



Mid-crustal shear zone development under retrograde conditions: pressure-temperature-fluid constraints from the Kuckaus Mylonite Zone, Namibia

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Abstract.

The Kuckaus Mylonite Zone (KMZ) forms part of the larger Marshall Rocks–Pofadder shear zone system, a 550 km-long, crustal-scale strike-slip shear zone system that is localised in high-grade granitoid gneisses and migmatites of the Namaqua Metamorphic Complex. Shearing along the KMZ occurred c. 40 Ma after peak granulite facies metamorphism, during a discrete

- 5 tectonic event, and affected the granulites that had remained at depth since peak metamorphism. Isolated lenses of metamafic rocks within the shear zone allow the P-T-fluid conditions under which shearing occurred to be quantified. These lenses consist of an unsheared core that preserves relict granulite-facies textures, and is mantled by a schistose collar and mylonitic envelope that formed during shearing. All three metamafic textural varieties contain the same amphibolite-facies mineral assemblage, from which calculated pseudosections constrain the P-T conditions of deformation at 2.7–4.2 kbar and 450–480 °C,
- 10 indicating that deformation occurred at mid-crustal depths through predominantly viscous flow. Calculated $T-M_{\rm H_2O}$ diagrams show that the mineral assemblages were fluid-saturated, and that lithologies within the KMZ must have been rehydrated from an external source and retrogressed during shearing. Given that the KMZ is localised in strongly dehydrated granulites, the most likely source of external fluid is meteoric, with fluid flow allowed by local dilation and increased permeability within the shear zone. The absence of hydrothermal fractures or precipitates indicates that, even though the KMZ was fluid-bearing, the
- 15 fluid–rock ratio and fluid pressure remained low. In addition, the fluid could not have contributed to shear zone initiation, as an existing zone of enhanced permeability is required for fluid infiltration. We propose that the KMZ initiated by the reactivation of existing, favourably-oriented ductile structures, following which fluid infiltration caused a positive feedback that allowed weakening and continued strain localisation. Therefore, the main contribution of the fluid was to produce retrograde mineral phases and facilitate grain size reduction. Features such as tectonic tremor, that are observed on active faults under similar con-
- 20 ditions as described here, may not require high fluid pressure, but could be explained by reaction weakening under hydrostatic fluid pressure conditions.





1 Introduction

Crustal-scale deformation is commonly localised into major faults, in the upper crust, and ductile shear zones, in the lower crust (e.g. Savage and Burford, 1973; Kirby, 1985; Zoback et al., 1985; Scholz, 1988; Wittlinger et al., 1998). This observation requires the presence of weakening mechanisms that both initiate and sustain strain localisation into lithospheric high strain
zones (Rutter et al., 2001). Such mechanisms include (1) high fluid pressures, which reduce the effective coefficient of friction and lead to localised and transient embrittlement (Hubbert and Rubey, 1959; Sibson, 1980; Rice, 1992), and also enhance microfracturing and mass transfer processes (Cox and Etheridge, 1989); (2) grain size reduction, and activation of diffusive mechanisms, particularly in the presence of a reactive fluid phase (Rutter, 1976; Brodie and Rutter, 1987); (3) geometric softening by alignment of easy slip planes and the shear plane, by development of a crystal preferred orientation (Poirier, 1980;
Schmid et al., 1987); (4) reaction weakening by creation of grain-scale porosity (Fusseis et al., 2009) and a fine-grained reaction product (White and Knipe, 1978; Beach, 1980); and (5) introduction of a new, weaker, mineral phase through retrograde

The mechanisms listed above are only effective at partitioning strain into a major shear zone if such a localised zone already exists. Shear zone initiation has been linked to the existence of brittle precursors, providing tabular zones of fine-grained

reactions, for example the development of an interconnected phyllosilicate fabric (Wintsch et al., 1995; Imber et al., 1997).

- 15 material deforming by diffusion creep at high strain rates with low driving stresses (Mancktelow and Pennacchioni, 2005; Mancktelow, 2006). However, shear zones can also reactivate existing ductile fabrics (Montesi, 2013; Rennie et al., 2013), or initiate through localised reaction softening (Beach, 1980; Holyoke and Tullis, 2006). In a prograde metamorphic setting, it is fairly straight-forward to imagine how an existing brittle discontinuity will transform to a ductile shear zone during progressive burial and increased temperature. Similarly, fluid release during prograde dehydration at greenschist facies or
- 20 above will provide a fluid phase, likely under low-porosity, undrained conditions, that can lead to increased fluid pressure associated with reaction weakening (e.g. Etheridge et al., 1983). On the other hand, in a retrograde metamorphic setting, rocks are not dehydrating, but are fluid-absent and capable of rehydration (e.g. Guiraud et al., 2001), and therefore a fluid source required for fluid-assisted weakening is less obvious (e.g. McCaig, 1988; Oliver, 1996). Similarly, if a shear zone develops within dry, previously migmatised crust under retrograde conditions, there are unlikely to be brittle discontinuities on which
- 25 a shear zone can initiate (Rennie et al., 2013). Under retrograde conditions, it is therefore not obvious how initial shear zone weakening occurs, as an external fluid is required for reaction weakening, but requires deformation to be introduced to the site of initiation. It is also not clear what weakening mechanisms remain active through the life of a retrograde shear zone, as elevated fluid pressures are hard to maintain in an open system, but retrograde reactions may lead to the growth of fine-grained products and the formation of new interconnected weak fabrics. We address these questions here by investigating the retrograde
- 30 metamorphic history of an exhumed, crustal-scale strike-slip shear zone, the Kuckaus Mylonite Zone in southern Namibia, to constrain its pressure-temperature-fluid history, and discuss the implications of our results for weakening mechanisms and strain localisation.

The problem of fluid flow and localised deformation in ductile shear zones is not restricted to exhumed examples, such as that presented here, but also a current question of interest in active plate boundaries. For example, the discovery of tectonic





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tremor and slow slip on the deep extensions of the Alpine and San Andreas Faults (Shelly, 2010; Shelly and Hardebeck, 2010; Wech et al., 2012) highlight the presence of localised structures below the brittle–viscous transition. The nature of these seismic signals also require the deep ductile root of these major faults to be significantly weaker than their surrounding rocks (Shelly, 2010; Shelly and Hardebeck, 2010; Wech et al., 2012). As opposed to similar features in subduction zones, commonly associated with prograde metamorphism and high fluid pressures, the tremors on the deep San Andreas and Alpine Faults cannot be easily explained by *in situ* production of fluids in low porosity fault zones. It is possible that San Andreas Fault tremor is related to retrograde weakening mechanisms associated with the introduction of an external fluid (Fagereng and Diener, 2011). An additional question to address here, is therefore how fluid flow and shear zone weakening mechanisms on the Kuckaus Mylonite Zone can serve as an analogue to those occurring on the deep extension of active faults exhibiting tremor and slow slip.

2 Regional and Outcrop Geology

The Kuckaus Mylonite Zone (KMZ; first described by Jackson, 1976) forms a segment of the larger Marshall Rocks–Pofadder shear zone system (MRPSZ, after Miller, 2008) that extends for more than 550 km from the Atlantic coast north of the town of Lüderitz in Namibia to its southern termination near the town of Pofadder in South Africa (Fig. 1; Moen and Toogood,

- 15 2007; Miller, 2008). The MRPSZ strikes WNW–ESE and exhibits a detral sense of strike-slip displacement (Jackson, 1976; Toogood, 1976; Moen and Toogood, 2007; Rennie et al., 2013). The MRPSZ is localised in mid-crustal rocks of the Namaqua Metamorphic Complex that experienced high-temperature (*T*)–low-pressure (*P*) amphibolite- to granulite-facies peak metamorphic conditions during the Mesoproterozoic at *c*. 1200–1050 Ma (Jackson, 1976; Blignaut, 1977; Waters and Whales, 1984; Waters, 1986, 1988; Robb et al., 1999; Clifford et al., 2004; Cornell et al., 2009; Diener et al., 2013; Diener, 2014; Bial et al.,
- 20 2015). The development of the MPRSZ post-dates peak metamorphism, with deformation having occurred under retrograde amphibolite- to greenschist-facies conditions, at *c*. 1005–960 Ma (Jackson, 1976; Toogood, 1976; Rennie et al., 2013; Macey et al., 2014; Melcher et al., 2015). Shearing along the MRPSZ resulted in the development of proto- to ultramylonites, indicating that deformation predominantly occurred by viscous flow of quartz and micas (Toogood, 1976; Moen and Toogood, 2007; Miller, 2008; Rennie et al., 2013; Lambert, 2013); however, a discrete cataclastic overprint indicative of lower-temperature
- 25 brittle deformation is present in the southeastern parts of the MRPSZ (Toogood, 1976; Moen and Toogood, 2007; Lambert, 2013; Macey et al., 2014).

In the study area, the KMZ occurs in granitic gneisses that form part of the Aus granulite terrain (Jackson, 1976; Rennie et al., 2013). These rocks experienced peak metamorphic conditions of 5.5 kbar and 825 °C, with the timing of metamorphism constrained at c. 1065–1045 Ma (Diener et al., 2013). Metamorphism is inferred to have been dominated by heating and

30 cooling, with only minor attendant crustal thickening and burial (Diener et al., 2013). The post-peak metamorphic retrograde path involved near-isobaric cooling, indicating that the terrain remained at depth as it cooled to a stable geotherm (Diener et al., 2013).





The shear zone core of the KMZ is about 1000 m in width, and consists of anastomozing high strain ultramylonite zones that wrap around lower-strain lozenges (Rennie et al., 2013). Rock types within the KMZ are dominated by granitic gneisses and mylonites, and only minor enclaves and lenses of retrogressed mafic granulite are present. These mafic lenses occur as discrete units, and range from a few centimetres to 10–15 m long, and are up to 5 m in width (Rennie et al., 2013). Larger mafic

- 5 lenses have a core of coarser-grained gneisses that are not pervasively mylonitised and in which remnant migmatitic granulitefacies textures can be recognised (Fig. 2a). The core is enveloped by more intensely sheared and retrogressed mylonitic schists, with the increase in strain occurring over a distance of 10–50 cm (Fig. 2b). The fabric in the coarser-grained gneisses and enveloping mylonites has a similar orientation to the penetrative subvertical foliation in the KMZ, and the weakly-developed amphibole lineation is parallel to the subhorizontal quartz rodding lineation that is present in the granite gneisses and mylonites
- 10 (Rennie et al., 2013). Whereas the volumetrically dominant felsic gneisses and mylonites do not contain mineral assemblages that record distinctive P-T conditions, the mafic enclaves provide a record of recrystallisation conditions from a preserved migmatitic core to a largely recrystallised mylonitic envelope. Therefore, to constrain the P-T-fluid conditions of shear zone deformation, three samples were chosen as a representative section from the core of a low strain lens, preserving peak fabrics and mineral assemblages, into the well-developed retrograde mylonite zone, and these are described further below.

15 3 Petrography and Mineral Chemistry

3.1 Petrography

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The three samples are from the relatively low-strain core of a mafic lens (sample KMZ28), the schistose collar (sample KMZ29) and the mylonitic envelope (sample KMZ30; all collected from 26°48'10''S 015°57'50''E). All three samples are hornblendeplagioclase-quartz amphibolites, and contain variable proportions of additional chlorite, epidote and sphene (Fig. 3). However, the texture, grain size and fabric intensity varies dramatically between the samples.

The low strain sample KMZ28 is coarse-grained and equigranular, with typical grain sizes on the order of 0.2–1 mm (Fig. 3a). The sample is dominated by hornblende, plagioclase and quartz, with chlorite and epidote only present as subordinate and finegrained phases on the edges of hornblende (Fig. 3a). Hornblende and plagioclase are weakly aligned, giving the sample a poorly-developed gneissose fabric. Notably, fine-grained chlorite and epidote do not appear to show a preferred orientation.

25 Sample KMZ29 is a medium-grained schist, with typical grain sizes on the order of 0.1–0.5 mm. Some hornblende grains appear to be larger, but are in fact aggregates made up of discrete subgrains (e.g. on the left side of Fig. 3b). Chlorite foliae form an interconnected network, giving the sample a well-developed schistosity (Fig. 3b). Hornblende and plagioclase aggregates are elongate and aligned parallel to this fabric.

Sample KMZ30 is a mylonite, consisting of approximately 30 % 0.2–0.8 mm-sized rounded plagioclase clasts in a matrix
of mylonitized hornblende, chlorite and quartz (Fig. 3c). Some recognisable hornblende occurs as 0.1–0.2 mm-sized rounded clasts, but most hornblende occurs as extremely fine grains in the mylonitic matrix. The presence of fine epidote and sphene in the mylonitic matrix was only detected by electron microprobe.



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3.2 Mineral Chemistry

Mineral compositions were determined using a JEOL JXA-8100 electron microprobe housed at the University of Cape Town. Analyses were carried out using a 15 kV acceleration voltage, 20 nA probe current and 2 to 3 μ m spot size. Counting times were 5 seconds for both backgrounds and 10 seconds for peaks on all elements. Data were processed with ZAF matrix corrections and reduced using the PAP procedure. Compositions were quantified using natural mineral standards. Representative mineral compositions for the three samples are presented in Table 1.

All samples show the same trends in mineral compositions, with the amphibole in all samples being hornblende (*sensu lato*), with appreciable Al and Na content (1.5–2 and 0.2–0.25 cations per formula unit, respectively), and X_{Fe} of 0.47–0.65 (Table 1). Plagioclase grains in all samples exhibit a core–to–rim compositional zonation, with anorthite-rich cores grading

10 to more albite-rich rims. Core compositions of $X_{an} = 0.68$, 0.59 and 0.47 are observed in the different samples, whereas plagioclase rims are consistently oligoclase with $X_{an} = 0.2-0.25$ (Table 1). Chlorite has X_{Fe} of 0.5–0.66, mimicking that of hornblende and indicating that the variation in X_{Fe} between samples is likely controlled by the bulk composition (see also Table 2). Epidote has a pistacite (Fe³⁺/Al + Fe³⁺) content of 0.17–0.3.

3.3 Inferred Equilibrium Mineral Assemblages

- 15 All samples contain mineral assemblages and mineral compositions indicative of having equilibrated under amphibolite-facies metamorphic conditions. Some remnants of the preceding granulite-facies history of these rocks is preserved as relict textures in outcrop (Fig. 2a), and possibly in the composition of anorthite-rich plagioclase cores (Table 1), but overall these rocks have been pervasively re-equilibrated (and likely re-hydrated) during retrogression. The current equilibrium assemblage in all samples is interpreted to consist of hornblende, plagioclase with $X_{an} \sim 0.20$, chlorite, epidote, sphene and quartz. Given that
- 20 this assemblage has experienced KMZ-related shearing to varying degrees, from being unaffected by it in sample KMZ28, to being pervasively recrystallised by it in sample KMZ30, the P-T conditions under which this assemblage was equilibrated will also bracket the conditions of shearing in the KMZ.

4 Mineral Equilibria Modelling

Mineral equilibria calculations were performed with the THERMOCALC program of Powell and Holland (1988) using the new
and expanded internally-consistent thermodynamic dataset of Holland and Powell (2011, dataset 6.2 created 6 February 2012).
Calculations were performed in the Na₂O–CaO–FeO–MgO–Al₂O₃–SiO₂–H₂O–TiO₂–Fe₂O₃ (NCFMASHTO) model system, disregarding the minor components MnO (less than 0.2 wt %) and K₂O (less than 1.5 wt %). The activity–composition models used are those of White et al. (2014) for chlorite, plagioclase and ilmenite, Green et al. (2016) for amphibole and Holland and Powell (2011) for epidote. Albite, sphene, quartz and H₂O are pure end-member phases. Although a melt model appropriate

30 for mafic rocks is included in Green et al. (2016), melt was not considered in the calculations as the conditions of interest are far below the solidus. However, the calculated equilibria above ~ 650 °C are likely to be metastable to melt.





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The bulk compositions used in the pseudosection calculations were determined by XRF analysis at the University of Cape Town. Analyses were converted to the NCFMASHTO model system by disregarding K₂O, MnO, Cr₂O₃ (< 0.03 wt %) and P₂O₅ (< 0.2 wt %) and assuming approximately 15 % of total Fe to be present as Fe³⁺, in line with typical values for metamafic rocks (cf. the compilation of Rebay et al., 2010). During initial modelling, the samples were assumed to be fully hydrated, such that water (H₂O) was taken to be present in excess. The possibility of variable re-hydration during retrogression is explicitly considered later. The bulk compositions used to construct the pseudosections are presented in Table 2.

4.1 P-T pseudosections

Fluid-saturated P-T pseudosections for samples KMZ28, KMZ29 and KMZ30 are presented in Fig. 4. The phase relations in all three samples have a similar topology, and consist of the typical greenschist-facies assemblage actinolite–chlorite–epidote– albite–sphene–quartz at T below 450 °C, and contain the typical amphibolite-facies assemblage of hornblende–plagioclase– ilmenite–quartz at T above 550–600 °C (Fig. 4). In the T range between 450 and 550–600 °C, these rocks undergo a series of phase changes, notably (1) the introduction of hornblende at the expense of actinolite, (2) the introduction of plagioclase and the demise of albite and epidote, (3) the replacement of sphene by ilmenite, and finally (4) the demise of chlorite (Fig. 4). Within

this T zone, the inferred equilibrium assemblage of hornblende–plagioclase–chlorite–epidote–sphene occurs in a narrow, Tsensitive field at around 450 °C and between 2 and 4 kbar in KMZ28 and KMZ29 (Fig. 4a,b), but spans the entire P range of interest in KMZ30 (Fig. 4c). This field is bound by the removal of plagioclase to lower T and the loss of epidote to higher T. Contours of X_{an} calculated for KMZ29 indicate that the composition of plagioclase varies substantially, from X_{an} = 0.32 to X_{an} = 0.82, at the stability conditions of the inferred equilibrium assemblage (Fig. 4b).

4.2 $T-M_{\rm H_2O}$ pseudosections

- 20 Calculated $T-M_{\rm H_2O}$ pseudosections allow the degree of fluid-saturation in these rocks to be quantitatively evaluated, and are presented for the three samples in Fig. 5. The diagrams are calculated at constant P of 4 kbar in order to bracket the peakto-retrograde evolution, with H₂O content chosen to vary such that the samples are fluid-saturated and -undersaturated over the T range of interest. THERMOCALC outputs H₂O content as a mol fraction, but this approximates volume percent when normalised to one oxide sum total.
- 25 The pseudosections all show a similar topology and exhibit the same features, notably that all samples require high H₂O content to be fluid-saturated at low-*T* greenschist-facies conditions (*M*_{H₂O} = 11 15 mol %), but that only about a third of this fluid is required for fluid-saturation under amphibolite- to granulite-facies conditions (*M*_{H₂O} = 3 5 mol %; Fig. 5). Consequently, all samples undergo large changes to their fluid content in the range between 450 and 550–600 °C, with ~ 7 10 vol. % H₂O being produced if the rocks were heating up, or the same amount of re-hydration from an external source required 30 to maintain fluid-saturation during cooling (Fig. 5).
 - The maximum amount of H₂O that these rocks could have retained from peak metamorphic conditions (T > 750 °C; Diener et al., 2013) is 3–5 mol %, depending on the sample (Fig. 5). However, the mineral assemblages observed in the three samples all straddle the H₂O saturation line at ~ 480 °C, indicating that they can occur at fluid-saturated or slightly fluid-undersaturated





conditions, but require a higher H₂O content of at least 5.5–11.5 mol %, depending on the sample (Fig. 5, red boxes). The observed assemblages are bound by the loss of epidote and plagioclase to lower H₂O content. As H₂O content is decreased further at 480 °C, ilmenite is introduced, prior to the loss of sphene and chlorite, and finally the introduction of orthopyroxene and garnet at the very low H₂O content that characterised peak metamorphic conditions ($M_{H_2O} < 3-5$ mol %; Fig. 5).

5 5 Discussion

5.1 *P*-*T* conditions of shearing

The three samples described above were affected by KMZ-related retrograde deformation to different degrees, and can therefore be used to effectively constrain the *P*-*T* conditions under which quasi-plastic shearing in the KMZ occurred. The stability of the observed assemblages are summarised in Fig. 6, and the overlap between the samples constrains the most likely *P*-*T*conditions experienced by these rocks at 2.7–4.2 kbar and 450–480 °C. Whereas *T* is tightly constrained, the *P* estimate is less precise, and straddles the kyanite–andalusite phase boundary. However, no aluminosilicates are present in the KMZ, nor have they been reported for other parts of the MRPSZ, and consequently the presence of kyanite or andalusite can not be used to refine the *P* estimate further.

The estimates indicate that the bulk of shearing in the KMZ occurred at 450–480 °C, at a depth of 10–16 km, assuming overlying granitic crust. These conditions are significantly warmer than the brittle–viscous transition in quartz (Hirth et al., 2001), and the unstable–stable frictional transition in granitic rocks (Blanpied et al., 1995), and roughly coincides with the onset of crystal-plastic deformation of feldspar at geological strain rates (Pryer, 1993; Rybacki and Dresen, 2000). These inferred conditions are consistent with frictional–viscous flow (*sensu* Handy et al., 1999) in felsic KMZ mylonites, where bulk deformation occurred by viscous flow of interconnected quartz–phyllosilicate networks surrounding locally brittle feldspar clasts (Rennie et al., 2013). The lack of a greenschist-facies overprint on the mineralogy of the samples, as well as lack

- of a pervasive brittle overprint to the deformation, strongly indicates that shearing in the KMZ ceased at these T, and that deformation along the shear zone did not lead to progressive exhumation and attendant cooling as the KMZ developed (c.f. Till et al., 2007).
- Whereas the KMZ lacks an obvious lower-T history, it is localised in lithologies that experienced earlier granulite-facies metamorphism, such that it could potentially have an inherited higher-T history. The available age data indicate that the MRPSZ was active at c. 1005–960 Ma (Macey et al., 2014; Melcher et al., 2015), such that the KMZ could post-date peak metamorphism (1065–1045 Ma; Diener et al., 2013) by as little as 40 Ma. However, apart from local textural indications preserved in low-strain areas (e.g. Fig. 2a), the mineralogical features have been pervasively overprinted at the P-T conditions constrained above. One mineralogical aspect that could potentially be inherited from the earlier, high-T history is the anorthite-rich composition
- 30 preserved in plagioclase cores. However, calculated isopleths of anorthite content in plagioclase (only shown for KMZ29 in Fig. 4b) indicate that the plagioclase composition varies widely at, or near, the P-T constrained for the KMZ. This does not preclude the plagioclase cores being inherited from earlier, higher-T conditions, but shows that the core compositions are not far from equilibrium with the remaining assemblage at 450–480 °C. Consequently, it appears plausible that shearing along the





KMZ occurred at near-constant T conditions of ~ 450 °C at a depth within the range of 10 to 16 km, and that the KMZ did not undergo progressive exhumation and cooling during its development. The KMZ is therefore related to a discrete tectonic event, and does not form a continuum of earlier granulite-facies metamorphism, which is supported by its large-scale structural discordance with the granulite-facies structures and fabrics (Jackson, 1976; Toogood, 1976; Moen and Toogood, 2007; Miller, 2008; Rennie et al., 2013). It also follows that the KMZ likely acted as a transcurrent shear zone, with little to no associated

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transpression or transtension.

The tectonic and P-T history of the KMZ is similar to that of modern examples of major continental strike-slip shear zones that are localised in isostatic / non-orogenic crust and do not involve large amounts of crustal thickening or thinning. Such modern examples include the San Andreas Fault away from the Mendocino Triple Junction and transpressional/transtensional

- bends (Guzofski and Furlong, 2002; Spotila et al., 2007) and the North Anatolian Fault east of the Aegean transtensional zone 10 (Hubert-Ferrari et al., 2002). The thermal profile of these shear zones follow the continental geotherm that is stable at the time, which in the case of the KMZ is estimated at 30-45 °C.km⁻¹. The uncertainty in this estimate is caused by uncertainty in the depth of the KMZ, but the entire range is significantly warmer than for stable continental lithosphere ($\sim 20^{\circ}$ C.km⁻¹; e.g. Cooper et al., 2002, and references therein). However, given that the Aus granulite terrain experienced granulite-facies
- 15 metamorphism associated with lithospheric thinning only 40 Ma earlier, it is to be expected that the terrain was characterised by higher than average heat flow at the time of shear zone formation (e.g. Morrissey et al., 2014; Bial et al., 2015). In fact, the estimated geotherm is comparable with those derived from crust underlain by young and thin lithosphere, such as the northern San Andreas Fault (Fagereng and Diener, 2011).

5.2 Fluid regime, fluid source and infiltration mechanisms

- The rocks in which the KMZ localised were dehydrated and experienced partial melting and melt loss during preceding meta-20 morphism (Diener et al., 2013). In the absence of rehydration, the rocks would have retained their (low) fluid content and granulite mineralogy from peak metamorphic conditions, and experienced shearing and reworking under fluid-absent conditions (Guiraud et al., 2001; White and Powell, 2002; Tenczer et al., 2006; Diener et al., 2008). If this were the case, the samples would have consisted of orthopyroxene-bearing assemblages, and would have grown garnet at the P-T conditions of shearing
- (450–480 °C and $M_{\rm H_2O} < 3-5$ mol %; Fig. 5; cf. Dziggel et al., 2012). For the rocks to have replaced their high-T assem-25 blages with the minerals observed in the samples described here, they must have experienced an addition of H_2O (Fig. 5). The observed assemblages in all three samples straddle the H₂O saturation line, indicating that they can occur at fluid-saturated or slightly fluid-undersaturated conditions. However, given that the absolute fluid content required by each assemblage differs widely between the samples, it appears unlikely that the samples were all rehydrated to be just fluid-undersaturated, and it is more plausible to conclude that they were fully rehydrated and fluid-saturated during shearing along the KMZ.

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The mineral assemblages described here therefore demand at least some syn-tectonic retrograde rehydration during strikeslip displacement in a dominantly viscous shear zone. Calculations show that rehydration requires the addition of 4–8 vol. % H₂O (Fig. 5), such that a fluid-rock ratio of at least 0.05–0.1 is necessary to ensure rehydration and fluid-saturation of the KMZ, if fluid uptake is assumed to be efficient. Other than the presence of hydrous mineral phases, formed syn-tectonically





from a relatively dry protolith, there are, however, few observed signs of extensive fluid flow. The shear zone is barren of quartz veins, other than for a few very late, subvertical, north-striking veins that cross-cut the KMZ mylonitic fabrics. There are also few, if any, signs of other hydrothermal precipitates. Thus, we envisage that fluid flow during shearing was sufficient to completely rehydrate the mineral assemblages and allow the presence of a free fluid phase, but that it was not extensive enough to allow widespread hydrothermal precipitation. Similarly, we envisage that fluid flow occurred either along grain

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enough to allow widespread hydrothermal precipitation. Similarly, we envisage that fluid flow occurred either along grain boundaries, or through small length-scale fracture systems that were subsequently healed and thus not preserved, rather than through long-lived, channelised conduits.

Kilometre-scale, open-system diffusion of water through crustal shear zones is not a unique phenomenon, and was proposed by Beach (1980) for major retrogression in ductile shear zones cross-cutting the Archaean Lewisian basement complex of

- 10 northern Scotland, in similar setting and metamorphic conditions to the current study. Similarly, significant retrograde fluid influx has been inferred for shear zones at Broken Hill, Australia (Etheridge and Cooper, 1981), the French Pyrenees (McCaig et al., 1990) and the Yellowknife gold district, Canada (Kerrich et al., 1977); in the latter location, fluid flux is associated with hydrothermal vein mineralization as well as retrograde reactions. Based on these, and other examples, it has been estimated that typical fluid–rock ratios in retrogressed shear zones can exceed 10² (Etheridge et al., 1983), and can locally be much greater
- 15 (Kerrich et al., 1977; McCaig et al., 1990). This is three orders of magnitude higher than the minimum ratio fluid–rock ratio required for the KMZ, which again indicates that, although the KMZ was fluid-saturated, it was likely not inundated with fluid to the same extent as many other examples of retrograde shear zones.

Achieving retrograde rehydration requires a significant source of fluids. Such a source is not obvious in a depleted, dry, granulite terrain such as the Aus granulites hosting the KMZ. Etheridge et al. (1983) suggest hydrothermal circulation of

- 20 prograde fluids, driven by a mantle heat source, as typical of regional metamorphism at depths > 10 km, but no prograde fluid source is available during strike-slip deformation of the KMZ. For retrograde metamorphism and dehydration, Etheridge et al. (1983) imply that tectonic juxtaposition of hot rocks and cool, fluid-saturated mineral assemblages can drive dehydration and provide local fluids. Again, this is not feasible in the KMZ, as the strike-slip motion provides neither a heat source, nor a fluid-saturated assemblage. In a review of fluids in deep fault zones, Kerrich et al. (1984) propose prograde deformation
- 25 in presence of low fluid/rock ratios and a locally-derived fluid, with subsequent retrograde deformation with high fluid/rock ratios and an external, typically meteoric, fluid source. Such a meteoric fluid source is evident in current deformation along and around the Alpine Fault, New Zealand, where retrograde deformation is associated with transpression and topographically-driven deep circulation of meteoric waters in the Southern Alps (Koons and Craw, 1991; Menzies et al., 2014). However, this model requires a component on crustal shortening and associated mountain building to create the hydraulic head to drive
- 30 surface fluids down to below the brittle–viscous transition.

McCaig et al. (1990) invoke that high fluid–rock ratios of up to 10^3 can be achieved through episodic seismic pumping of a meteoric fluid, and local, transiently-enhanced permeability of 10^{-17} to 10^{-15} m². In their model, the meteoric fluids move down a gently dipping décollement and then up through steeply-dipping shear zones. No such gently dipping décollement is know to exist below the KMZ, but one could potentially envisage seismically-driven meteoric fluid-flow down to the KMZ,

35 from the brittle crust above (McCaig, 1988), but this mechanism still requires high permeability into the ductile lower crust.





Such enhanced permeability may come about through aseismic processes, considering that retrograde reactions lead to volume change, as do crystal plastic deformation in mylonitic shear zones. O'Hara (1988) invokes volume loss during retrograde breakdown of feldspar, coupled to fluid influx, as the origin of phyllonitization, reaction weakening, and mylonitization in an overthrust setting in the Appalachians. Jamtveit et al. (2008), on the other hand, suggest extensive microfracturing associated

- 5 with retrograde hydration and increase in solid volume as another mechanism to get fluids into otherwise low permeability, high-grade crystalline rocks. Even without associated retrograde reaction, creep has been shown to enhance permeability through generation of grain boundary microcracks (McCaig and Knipe, 1990; Peach and Spiers, 1996), and through a dynamic process of creep cavitation (Fusseis et al., 2009; Menegon et al., 2015). Thus, the presence of a retrograde shear zone, once actively deforming, is a source of locally elevated permeability — either from solid volume increase and associated microfrac-
- 10 turing, or solid volume decrease and associated grain boundary dilatancy. This permeability may be transiently enhanced by earthquake rupture and associated fault zone damage in the brittle crust overlying the shear zone, and potentially through downward propagation of such rupture fronts into the ductile regime (McCaig, 1988).

The above examples all include an element of dip-slip displacement. In another example of fluids in a subvertical strike-slip shear zone, the deep San Andreas Fault is suspected to be fluid-rich, based on high Vp/Vs in the lower crust (Ozacar and

- 15 Zandt, 2009). A likely source for this fluid is a serpentinized mantle wedge, where serpentinization dates to past subduction, and the absence of a cool, insulating slab now leads to heating and dehydration (Kirby et al., 2002; Fulton and Saffer, 2009). This San Andreas Fault case is, however, somewhat special in requiring a transition from subduction to strike-slip tectonics, and we do not see evidence for the presence of a similar serpentinized mantle wedge as a source of fluids for KMZ rehydration, neither does the tectonic history of the Namaqua-Natal Belt call for an initial subduction origin for the MRPSZ. Thus, our best
- 20 hypothesis is that the external fluid source for KMZ rehydration was meteoric, and fluid flow was allowed by local dilation and/or increased fracture permeability within the shear zone, thus accounting for retrograde metamorphic reactions within the mylonites, and absence of such reactions outside the KMZ.

5.3 Initiation and feedback mechanisms in a retrograde shear zone

In the previous section, we argue for an external fluid source to allow retrograde dehydration reactions to occur in the KMZ. 25 Retrograde minerals within the mylonites define syn-tectonic fabric elements (Fig. 3b,c), and thus indicate syn-tectonic retrogressive reaction and hydration. The implication that hydration, metamorphism, and deformation occurred concurrently, and were mutually enhancing, raises a chicken-and-egg question regarding the onset of retrograde metamorphism and shear zone deformation. However, if the interpretation that the fluids source was external is correct, and we know retrograde mineral assemblages are localised in the KMZ, it is implicit that the shear zone must have been a region of enhanced permeability before

30 retrograde reactions could initiate. Moreover, if the fluid source was near-surface, and fluids came into the KMZ through the overlying brittle crust, it is required that (1) a fault system in the brittle crust was present and linked to the KMZ; and (2) that the KMZ was already there to provide a low permeability zone for such fluids to localise into.

Beach (1980) concluded that in early stages of ductile deformation, fluids preferentially flow into the deforming zone, and the consequent initiation of retrograde metamorphic reactions initiate reaction softening and further strain localisation. Thus, as





soon as a shear zone is active at retrograde conditions, and connected to an external fluid reservoir, we envisage a positive feedback loop where reaction softening and ongoing metamorphic reactions lead to progressive strain accumulation, weakening, and permeability enhancement. The feedback mechanisms involved include: (1) grain size reduction through growth of new minerals, enhancing diffusion rates (Rutter, 1976; Beach, 1980); low cohesion along new grain boundaries, enhancing grain

- 5 boundary sliding (White and Knipe, 1978); and (3) replacement of strong mineral phases with weaker phyllosilicates (Wintsch et al., 1995; Imber et al., 1997). We do not exclude a possibility that this early stage of ductile deformation initiated on a pre-existing brittle fracture (as proposed by Mancktelow and Pennacchioni, 2005); however, it seems equally or more likely that a new shear zone within a dry granulite terrane should initiate either along an existing well-oriented fabric (Worley and Wilson, 1996; Montesi, 2013; Rennie et al., 2013), or around a stress riser such as a pre-tectonic granitic intrusion (Goodwin
- 10 and Tikoff, 2002; Rennie et al., 2013). Independently of the exact initiation mechanism, we stress that as soon as a shear zone has initiated in strong, dry rocks at retrograde conditions, the interplay between reaction and deformation will cause further weakening, enhancing strain localization, and thus significant local weakening of the lower crust.

It has long been envisaged that as a viscous shear zone accumulates strain, grain size reduction caused by metamorphic growth of new grains and recrystallisation through dislocation creep, competes with grain growth through diffusion (White,

- 15 1976). Thus, retrograde shear zones are commonly predicted to initiate with fine grain sizes and dominantly deform by diffusion creep, but as grains grow and the mineral assemblage equilibrates at the retrograde *P*–*T* conditions, grain size should increase and the deformation mechanism change to dominantly dislocation creep (White, 1976; Beach, 1980). We note, however, that in our samples (Fig. 3), as in microstructures reported by Rennie et al. (2013) from the KMZ, the highest strain rocks are characterised by a very fine-grained, intensely foliated, retrograde mineral assemblage. Thus, we do not identify a change to
- 20 dislocation creep processes in the highest strain regions, but rather infer continued weakening and grain size reduction until the end of mylonitization. This observation and inference may indicate that the shear zone experienced continued fluid flow and reaction during its life time, possibly because retrograde reactions did not go to completion as reactants were not exhausted. The lack of veins may further imply that fluid pressures were not sufficient to allow hydrofracturing and mineral precipitation; however, precipitation may also have been hindered by low solubility and low dissolved mineral content in cool fluids derived
- 25 from above the shear zone. It is, however, implied by a meteoric fluid source that connectivity with the surface existed, at least temporarily, under which fluid pressure cannot have been greater than hydrostatic. Thus, overall, we do not see high fluid pressures as a necessary, nor likely, weakening mechanism in retrograde shear zones that are connected to an external fluid source.

5.4 Implications for strength and deformation mechanisms in active retrograde viscous shear zones

30 We have inferred from the P-T path derived from low- and high-strain rocks that the KMZ represents a retrograde shear zone deformed at relatively constant temperature just warmer than the brittle–viscous transition in granitic rocks. Further, the mylonites record simultaneous retrograde grain growth and strike-slip deformation, explained by localised fluid flow through an active shear zone. Because the shear zone was hosted in dry, strong rocks that retain migmatitic and gneissic fabrics, the bulk of the fluid must have been derived externally. The shear zone does not preserve hydrofractures, but does preserve very





fine-grained mineral assemblages likely associated with diffusive mass transfer. Coupled to the inference of an external fluid source, the lack of veins and prevalence of a fine-grained assemblage lead to the inference that the shear zone was active at low fluid pressure conditions, and weakening relative to surrounding wall rocks was caused by reaction weakening, involving grain size reduction and growth of relatively weak minerals (e.g. chlorite). These inferences imply that as soon as a retrograde shear zone has formed, and as long as it retains connection to a reservoir of fluids, such a shear zone is a long-lived, strain weakening

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feature that controls the strength of the lower crust over its along-strike extent.

The San Andreas Fault is inferred to be weak and wet (e.g. Ozacar and Zandt, 2009), commonly explained by high fluid pressures (Rice, 1992). The Alpine Fault, New Zealand, has on the other hand been interpreted as frictionally strong (Boulton et al., 2014), and potentially weakened at depths by fluid presence (Wannamaker et al., 2002). Both of these faults are currently

- 10 active under retrograde metamorphic conditions, and exhibit tectonic tremor, a persistent low-frequency seismic signal characterised by lack of impulsive body wave arrivals, emanating from below the brittle-viscous transition (Shelly, 2010; Shelly and Hardebeck, 2010; Wech et al., 2012). These tremor signals have, in both places, been interpreted as fluid-enabled slip on the deep extension of the plate boundary faults, below the base of the seismogenic zone (Shelly and Hardebeck, 2010; Wech et al., 2012). The KMZ is exhumed from the same thermal and metamorphic regime as where San Andreas and Alpine Fault tremor is
- 15 occurring. The KMZ also deformed under fluid-present conditions, and was significantly weak compared to surrounding rock. However, our observations and inferences along the KMZ require fluid presence, but do not require elevated fluid pressure to explain this weakening. As suggested by Fagereng and Diener (2011) for the San Andreas Fault, we therefore suggest that deformation localisation below the brittle–viscous transition at retrograde conditions may be a function of reaction weakening and metamorphic rehydration. At these conditions, localised slip may occur along weak planes characterised by aligned
- 20 phyllosilicates (Wintsch et al., 1995; Imber et al., 1997), possibly associated with transient aseismic creep accommodated in fine-grained mylonites deforming by diffusion creep. If this interpretation is correct, high fluid pressures are not required for tremor and slow slip in the viscous regime in retrograde shear zones. Instead, weakness of fluid-saturated, retrograde faults and shear zones may be explained by reaction weakening under hydrostatic fluid pressure conditions.

6 Conclusions

- 25 The KMZ was localised in dry, high-grade mid-crustal gneisses, such that shear zone initiation most likely occurred through reactivation of existing favourably-oriented high-temperature, ductile structures (Worley and Wilson, 1996; Montesi, 2013). Once shearing was active, it allowed fluids, most likely meteoric, to infiltrate the KMZ and activate a number of positive feedback processes that allowed weakening and continued strain localisation. The observed mineral assemblages lead us to conclude that the KMZ was fluid-bearing during deformation, but the absence of hydrofractures and hydrothermal precipitates
- 30 indicate that fluid pressures and the fluid-rock ratio remained low. In this regard the KMZ differs from most other exhumed and active continental retrograde shear zones for which high fluid-rock ratios have been suggested (Kerrich et al., 1977; Etheridge et al., 1983; McCaig et al., 1990), or for which high fluid pressures are inferred (Rice, 1992; Ozacar and Zandt, 2009). It consequently appears that retrograde shearing can be sustained under a variety of fluid regimes, from dry and entirely





fluid-absent (Tenczer et al., 2006), through low-volume fluid presence such as described here, to examples where shear zones are inundated and dominated by fluid. There is also a range in cases from where high fluid pressures are sustained by a combination of high fluid volumes and low permeability, to shear zones where either low fluid volumes or high permeability prevents the build up of high fluid pressures. We therefore conclude that the dominant contribution of fluids to sustaining

5 localised deformation under retrograde conditions can be through reaction weakening, by producing weaker mineral phases and facilitating grain size reduction. We also conclude that weak lower crustal, fluid-bearing shear zones do not need to imply high fluid pressures, but can also be significantly weaker than surrounding wall rocks from reaction weakening at hydrostatic fluid pressure conditions.

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References

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- Beach, A.: Retrogressive metamorphic processes in shear zones with special reference to the Lewisian complex, Journal of Structural Geology, 2, 257–263, 1980.
- Bial, J., Buettner, S. H., Schenk, V., and Appel, P.: The long-term high-temperature history of the central Namaqua Metamorphic Complex: Evidence for a Mesoproterozoic continental back-arc in southern Africa, Precambrian Research, 268, 143–278, 2015.
- Blanpied, M. L., Lockner, D. A., and Byerlee, J. D.: Frictional slip of granite at hydrothermal conditions, Journal of Geophysical Research, 100, 13,045–13,064, 1995.
- Blignaut, H. J.: Structural-metamorphic inprint on part of the Namaqua Mobile Belt in South West Africa, Bulletin of the Precambrian Research Unit, 23, University of Cape Town, 197pp, 1977.
- 10 Boulton, C., Moore, D. E., Lockner, D. A., Toy, V. G., Townend, J., and Sutherland, R.: Frictional properties of exhumed fault gouges in DFDP-1 cores, Alpine Fault, New Zealand, Geophysical Research Letters, 41, 356–362, 2014.

Brodie, K. H. and Rutter, E. H.: The role of transiently fine grained reaction products in syntectonic metamorphism: natural and experimental examples, Canadian Journal of Earth Sciences, 24, 554–564, 1987.

Clifford, T. N., Barton, E. S., and Stern, R. A.: U-Pb calendar for Namaqua (Grenville) crustal events in the granulite facies terrane of the

- 15 O'okiep Copper District of South Africa, Journal of Petrology, 45, 669–691, 2004.
 - Cooper, C. M., Lenardic, A., and Moresi, L.: The thermal structure of stable continental lithosphere within a dynamic mantle, Earth and Planetary Science Letters, 222, 807–817, 2002.
 - Cornell, D. H., Pettersson, Å., Whitehouse, M. J., and Schersten, A.: A new chronostratigraphic paradigm for the age and tectonic history of the Mesoproterozoic Bushmanland ore district, South Africa, Economic Geology, 104, 385–404, 2009.
- 20 Cox, S. F. and Etheridge, M. A.: Coupled grain-scale dilatancy and mass transfer during deformation at high fluid pressures: examples from Mount Lyell, Tasmania, Journal of Structural Geology, 11, 147–162, 1989.

Diener, J. F. A.: Low-*P*-high-*T* metamorphism of the Aggeneys Terrane, Namaqua Metamorphic Complex, South Africa, South African Journal of Geology, 117, 31–44, 2014.

Diener, J. F. A., White, R. W., and Powell, R.: Granulite facies metamorphism and subsolidus fluid-absent reworking, Strangways Range,

- 25 Arunta Block, central Australia, Journal of Metamorphic Geology, 26, 603–622, 2008.
- Diener, J. F. A., White, R. W., Link, K., Dreyer, T. S., and Moodley, A.: Clockwise, low-P metamorphism of the Aus granulite terrain, southern Namibia, during the Mesoproterozoic Namaqua Orogeny, Precambrian Research, 224, 629–652, 2013.

Dziggel, A., Diener, J. F. A., Stoltz, N. B., and Kolb, J.: Role of H₂O in the formation of garnet coronas during near-isobaric cooling of mafic granulites: the Tasiusarsuaq terrane, southern West Greenland, Journal of Metamorphic Geology, 30, 957–972, 2012.

- 30 Etheridge, M. A. and Cooper, J. A.: Rb/Sr isotopic and geochemical evolution of a recrystallized shear (mylonite) zone at Broken Hill, Contributions in Mineralogy and Petrology, 78, 74–84, 1981.
 - Etheridge, M. A., Wall, V. J., and Vernon, R. H.: The role of the fluid phase during regional metamorphism and deformation, Journal of Metamorphic Geology, 1, 205–226, 1983.
- Fagereng, Å. and Diener, J. F. A.: San Andreas Fault tremor and retrograde metamorphism, Geophysical Research Letters, 38, L23 303,
 2011.
 - Fulton, P. M. and Saffer, D. M.: Potential role of mantle-derived fluids in weakening the San Andreas Fault, Journal of Geophysical Research, 114, B07 408, doi:10.1029/2008JB006 087, 2009.





- Fusseis, F., Regenauer-Lieb, K., Liu, J., Hough, R. M., and De Carlo, F.: Creep cavitation can establish a dynamic granular fluid pump in ductile shear zones, Nature, 459, 974–977, 2009.
- Goodwin, L. B. and Tikoff, B.: Competency contrast, kinematics and the development of foliations and lineations in the crust, Journal of Structural Geology, 24, 1065–1085, 2002.
- 5 Green, E. C. R., White, R. W., Diener, J. F. A., Powell, R., Holland, T. J. B., and Palin, R. M.: Activity-composition relations for the calculation of partial melting equilibria in metabasic rocks, Journal of Metamorphic Geology, p. submitted, 2016.
 - Guiraud, M., Powell, R., and Rebay, G.: H₂O in metamorphism and unexpected behaviour in the preservation of metamorphic assemblages, Journal of Metamorphic Geology, 19, 445–454, 2001.
 - Guzofski, C. A. and Furlong, K. P.: Migration of the Mendocino triple junction and ephemeral crustal deformation: Implications for California
- 10 Coast Range heat flow, Geophysical Research Letters, 29, 1012, doi: 10.1029/2001GL013 614, 2002.
 - Handy, M. R., Wissing, S., and Streit, L.: Frictional-viscous flow in mylonite with a varied bimineralic composition and its effect on lithospheric strength, Tectonophysics, 303, 175–191, 1999.
 - Hirth, G., Teyssier, C., and Dunlap, W.: An evaluation of quartzite flow laws based on comparisons between experimentally and naturally deformed rocks, International Journal of Earth Sciences, 90, 77–87, 2001.
- 15 Holland, T. J. B. and Powell, R.: An improved and extended internally consistent thermodynamic dataset for phases of petrological interest, involving a new equation of state for solids, Journal of Metamorphic Geology, 29, 333–383, 2011.
 - Holyoke, C. W. and Tullis, J.: Formation and maintenance of shear zones, Geology, 34, 105–108, 2006.
 - Hubbert, M. K. and Rubey, W. W.: Role of fluid pressure in mechanics of overthrust faulting, Geological Society of America Bulletin, 70, 115–206, 1959.
- 20 Hubert-Ferrari, A., Armijo, R., King, G., Meyer, B., and Barka, A.: Morphology, displacement, and slip rates along the North Anatolian Fault, Turkey, Journal of Geophysical Research, 107, 2235, doi:10.1029/2001JB000393, 2002.
 - Imber, J., Holdsworth, R. E., Butler, C. A., and Lloyd, G. E.: Fault zone weakening processes along the reactivated Outer Hebrides Fault Zone, Scotland, Journal of the Geological Society of London, 154, 105–109, 1997.
- Jackson, M. P. A.: High-grade metamorphism and migmatisation of the Namaqua metamorphic complex around Aus in the southern Namib desert, South West Africa, Bulletin of the Precambrian Research Unit, 18, University of Cape Town, 299pp, 1976.
 - Jamtveit, B., Malthe-Soerenssen, A., and Kostenko, O.: Reaction enhanced permeability during retrogressive metamorphism, Earth and Planetary Science Letters, 267, 620–627, 2008.
 - Kerrich, R., Fyfe, W. S., and Allison, I.: Iron reduction around gold-quartz veins, Yellowknife district, Northwest Territories, Canada, Economic Geology, 72, 657–663, 1977.
- 30 Kerrich, R., La Tour, T. E., and Willmore, L.: Fluid participation in deep fault zones: Evidence from geological, geochemical, and ¹⁸O/¹⁶O relations, Journal of Geophysical Research, 89, 4331–4343, 1984.
 - Kirby, S., Wang, K., and Brocher, T.: A possible deep, long-term source for water in the northern San Andreas Fault system: A ghost of Cascadia subduction past?, EOS Transactions (Fall Meeting Supplement), 83, S22B–1038, 2002.

Kirby, S. H.: Rock mechanics observations pertinent to the rheology of the continental lithosphere and the localization of strain along shear

- 35 zones, Tectonophysics, 119, 1–27, 1985.
 - Koons, P. O. and Craw, D.: Gold mineralization as a consequence of continental collision: an example from the Southern Alps, New Zealand, Earth and Planetary Science Letters, 103, 1–9, 1991.





- Lambert, C. W.: Granitic melt transport and emplacement along transcurrent shear zones: Case study of the Pofadder Shear Zone in South Africa and Namibia, Master's thesis, University of Stellenbosch, 128pp., 2013.
- Macey, P. H., Minnaar, H., Miller, J. A., Lambert, C. W., Groenwald, C., Diener, J. F. A., Le Roux, P. J., and Frei, D.: The Precambrian geology of the region south of Warmbad from Haib to Velloorsdrift, southern Namibia, Geological Survey of Namibia, Windhoek, 476pp, 2014.

5

Mancktelow, N. S.: How ductile are ductile shear zones?, Geology, 34, 345-348, 2006.

Mancktelow, N. S. and Pennacchioni, G.: The control of precursor brittle fracture and fluid-rock interaction on the development of single and paired ductile shear zones, Journal of Structural Geology, 27, 645–661, 2005.

McCaig, A. M.: Deep fluid circulation in fault zones, Geology, 16, 867-870, 1988.

10 McCaig, A. M. and Knipe, R. J.: Mass-transport mechanisms in deforming rocks: Recognition using microstructural and microchemical criteria, Geology, 18, 824–827, 1990.

McCaig, A. M., Wickham, S. M., and Taylor, H. P.: Deep fluid circulation in alpine shear zones, Pyrenees, France: field and oxygen isotope studies, Contributions to Mineralogy and Petrology, 106, 41–60, 1990.

Melcher, F., Graupner, T., Gäbler, H.-E., Sitnikova, M., Henjes-Kunst, F., Oberthür, S., Gerdes, A., and Dewaele, S.: Tantalum-(niobium-

- 15 tin) mineralisation in African pegmatites and rare metal granites: Constraints from Ta–Nb oxide mineralogy, geochemistry and U–Pb geochronology, Ore Geology Reviews, 64, 667–719, 2015.
 - Menegon, L., Fusseis, F., St[']unitz, H., and Xiao, X.: Creep cavitation bands control porosity and fluid flow in lower-crustal shear zones, Geology, 43, 227–230, 2015.

Menzies, C. D., Teagle, D. A. H., Craw, D., Cox, S. C., Boyce, A. J., Barrie, D., and Roberts, S.: Incursion of meteoric waters into the ductile

20 regime in an active orogen, Earth and Planetary Science Letters, 399, 1–13, 2014.

Miller, R. M.: The Geology of Namibia, vol. 2, Geological Survey of Namibia, Windhoek, 2008.

Moen, H. F. G. and Toogood, D. J.: The geology of the Onseepkans area. Explanation: Sheet 2818, Council for Geoscience, 2007.

- Montesi, L. G. J.: Fabric development as the key for forming ductile shear zones and enabling plate tectonics, Journal of Structural Geology, 50, 254–266, 2013.
- 25 Morrissey, L. J., Hand, M., Raimondo, T., and Kelsey, D. E.: Long-lived high-temperature, low-pressure granulite facies metamorphism in the Arunta Region, central Australia, Journal of Metamorphic Geology, 32, 25–47, 2014.
 - O'Hara, K.: Fluid flow and volume loss during mylonitization: an origin for phyllonite in an overthrust setting, North Carolina, U.S.A., Tectonophysics, 156, 21–36, 1988.

Oliver, N. H. S.: Review and classification of structural controls on fluid flow during regional metamorphism, Journal of Metamorphic

30 Geology, 14, 477–492, 1996.

- Ozacar, A. A. and Zandt, G.: Crustal structure and seismic anisotropy near the San Andreas Fault at Parkfield, California, Geophysical Journal International, 178, 1098–1104, 2009.
- Peach, C. J. and Spiers, C. J.: Influence of crystal plastic deformation on dilatancy and permeability development in synthetic rock salt, Tectonophysics, 256, 101–128, 1996.
- Poirier, J. P.: Shear localization and shear instability in materials in the ductile field, Journal of Structural Geology, 2, 135–142, 1980.
 Powell, R. and Holland, T. J. B.: An internally consistent thermodynamic dataset with uncertainties and correlations: 3. Application, methods, worked examples and a computer program, Journal of Metamorphic Geology, 6, 173–204, 1988.





10

- Pryer, L. L.: Microstructures of feldspars from a major crustal thrust zone: the Grenville Front, Ontario, Canada, Journal of Structural Geology, 15, 21–36, 1993.
- Rebay, G., Powell, R., and Diener, J. F. A.: Calculated phase equilibria for a MORB composition in a *P*–*T* range, 450–650°C and 18–28 kbar: the stability of eclogite, Journal of Metamorphic Geology, 28, 635–645, 2010.
- 5 Rennie, S. F., Fagereng, Å., and Diener, J. F. A.: Strain distribution within a km-scale, mid-crustal shear zone: The Kuckaus Mylonite Zone, Namibia, Journal of Structural Geology, 56, 57–69, 2013.
 - Rice, J. R.: Fault stress states, pore pressure distributions, and the weakness of the San Andreas fault, in: Fault Mechanics and Transport Properties of Rocks, edited by Evans, B. and Wong, T., pp. 475–503, Academic Press, San Diego, 1992.
 - Robb, L. J., Armstrong, R. A., and Waters, D. J.: Nature and duration of mid-crustal granulite facies metamorphism and crustal growth: evidence from single zircon U–Pb geochronology in Namaqualand, South Africa, Journal of Petrology, 40, 1747–1770, 1999.
- Rutter, E. H.: The kinetics of rock deformation by pressure solution, Philosophical Transactions of the Royal Society of London, 283, 203–219, 1976.
 - Rutter, E. H., Holdsworth, R. E., and Knipe, R. J.: The nature and significance of fault zone weakening: an introduction, in: The Nature and Significance of Fault Zone Weakening, edited by Holdsworth, R. E., Strachan, R. A., Magloughlin, J. F., and Knipe, R. J., vol. 186 of
- 15 *Special Publications*, Geological Society of London, 2001.
 - Rybacki, E. and Dresen, G.: Dislocation and diffusion creep of synthetic anorthite aggregates, Journal of Geophysical Research, 105, 26017–26036, 2000.
 - Savage, J. C. and Burford, R. O.: Geodetic determination of relative plate motion in central California, Journal of Geophysical Research, 78, 832–845, 1973.
- 20 Schmid, S. M., Panozzo, R., and Bauer, S.: Simple shear experiments on calcite rocks: rheology and microfabric, Journal of Structural Geology, 9, 747–778, 1987.
 - Scholz, C. H.: The brittle-plastic transition and the depth of seismic faulting, Geologische Rundschau, 77, 319–328, 1988.
 - Shelly, D. R.: Migrating tremors illuminate complex deformation beneath the seismogenic San Andreas Fault, Nature, 463, 648-652, 2010.
- Shelly, D. R. and Hardebeck, J. L.: Precise tremor source locations and amplitude variations along the lower-crustal central San Andreas
 Fault, Geophysical Research Letters, 37, L14 301, doi:10.1029/2010GL043 672, 2010.
 - Sibson, R. H.: Transient discontinuities in ductile shear zones, Journal of Structural Geology, 2, 165–171, 1980.
 - Spotila, J. A., Niemi, N., Brady, R., House, M. A., Buscher, J., and Oskin, M.: Long-term continental deformation associated with transpressive plate motion: The San Andreas fault, Geology, 35, 967–970, 2007.
- Tenczer, V., Powell, R., and Stüwe, K.: Evolution of H₂O content in a polymetamorphic terrane: the Plattengneiss Shear Zone (Koralpe, Austria), Journal of Metamorphic Geology, 24, 281–295, 2006.
 - Till, A. B., Roeske, S. M., Sample, J. C., and Foster, D. A.: Exhumation Associated with Continental Strike-Slip Fault Systems, vol. 434 of *Special Papers*, Geological Society of America, 2007.
 - Toogood, D. J.: Structural and metamorphic evolution of a gneiss terrain in the Namaqua Belt near Onseepkans, South West Africa, Bulletin of the Precambrian Research Unit, 19, University of Cape Town, 220pp, 1976.
- 35 Wannamaker, P. E., Jiracek, G. R., Stodt, J. A., Caldwell, T. G., Gonzalez, V. M., McKnight, J. D., and Porter, A. D.: Fluid generation and pathways beneath an active compressional orogen, the New Zealand Southern Alps, inferred from magnetotelluric data, Journal of Geophysical Research, 107, doi:10.1029/2001JB000 186, 2002.





- Waters, D. J.: Metamorphic history of sapphirine-bearing and related magnesian gneisses from Namaqualand, South Africa, Journal of Petrology, 27, 541–565, 1986.
- Waters, D. J.: Partial melting and the formation of granulite facies mineral assemblages in Namaqualand, South Africa, Journal of Metamorphic Geology, 6, 387–404, 1988.
- 5 Waters, D. J. and Whales, C. J.: Dehydration melting and the granulite transition in metapelites from southern Namaqualand, South Africa, Contributions to Mineralogy and Petrology, 88, 269–275, 1984.
 - Wech, A. G., Boese, C. M., Stern, T. A., and Townend, J.: Tectonic tremor and deep slow slip on the Alpine Fault, Geophysical Research Letters, 39, L10 303/doi:10.1029/2012GL051751, 2012.
 - White, R. W. and Powell, R.: Melt loss and the preservation of granulite facies mineral assemblages, Journal of Metamorphic Geology, 20,
- 10 621–632, 2002.

White, R. W., Powell, R., Holland, T. J. B., Johnson, T. E., and Green, E. C. R.: New mineral activity–composition relations for thermodynamic calculations in metapelitic systems, Journal of Metamorphic Geology, 32, 261–286, 2014.

- White, S.: Strain and the development of deformation features in quartz tectonites, Philosophical Transactions of the Royal Society of London, 283A, 69–86, 1976.
- 15 White, S. H. and Knipe, R. J.: Transformation and reaction enhanced ductility in rocks, Journal of the Geological Society of London, 135, 513–516, 1978.
 - Wintsch, R. P., Christoffersen, R., and Kronenberg, A. K.: Fluid-Rock Reaction Weakening of Fault Zones, Journal of Geophysical Research-Solid Earth, 100, 13 021–13 032, 1995.

Wittlinger, G., Tapponnier, P., Poupinet, G., Mei, J., Danian, S., and Herquel, G. an Masson, F.: Tomographic evidence for localized litho-

- 20 spheric shear along the Altyn Tagh Fault, Science, 282, 74–76, 1998.
 - Worley, B. A. and Wilson, C. J. L.: Deformation partitioning and foliation reactivation during transpressional orogenisis, an example from the Central Longmen Shan, China, Journal of Structural Geology, 18, 395–411, 1996.
 - Zoback, M. D., Prescott, W. H., and Krueger, S. W.: Evidence for lower crustal ductile strain localization in southern New York, Nature, 317, 705–707, 1985.





 Table 1. Representative mineral compositions.

	KMZ28				KMZ29					KMZ30					
	hb	pl core	pl rim	chl	ep	hb	pl core	pl rim	chl	ep	hb	pl core	pl rim	chl	ep
SiO ₂	45.83	51.15	63.37	26.39	37.64	47.58	53.45	61.67	29.17	38.9	44.41	55.96	60.11	26.29	37.53
TiO_2	1.00	0.01	0.01	0.1	0.03	0.83	b.d.	0.05	0.03	0.09	0.42	b.d.	0.01	0.05	b.d.
Al_2O_3	10.61	31.97	23.49	22.33	27.04	8.51	30.86	22.85	19.1	27.76	11.5	28.67	24.8	22.37	23.52
Cr_2O_3	0.22	n.d.	n.d.	0.08	b.d.	0.14	n.d.	n.d.	0.24	b.d.	0.03	n.d.	n.d.	b.d.	0.03
FeO	15.5	0.05	0.28	23.36	9.45	13.18	0.09	1.26	20.11	8.1	18.52	0.17	0.14	26.58	14.21
MnO	0.3	0.02	0.05	0.23	b.d.	0.34	0.05	0.04	0.27	0.19	0.58	0.03	b.d.	0.48	0.27
MgO	12.36	b.d.	b.d.	15.8	b.d.	14.76	b.d.	0.8	19.56	0.05	10.14	0.02	b.d.	13.44	0.01
CaO	11.39	13.3	3.75	0.12	23.23	11.77	11.75	3.18	0.08	22.93	11.84	9.6	4.88	0.09	22.59
Na_2O	0.73	3.38	8.49	0.04	0.08	0.74	4.46	7.01	b.d.	0.03	0.95	5.96	8.13	0.05	0.01
K_2O	0.36	0.06	0.1	0.46	0.14	0.24	0.07	2.36	0.03	0.02	0.61	0.09	0.93	0.34	0.01
Total	98.28	99.94	99.55	88.9	97.61	98.17	100.72	99.71	88.58	98.08	98.99	100.5	99	89.69	98.18
Oxygens	23	8	8	14	25	23	8	8	14	25	23	8	8	14	25
Si	6.72	2.32	2.8	2.71	6.03	6.91	2.39	2.77	2.94	6.13	6.59	2.5	2.7	2.72	6.13
Ti	0.11	0	0	0.01	0	0.09	-	-	0	0.01	0.05	0	0	0	0
Al	1.83	1.71	1.22	2.71	5.11	1.46	1.63	1.21	2.27	5.16	2.01	1.51	1.31	2.73	4.53
Cr	0.03	-	-	0.01	0	0.02	0	0	0.02	0	0	-	-	0	0
Fe*	1.9	0	0.01	2.01	1.27	1.60	0	0.05	1.7	1.07	2.3	0.01	0.01	2.3	1.94
Mn	0.04	0	0	0.02	0	0.04	0	0	0.02	0.02	0.07	0	0	0.04	0.04
Mg	2.7	0	0	2.42	0	3.19	0	0.05	2.94	0.01	2.24	0	0	2.07	0
Ca	1.79	0.65	0.18	0.01	3.99	1.83	0.56	0.15	0.01	3.87	1.88	0.46	0.24	0.01	3.95
Na	0.21	0.3	0.73	0.01	0.02	0.21	0.39	0.61	0	0.01	0.27	0.52	0.71	0.01	0
Κ	0.07	0	0.01	0.06	0.03	0.04	0	0.14	0	0	0.12	0.01	0.05	0.04	0
Total	15.38	4.98	4.95	9.96	16.44	15.4	4.99	4.99	9.91	16.29	15.55	5	5.02	9.94	16.61
X_{an}		0.68	0.20				0.59	0.20				0.47	0.25		
$X_{\rm Fe}$	0.56			0.6		0.47			0.51		0.65			0.66	
$X_{\rm ps}$					0.20					0.17					0.30

b.d.: below detection limit; n.d.: not determined; *: All Fe is recalculated as Fe^{2+} , except for epidote, where all Fe is assumed to be Fe^{3+} .





	SiO_2	TiO_2	Al_2O_3	FeO	MgO	CaO	Na ₂ O	0	H_2O
Fig. 4a	51.33	0.98	10.45	9.68	13.76	10.90	2.20	0.70	excess
Fig. 4b	53.98	1.02	9.32	8.94	15.73	9.17	1.11	0.72	excess
Fig. 4c	61.53	0.95	10.26	7.95	7.17	8.14	3.28	0.71	excess
Fig. 5a $(M_{\rm H_2O}=15)$	43.64	0.83	8.88	8.23	11.69	9.27	1.87	0.60	15
Fig. 5a ($M_{\rm H_2O} = 3$)	49.80	0.95	10.13	9.39	13.35	10.57	2.13	0.68	3
Fig. 5b $(M_{\rm H_2O}=16)$	45.35	0.86	7.83	7.51	13.21	7.70	0.93	0.60	16
Fig. 5b $(M_{\rm H_2O}=2)$	52.91	1.00	9.14	8.76	15.42	8.98	1.09	0.71	2
Fig. 5c $(M_{\rm H_2O}=12)$	54.15	0.84	9.03	6.99	6.31	7.16	2.89	0.62	12
Fig. 5c $(M_{\rm H_2O}=2)$	60.30	0.94	10.06	7.79	7.03	7.98	3.22	0.70	2

Table 2. Bulk compositions (in mole %) used to construct the pseudosections.



Figure 1. Geological setting of the study area. (a) Map of southern Africa showing the extent of the Namaqua Metamorphic Complex (NMC). (b) Location of the study area to the southwest of Aus in southern Namibia. The Kuckaus Mylonite Zone (KMZ) forms part of the larger Marshall Rocks–Pofadder shear zone (MRPSZ) and has a similar orientation, kinematics and age as the Southern Namaqua Front that separates the Richtersveld and Gordonia Subprovinces of the NMC, and the Lord Hill–Excelsior Shear Zone that separates the Gordonia and Konkiep Subprovinces. After Miller (2008) and Macey et al. (2014).







Figure 2. Field photographs of mafic lenses within the KMZ. (a) Detail of the unsheared core of a lens, showing coarse-grained amphibolite with evidence of small-scale migmatisation in the form of leucosome stringers and ponds, as indicated by arrowheads. (b) Boundary of mafic lens showing the increase in strain over a distance of 50 cm. Lens cap in (a) is 62 mm in diameter and hammer in (b) is 30 cm long.



Figure 3. Photomicrographs of (a) KMZ28, (b) KMZ29, (c) KMZ30. All photographs are in plane-polarised light, with the long axis being 4.5 mm.







Figure 4. P-T pseudosections calculated for mafic schists from the KMZ. The inferred equilibrium mineral assemblages are outlined by red boxes and indicated in bold type. Contours in (b) are for X_{an} in plagioclase.







Figure 5. $T-M_{\rm H_2O}$ pseudosections for mafic schists from the KMZ. H₂O-saturated assemblages are separated from H₂O-undersaturated assemblages by the thick dashed line. The observed assemblages are outlined by red boxes.







Figure 6. Summary of estimated P-T conditions for the KMZ, constrained from the P-T overlap of the equilibrium assemblages that occur in the various mafic schists.