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Reply to Comment on: "Evidence for shear-heating, Musgrave Block, central Australia" by A. Camacho, I. McDougald, R. Armstrong, J. Braun

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I thank Bjørnerud and Austrheim for their comments. They discuss our paper (Camacho et al., 2001) in the context of their own extensive work in the Bergen Arcs, Norway. Therefore, I will take this opportunity to compare the two terranes and consider the general question of whether temperatures recorded in shear zones reflect the ambient thermal regime. In addition, I will assess the implications for tectonic rates in collisional settings.

The Musgrave Block, central Australia and the Bergen Arcs, Norway are comparable to the extent that granulites have been locally transformed to eclogite at ~700 °C. In both areas there is a clear spatial association between shear zones and eclogite formation. In the undeformed granulites biotites preserve Proterozoic ages, whereas minerals in the shear zones yield Palaeozoic ages. Although the data sets for both areas are similar, Camacho and McDougall (2000) and Camacho et al. (2001) arrived at a fundamentally different interpretation from that by Kühn et al. (2000). We inferred a temperature difference between the shear zones and country rocks, whereas Kühn et al. (2000) invoked Rb–Sr phlogopite closure temperatures of ~250 °C in excess of published values (e.g. Jäger, 1979).

The implicit assumption underlying the conclusion of Kühn et al. (2000) and all other workers in the Bergen Arcs (e.g. Austrheim and Griffin, 1985; Jamtveit et al., 1990; Erambert and Austrheim, 1993; Boundy et al., 1997; Austrheim, 1998; Bjørnerud and Austrheim, 2002) is that the temperature estimate for the eclogite mineral assemblage reflects the ambient thermal regime. I question the universal validity of this assumption, particularly in collisional settings in which tectonic processes and, specifically, exhumation rates are fast (e.g. Rubatto and Hermann, 2001). We prefer to take the thermochronological data from both terranes at face value and infer that the temperature in the undeformed granulite remained 200–350 °C below that recorded by eclogite facies shear zones.

In the eastern Musgrave Block, the shear zones in question are devoid of hydrous minerals. Thus, we argued for shear-heating as the most plausible mechanism to cause local temperature increases. In the absence of any evidence for fluid infiltration (e.g. eclogites and granulites have similar concentrations of volatiles) we ruled out heat advection by fluid as a possible explanation.

By contrast, in the Bergen Arcs, the vital role of fluids in promoting the transformation from granulite to eclogite has been documented convincingly by Austrheim and coworkers (e.g. Austrheim and Griffin, 1985; Jamtveit et al., 1990; Erambert and Austrheim, 1993; Rockow et al., 1997; Austrheim, 1998). I suggest that in addition to the important role of fluid in the kinetics of the transformation, heat advection by the fluid has played a key role. In New Hampshire, USA, Chamberlain and Rumble (1989) estimated that advection of heat by fluids can cause local temperature increases of about 250 °C over a short period of time (ca. 100,000 years).

Contrary to Bjørnerud and Austrheim's (2001) argument, it is unlikely that diffusion data underpinning closure temperature estimates, which are typically estimated from controlled experiments under dry static conditions (e.g. Foland, 1974; Cygan and Lasaga, 1985), would not apply to the undeformed granulites in the Musgrave Block and Bergen Arcs. Diffusion experiments are assumed to reflect the same, thermally activated volume diffusion process that governs elemental diffusion, but at higher temperatures. We agree that deformation, dislocation densities in minerals and fluid infiltration will all result in faster equilibration than the limiting process represented by intracrystalline (volume) diffusion.

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By assuming that: (a) the experimental diffusion data are valid, (b) the terrane did not thermally equilibrate to temperatures of ~700 °C, and (c) that heat advection is important, we can account for two key phenomena previously reported for the Bergen Arcs and Western Gneiss Region. (1) The widely described 'metastability' of non-eclogitised domains in the Bergen Arcs (e.g. Jamtveit et al., 1990) and Western Gneiss Regions (e.g. Krabbendam et al., 2000), and (2) steep diffusion profiles in relic minerals (Erambert and Austrheim, 1993).

In considering the thermal evolution of a terrane, two principal factors have to be considered, transient thermal perturbations (e.g. shear-heating or heat advection by fluid) and the overall thermal evolution of the terrane. We agree with the interpretation by Erambert and Austrheim (1993) that steep diffusion profiles represent a short duration of fluid activity. However, I also consider this to represent the length scale of the thermal perturbation. By accepting the diffusion data (compositional and isotopic) we can begin to constrain the duration of geological processes. Erambert and Austrheim (1993) calculated time scales of 1–4 Ma for fluid infiltration at 700 °C under eclogite–facies conditions. In addition, according to our interpretation, burial and exhumation in the Musgrave Block and Bergen Arcs must have been fast (≤ 30 Ma) for the isotopic system not to reset.

In conclusion, in tectonic settings, such as collisional zones, where crust is rapidly buried and exhumed, temperatures recorded in shear zones need not reflect the ambient thermal regime. An inferred non-equilibrium temperature difference between shear zones and surrounding country rocks can be explained in several ways (e.g. shear-heating, heat advection by fluids or melt) depending on the tectonic regime.

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