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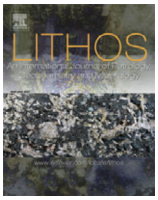

# Initiating intermediate-depth earthquakes: Insights from a HP–LT ophiolite from Corsica

N. Deseta [a,*], L.D. Ashwal [a], T.B. Andersen [b]

[a] *Department of Geosciences, University of the Witwatersrand, Private Bag 3, 2050 Johannesburg, South Africa*
[b] *Department of Geosciences and CEED, University of Oslo, P O Box 1047, Blindern, 0316 Oslo, Norway*

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ABSTRACT

The hypocentres of intermediate-depth earthquakes have been shown to overlap with the regions in subducting slabs that contain high abundances of hydrous minerals. This relationship was initially revealed using geophysical and numerical modelling and until recently has lacked corroboration from direct field-based research. We evaluated the relationship of the coincidence of intermediate-depth earthquakes with hydrous minerals in the slab by undertaking detailed geochemical analyses of blueschist to lawsonite to eclogite facies pseudotachylytes and their hostrocks located within an exhumed ophiolite, the Eocene Schistes Lustres Complex in Corsica. These units comprise incompletely metamorphosed metagabbro and peridotite. The wallrocks of the pseudotachylytes contain variable amounts of hydrous minerals: tremolite, Mg-hornblende, glaucophane in the metagabbro, and serpentine, tremolite and chlorite in the peridotite. Back-scatter-electron images show that the hydrous minerals entrained in the melt undergo fusion rather than dehydration. Vesicular and $H_2O$-rich melt veins are observed cross-cutting partially molten pseudotachylyte fault veins and show evidence of $H_2O$ exsolution during melt solidification. The crystallisation products of these melts indicate formation under high temperature, high pressure conditions (1400–1700 °C; 1.5 GPa). The peridotite-hosted pseudotachylytes crystallised olivine, orthopyroxene and diopside, which are surrounded by interstitial Al- and $H_2O$-rich glass. The metagabbro pseudotachylyte is dominated by Al-rich omphacite, ilmenite and high-Fe anorthite. XRF bulk analyses of the wallrock of the pseudotachylyte and electron microprobe analyses of the pseudotachylyte matrix, entrained survivor clasts and the crystallisation products show that near-total disequilibrium melting took place. The peridotite-hosted pseudotachylyte composition is skewed strongly towards chlorite; however, the preservation of delicate dendritic diopside and olivine hopper crystals suggests that the pseudotachylyte is unaltered, indicating that preferential fusion of chlorite took place. The metagabbro-hosted pseudotachylyte matrix composition is very similar to the bulk wallrock composition but slightly skewed by the preferential melting of Mg-hornblende and tremolite. Not all the pseudotachylytes are hydrous as the $H_2O$ content of the melts is highly variable; the metagabbro–pseudotachylyte ranges from 0 to 4 wt.% and the peridotite–pseudotachylyte ranges from 0 to 14 wt.%. The range in $H_2O$ content of the pseudotachylytes has lead us to conclude that the localised dehydration of hydrous minerals may be a second order factor in initiating intermediate-depth seismicity. However, we have observed that the pseudotachylytes with the most chaotic vein networks, thickest fault veins and most comminuted material have the highest abundances of hydrous wallrock minerals, possibly owing to repeated fluid ingress in between pseudotachylyte-generating events. This implies that free fluids enhance pseudotachylyte generation and possibly seismicity, but are not a first order requirement. Microtextural and geochemical results from this study suggest that the presence of abundant $H_2O$-rich minerals in the slab exerts a strong rheological control during high strain-rate deformation, facilitating thermally-triggered localising shear instabilities. These field-based observations allow us to explore the assumption of the causal link between slab hydration and earthquake nucleation, and offer fresh insight into the debate of how intermediate-depth earthquakes take place.

## 1. Introduction

Intermediate-depth earthquakes occur in subduction zones at depths of 50–300 km. This is contrary to the expectation that brittle failure should be inhibited by the high pressure and temperature conditions in the subducting slab (Green and Houston, 1995; Hacker et al., 2003). Seismic data show that the hypocentres of such earthquakes occur in the regions where sinking slabs are likely to have high contents of hydrous minerals (Hacker et al., 2003; Yamasaki and Tetsuzo, 2003). Whether these earthquakes and hydrous minerals are causally linked remains uncertain, although experimental and numerical studies have

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* Corresponding author.
*E-mail address:* suridae@gmail.com (N. Deseta).

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put forward several hypotheses: dehydration embrittlement, mineral transformational faulting and thermally-induced shear instabilities (Dobson et al., 2002; Green, 2003; Hacker et al., 2003; John et al., 2009; Jung et al., 2004). The aim of this study was to test the link between hydrous minerals and intermediate-depth seismicity using direct analysis of paleofaults. We present the first combined detailed geochemical and microstructural study of the blueschist to eclogite facies pseudotachylytes from Corsica, which have been interpreted as relics of intermediate-depth seismic events (Andersen and Austrheim, 2006; Austrheim and Andersen, 2004). The pseudotachylytes are hosted in lower crustal metagabbros and mantle peridotites in an Eocene Alpine subduction complex and comprise both mafic and ultramafic fusion melts (Austrheim and Andersen, 2004). The pseudotachylytes are quenched fusion melts formed at pressures of 1.5–2.6 GPa and ambient slab temperatures of ~420–500 °C, with melting temperatures of 1400 °C upward, and are variably hydrous, with 0–14 wt.% $H_2O$ (Andersen and Austrheim, 2006; Deseta et al., 2014; Ravna et al., 2010; Vitale Brovarone et al., 2011, 2013).

By analysing the fault rocks of intermediate-depth earthquakes directly we can evaluate the proposed importance of hydrous minerals in generating these phenomena. Do they facilitate dehydration embrittlement, weakening in wallrock or does the $H_2O$ released by dehydration of these minerals act as a flux for melting?

### 1.1. Pseudotachylyte formation and flash melting

High pressure pseudotachylytes from various localities (Blue Ridge Province, North Carolina; the Ivrea-Verbano zone, Italy; the Krakeneset gabbro, Norway) have been studied on a number of scales and from various aspects in order to ascertain the mechanism by which they form (Camacho et al., 2001; Jin et al., 1998; John et al., 2009; Lin, 1994; Lund and Austrheim, 2003). The majority of pseudotachylytes are derived from relatively shallow crustal lithologies and are hence associated with a brittle deformation regime (Jin et al., 1998; Magloughlin and Spray, 1992; O'Hara, 1992; Spray, 1992). However, ultramafic pseudotachylytes occurring in association with lower crustal metagabbro in contact with mantle peridotite (as observed in Corsica) implies that these melts can form at depths greater than 50 km (Jin et al., 1998; Kelemen and Hirth, 2007; Ravna et al., 2010). Generally viewed as frictional melts, the formation of high pressure pseudotachylytes in mafic and ultramafic rocks appears paradoxical, as they should be inhibited by high confining stresses. However, it needs to be taken into account that the brittle–ductile transition zone of mafic and ultramafic rocks is controlled by olivine flow laws (Boland and Tullis, 1986; Demouchy et al., 2009), rather than quartz and feldspar, and can therefore extend beyond the brittle–ductile zone determined for crustal rocks (Kirby et al., 1991; Swanson, 1992). When it is further considered that the geotherm for the Corsican pseudotachylytes was cold and steep, and eclogites from Cape Corse record ambient temperatures of 420 °C at 1.5–2.6 GPa, it becomes apparent that the brittle–ductile transition in the slab extended to nearly 80 km in some places (Vitale Brovarone et al., 2013).

### 1.2. Current models of high pressure pseudotachylyte formation

Several mechanisms have been proposed to explain intermediate-depth seismicity and associated pseudotachylyte generation under blueschist and eclogite facies conditions. These mechanisms encompass a range between two end-member processes, which will be discussed in more detail: dehydration embrittlement and a-thermally induced shear instability end-member (TSI). The hypothesis tested in this study is that a form of TSI is the initiating process of intermediate-depth seismicity and associated PST generation, as implicated by the observations discussed in this paper. The principles of these two mechanisms are summarised briefly below.

Dehydration embrittlement is based on experimental observations that show that rock materials become weak and brittle upon dehydration of their hydrous minerals, facilitating unstable faulting and inducing seismic failure (Green, 1995; Jung et al., 2006; Kirby et al., 1995, 1996). This process allows brittle failure to initiate at high pressures where fracturing would typically be inhibited by high confining pressures (>1 GPa) (Green and Jung, 2005; John et al., 2009). The weakening of rock under such conditions has been attributed to the volume change generated by the production of free water and its thermal expansion resulting from the dehydration of minerals such as serpentine and chlorite (Green, 1995). The increased pore fluid pressure offsets the high confining pressure on the PST hostrocks and on the potential slip planes within them, thereby facilitating brittle failure (Hacker et al., 2003; Jung et al., 2004). Due to dehydration-induced volume changes in individual minerals, the cohesive strength of the hostrock is reduced and this also facilitates brittle failure (Hacker et al., 2003).

To date there are several models of how high pressure pseudotachylytes might form, all of which are based on thermally-activated shear instabilities (John et al., 2009; Kelemen and Hirth, 2007; Ogawa, 1987; Orowan, 1960; Warren and Hirth, 2006). Each model has its own prerequisites and thermal equations; only the general principles of thermal shear instabilities (TSI) will be covered here.

Unlike dehydration embrittlement, TSI is a process by which coseismic shear heating under high differential stresses induces localised viscous deformation, in a visco-elastic material, such as silicate rocks (Braeck and Podladchikov, 2007; Spray, 2010). As viscous deformation progresses, there is a reduction in viscosity along the slip plane, which in turn feeds back positively and non-linearly on strain rate and temperature. This results in a massive release of elastic energy stored in the surrounding rock (or any visco-elastic material), inducing failure (Braeck and Podladchikov, 2007; Rice, 2006) (Braeck and Podladchikov, 2007; Hogan et al., 2011; John et al., 2009; Kelemen and Hirth, 2007; Ogawa, 1987).

At such high strain rates ($>10^{-2}$ $s^{-1}$) the temperature increases too rapidly to be diffused away from the shear zone and the shear instabilities become self-localising (Braeck and Podladchikov, 2007). Due to the fact that heat transferred away from the shear plane occurs by diffusion, peak temperatures are located in the centre of the shear plane. As the temperature in the narrow shear zone, viscosity decreases, generating a positive feed-back effect (and self-localising effect) that can eventually lead to melting and the formation of a fault plane (less than ~200 μm) (Braeck and Podladchikov, 2007; Kelemen and Hirth, 2007; Rice, 2006).

There may be several alternatives for precisely how TSI is initiated, but current experimental research and numerical modelling suggest that as rocks are heterogeneous materials, the stress imposed will be concentrated in minute domains where the effective viscosity in the rock is locally greatly decreased and acts as strain concentrators (Bestmann et al., 2011; John et al., 2009, Kelemen and Hirth, 2007). Preferential shear heating will take place in these low viscosity zones, eventuating in a positive feedback effect where an exponentially increasing strain rate and temperature will take place resulting in failure, melting and or comminution (John et al., 2009; Kelemen and Hirth, 2007). The perturbations in rheology result in extremely localised regions of low viscosity expressed in the rock as either reduced grain size and/or the presence of hydrous minerals such as serpentine, chlorite or muscovite (Bestmann et al., 2011; Hacker et al., 2003; John et al., 2009). With regard to hydrous minerals it should be noted that, in the case of TSI, it is their mechanical properties at high strain rates that causes the rocks to weaken and fail, not the release of free water (Sibson, 1977a; Spray, 2010). The eclogite facies pseudotachylytes hosted by the Krakeneset metagabbro, western Norway have been suggested as a natural example of TSI (John et al., 2009). The Krakeneset pseudotachylyte-fault veins occur in domains of the hostrock metagabbro, within which there is a marked decrease in grain size towards the fault plane and a relatively high degree of hydration reflected by the presence of phengite, clinozoisite linozoisite (Haakon et al., 1997; Lund and Austrheim, 2003; John et al., 2009). TSI ultimately differs from dehydration embrittlement, as fault weakening is rheologically controlled