *et al.*, 1993, Downes *et al.*, 2004); Williams (W) (Hearn & McGee, 1984, Carlson *et al.*, 1999, 2004); Macdougal Springs (MS) (McGee & Hearn, 1989); Homestead (H) (Irving *et al.*, 2003, Carlson *et al.*, 2004, Hearn, 2004); Porcupine Dome (PD) (Hearn, 1999). Derivation depths of peridotite xenoliths from Hearn (2004). Age data, where available, shown (in Ga) in square brackets. Other abbreviations: WLT and WHT = Williams low-temperature and high-temperature peridotites, respectively; LBM = Little Belt Mountains; GFTZ = Great Falls Tectonic Zone; MSL = mean sea level. Data on LBM from Mueller *et al.*, (2002); on Beartooth Mountains from Meen & Eggler (1987) and on Stillwater from DePaolo & Wasserburg (1979). Xenolith and other locations have been projected from east and west into this north-south cross-section. (Adapted from Clowes *et al.*, 2002).

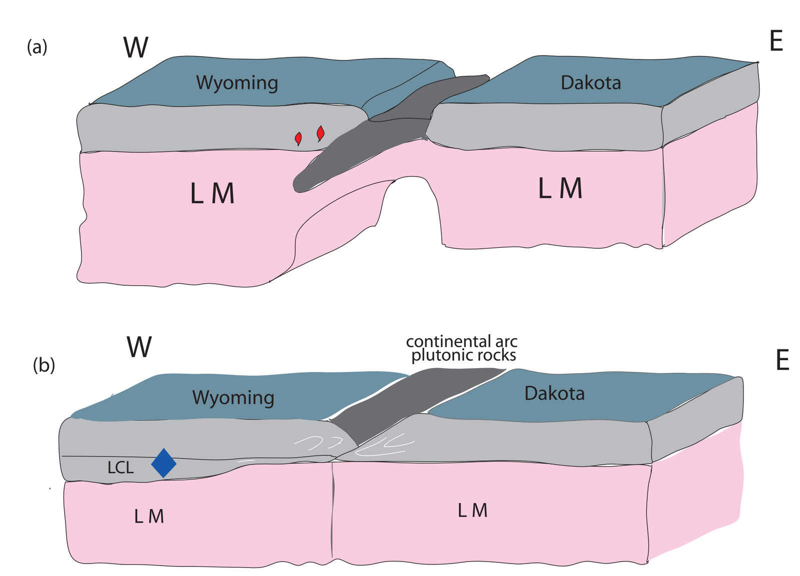

Figure 5. Cartoon showing the collision of the Archean Dakota Block segment of the Trans-Hudson Orogen (D-THO) with the Wyoming craton ~1.8 Ga. (a) Subduction of ocean basin beneath the eastern margin of the Wyoming craton; (b) Collision of Wyoming and D-THO; continental arc plutonic rocks emplaced in suture zone (Baird *et al.*, 1996) and a thick mafic underplate (evidenced by granulite xenoliths dated at 1.8 Ga, see Figure 4) added to the base of the Wyoming continental crust. LM = lithospheric mantle; LCL = lower crustal layer. (Adapted from Clowes *et al.*, 2002).

Figure 4 shows garnet peridotite xenoliths originating from depths of up to 180 km. There is some evidence that the base of the keel was removed below ~150 km, possibly during the Cretaceous to early Tertiary. Carlson *et al*. (1999) found that low-temperature peridotites from the Williams kimberlite have Re-depletion ages of 1.7 to 2.5 Ga whereas high-temperature peridotites (> 150 km) are much younger. The implication is that the high-T peridotites are not part of the Archean keel but have been added to the base of the lithosphere more recently. Surprisingly, however, these high-T peridotites show a similar degree of melt-depletion as the Archean peridotites. Garnet peridotites from the Homestead kimberlite in central Montana originate from depths of up to ~150 km but at temperatures similar to those of the Williams high-T peridotites. Carlson *et al*. (2004) found that all but one of the eight Homestead peridotites studied by them yielded Re-depletion ages between 2.30 and 2.77 Ga which contrasts with the less conclusive Archean ages of the Williams low-T peridotites and the much younger ages of the high-T samples.

It seems from these studies that around the time of the kimberlite eruptions, the mantle keel was being eroded, particularly at its NE margin, by hot asthenosphere. If so, there may have been considerable local variations. For example, xenoliths from Macdougal Springs (like Williams, one of the Missouri Breaks diatremes) extend to depths of ~180 km but lie on a much cooler geotherm (Hearn, 2004). The thermal erosion of the keel may have resulted from an upwelling of asthenosphere into the space left by the steepening subduction of the Farallon plate. In this back-arc model (Figure 6), secondary convection cells at the base of the lithosphere, in which partially melted lithosphere convected, may explain both the local variations and the depleted nature of the young Williams high-T peridotites.

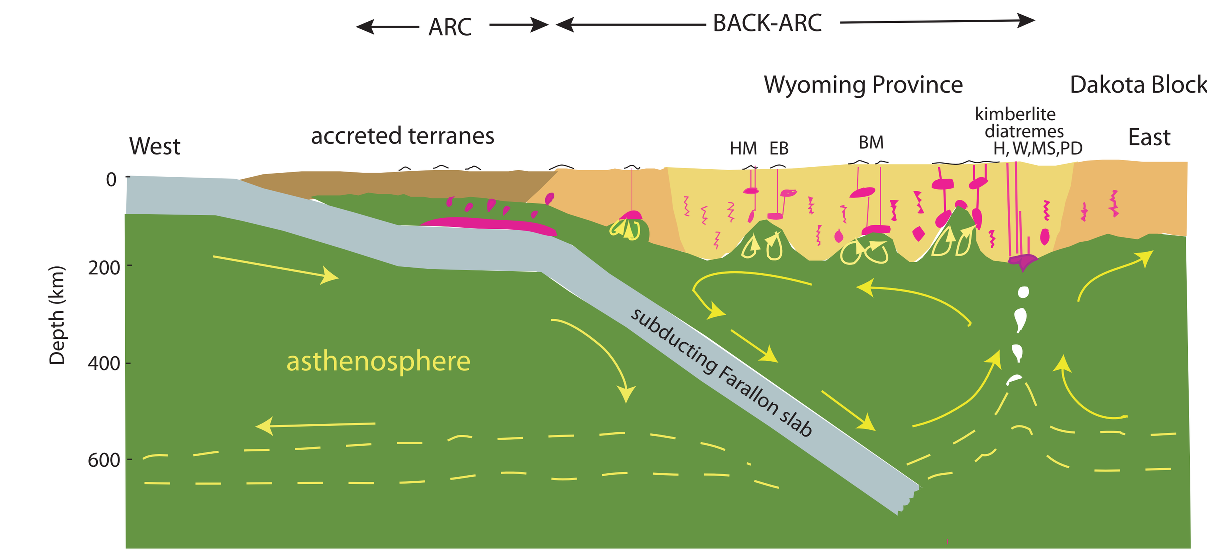

Figure 6. Cartoon showing back-arc magmatism beneath the Wyoming craton in the Eocene resulting from subduction of the (initially) flat Farallon slab. In this model, conductive heat transfer from the asthenosphere may cause melting near a thinning lithosphere-asthenosphere boundary and melting may, additionally, occur in secondary cells in which partially melted lithosphere convects. The line of the section is west-east but magmatic fields have been projected from north and south into the section. Part of the western end of the section is subparallel to the arc, accounting for the anomalous width of the arc front. For abbreviations of location names see caption to Figure 4. (Adapted from Eggler *et al.*, 1988)

4. What we need to know from integrated geophysical, petrological and geochemical studies

(A) *Geophysical studies*

The USArray transportable seismic network of the EarthScope experiment will provide the opportunity to:

1. Investigate the crustal and upper mantle structure of the Wyoming craton perpendicular to the Deep Probe profile and, in particular, whether the LCL extends east-west beneath the craton.
2. Determine the present-day lithosphere-asthenosphere boundary beneath the craton and any topographical variations at the base of the lithosphere.

(B) *Petrological and Geochemical studies*

1. We need more dates for lower crustal granulites in order to determine whether the LCL is Proterozoic or Archean. In particular, we need dates for granulites reported from locations away from the tectonically disturbed GFTZ e.g., Williams, Homestead and Porcupine Dome.
2. We need dates for garnet peridotites from Macdougal Springs and Porcupine Dome.
3. One of the greatest concentrations of spinel peridotite xenoliths from the Wyoming craton is in the Bearpaw Mountains (Figure 7) and, building on the work of Downes *et al*. (2004), further geochemical analyses of these samples is planned including the study of foliated mica websterites (Figure 7(B)), in order to better constrain the geochemistry of the migrating fluids and/ or melts which may have been responsible for the mid-Proterozoic magmatic underplating and the paleotectonic environment in which this occurred, and the study of the poorly understood origin of the white orthopyroxene porphyroclasts (Figure 7 (C)). Re-Os *in situ* analysis of sulphides is planned to determine primary melt-depletion ages and ages of later metasomatic events.

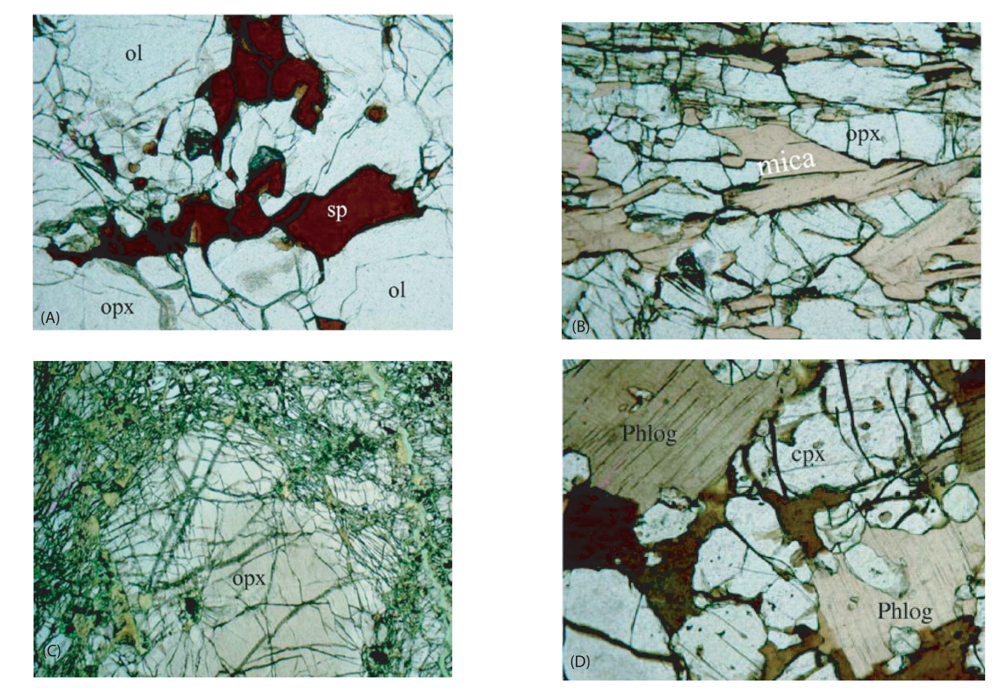

Figure 7. Photomicrographs of ultramafic xenoliths from the Bearpaw Mountains, Montana. (A) Spinel peridotite tectonite (Nd model age 2.45 Ga) depleted by up to 30% melting. PPL. Field of view 2mm. (B) Foliated mica websterite showing tabular mica and elongate orthopyroxene which may represent the migrating fluids and/or melts responsible for the mid-Proterozoic magmatic underplating of the LCL. PPL. Field of view 2mm. (C) Prominent white orthopyroxene porphyroclast in harzburgite. PPL. Field of view 6mm. (D) Cumulate mica pyroxenite showing phlogopite mica inferred to be crystallization products of Eocene magmas. PPL. Field of view 2mm. (Downes *et al.*, 2004).

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