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Oxygen, carbon and strontium isotope constraints on the mechanisms of nappe emplacement and fluid–rock interaction along the subhorizontal Naukluft Thrust, central Namibia

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Abstract: The Naukluft Thrust forms the floor thrust to the Naukluft Nappe Complex, a far-travelled, nappe stack of the Pan-African Damara belt in Namibia. The thrust tectonostratigraphy comprises three dolomitic components, a calc-mylonite horizon, and a discrete brittle fault. Stable isotope data indicate that the leading edge is characterized by positive $\delta^{13}C$ values, whereas the trailing edge is characterized by negative $\delta^{13}C$ values. There is a significant range in the $\delta^{18}O$ values, over 15‰ in different sections, with the leading edge showing a larger range than the trailing edge. $\delta^{18}O$ values are characteristic of burial dolomites and secondary dolomitization is indicated by the presence of networks above and below the Naukluft Thrust zone. The large range in $\delta^{18}O$ values and variations in $\delta^{13}C$ vs. $\delta^{18}O$ patterns are interpreted to be the result of interaction between the precursor to the Naukluft Thrust zone dolomites and fluids derived from different footwall lithologies. $^{87}Sr/^{86}Sr$ isotope ratios indicate that some fluids were derived from the basement. The data presented in this study suggest that an original carbonate-dominated horizon existed prior to thrusting and that the basal thrust of the nappe complex exploited this horizon.

Understanding the development of large-scale low-angle thrust faults has posed a major challenge to geologists since the existence of far-travelled nappe sheets was first recognized more than a century ago (e.g. Bertrand 1884). If the fault does not follow an obvious weak detachment layer (e.g. horizons of salt or shale), recent models generally follow Hubbert & Rubey (1959) in proposing that frictional resistance within the fault zone is reduced by localized high pore-fluid pressure, irrespective of the competence of the lithologies involved (e.g. Fyfe & Kerrich 1985; Burkhard *et al*. 1992; Viola *et al*. 2006). Fluids affect the physical and chemical environment in the vicinity of a fault, with the fault strength potentially modified through the following processes: (1) solution-transfer processes; (2) reaction softening and metasomatism, especially hydration reactions that form new, weaker minerals; (3) recrystallization and/or neocrystallization leading to changes in grain size; (4) embrittlement as a result of high pore-fluid pressure, resulting in cataclasis and mechanical reduction of grain size (e.g. Simpson 1985; Segall & Simpson 1986; Dipple *et al*. 1990; Wintsch *et al*. 1995; Oliver 1996; Kennedy & Logan 1997; McCaig 1997; Guermani & Pennacchioni 1998; Bos & Spiers 2002; Mancktelow & Pennacchioni 2005; Viola *et al*. 2006). Characterization of the fluid regime is therefore crucial to understanding the mechanical behaviour of fault zones. Stable isotopes (e.g. of C, O and Sr) are an effective tool for monitoring the compositions, sources and volumes of fluids involved, as well as the temperature of fluid–rock interaction, and can therefore be used to characterize the fluid regime that existed during thrust fault development (e.g. Burkhard *et al*. 1992).

In central Namibia, the spectacular Naukluft Nappe Complex of Pan-African age has been transported to its current position along the nearly planar, horizontal Naukluft Thrust (Korn & Martin 1959; Hartnady 1978; Viola *et al*. 2006). As a result of movement on this basal thrust, the Naukluft Nappe Complex now forms an isolated fold-and-thrust belt klippe of the Damara Belt resting on foreland units of the Nama basin, with a total displacement to the SE of some 50–80 km (Ahrendt *et al*. 1978; Hartnady 1978). The Naukluft Thrust is outlined in the field by several distinct lithologies, of which the most typical is a characteristic polymict, gritty dolomite, originally called the 'Unconformity Dolomite' by Korn & Martin (1959) but more recently (and less genetically) referred to as the 'Sole Dolomite' (Weber & Ahrendt 1983; Viola *et al*. 2006). Largely on the basis of field observations, Viola *et al*. (2006) recently proposed that the evolution of structures in the Naukluft Thrust was genetically linked to episodic high pore-fluid pressures, resulting in cyclic fluid-induced brittle deformation interspersed with aseismic ductile creep. Intermittent high fluid pressure caused the injection of fluidized, brecciated gritty dolomite dykes into both footwall and hanging wall. In the proposed model, these dykes document fluid escape from the thrust zone, leading to a rapid reduction in pore-fluid pressure and a local return to aseismic creep conditions. Field evidence demonstrates that this was not a unique event but occurred in cycles, requiring a repeated build-up in fluid pressure and presumably therefore an external source of fluid replenishment. Similar models of episodic, transient high pore-fluid pressure in thrust faults resulting in cycles of cataclasis and dominantly crystal–plastic creep have been proposed by Badertscher & Burkhard (2000), Abart & Ramseyer (2002) and Abart *et al*. (2002) for the Glarus Thrust in the Alps, and by Kirschner & Kennedy (2001) for thrust faults in the Front Ranges of the Canadian Rockies. Kirschner & Kennedy (2001) argued from isotopic data for a limited amount of fluid confined within very narrow zones surrounding the thrusts. In their model, these zones formed a semi-closed system that was not replenished by large amounts of fluid from the thrust's footwall or from