Pseudotachylytes from Corsica: fossil earthquakes from a subduction complex

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ABSTRACT

Subduction zones are the most seismically active tectonic environment on Earth. Here we report fault-rock evidence of palaeoearthquakes from a subduction complex. Pseudotachylyte veins formed by shear heating on faults at seismic strain rates contain dendrites, spherulites and acicular minerals characteristic of blueschist facies conditions. The veins have

been found in both mantle peridotite and gabbro. Our discovery from Corsica opens a new avenue of research towards understanding mechanisms related to subduction zone earthquakes and the conditions at which these are released.

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Introduction

Tectonic processes along convergent plate margins, particularly in subduction zones, generate most of the global energy radiated by earthquakes. Although the mechanism behind interplate earthquakes is generally related to stick-slip during underthrusting on shallowly dipping fault planes, there are a number of phenomena regarding intra- and interplate earthquakes that await explanation. A major unresolved question concerns the interaction of earthquakes with fluids and metamorphic processes (Hacker *et al.*, 2003; Lund and Austrheim, 2003). Subduction zones are typified by low geothermal gradients, where high differential stresses may result in fracturing rather than creep. Although most models view the properties of subducted crust as a function of temperature, it is increasingly recognized that the rheological properties of rocks depend on their metamorphic status and importantly on the fluid content. Release of fluids from dehydration reactions in subduction complexes will reduce the effective stress and allow brittle failure (Hacker *et al.*, 2003), but fluids may also reduce the likelihood for frictional melting in shear zones (Sibson, 1975). Blueschist terrains are characterized by low-temperature and high-pressure (LT–HP) metamorphism and are often regarded

as having formed in the upper 15–50 km of subduction zones. Such rock complexes are potential sources for direct observational information regarding the physical properties of subducted rocks.

Geological setting

The Alpine HP–LT complex of Corsica (Fig. 1) contains carpholite schists, blueschist and eclogite facies rocks formed by late Cretaceous (?) – early Tertiary subduction, involving thrust stacking and accretion of European continental crust and Ligurian oceanic units on to the margin of Europe (cf. Figure 4 in Jolivet *et al.*, 2003). The HP–LT rocks include a dismembered ophiolite dominated by variably metamorphosed ultramafics, gabbros, pillow lavas and metasedimentary schists (the Schistes Lustrés units), as well as allochthonous blueschist (Sera di Pigno Unit) and eclogite facies (Monte Pinatelle – Farinole Unit) rocks developed from the Hercynian basement (Warburton, 1986; Fournier *et al.*, 1991). The eclogites of the Cap Corse Region record peak Alpine metamorphic conditions of $P \approx 15\text{--}20$ kbar and $T \approx 550 \pm 50$ °C. They were exhumed on a cold geotherm through the blueschist facies at $P \approx 7\text{--}9$ kbar and $T \approx 450\text{--}500$ °C and eventually to greenschist facies (Fournier *et al.*, 1991; Lahondre, 1988). Other units without eclogites reached P_{max} at lawsonite-blueschist facies ($P \approx 13\text{--}15$ kbar at $T \approx 350\text{--}400$ °C) and decompressed on a cold geotherm through blueschist ($P \approx 10$ kbar, $T \approx 350$ °C) to greenschist facies conditions (Fournier *et al.*, 1991).

The fault rocks

Pseudotachylyte veins occur in gabbros and mantle peridotites exposed around the peak of Cima di Gratera (Fig. 1). The Cima di Gratera gabbro is a cumulate-layered to varied-textured gabbro. The gabbro is partly transformed to blueschist facies, except in shear zones (Fournier *et al.*, 1991) where the transformation has run to completion. Our field observations suggest that parts of the gabbros that were incorporated into the subduction complex remained undeformed and partly unreacted during both subduction and the subsequent exhumation, and that the pseudotachylytes are located in the least reacted parts. The pseudotachylytes can also be studied in boulders on the beach at Sole du Marine (Fig. 1) and along the river Fium Albino, draining the Cima di Gratera area (dotted line in Fig. 1). A large number of gabbro and some peridotite boulders with partly preserved primary structures, textures and mineralogy display fine-grained, brittle-deformation zones and pseudotachylyte zones (Figs 2 and 3).

The pseudotachylytes are dark, grey, occasionally greenish to bluish, aphanitic veins, < 3 cm thick. They are clearly related to faults and form single discrete veins, injection-vein complexes and ladder-network breccias (Fig. 2a,b). Several examples of cross-cutting veins of different generations (Fig. 2a) indicate a polyphase slip history on the faults. Locally, small pull-apart mesoscopic structures have been opened and filled with pseudotachylyte (Fig. 2a). Some samples preserve evidence of interaction between brittle and ductile deforma-

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Fig. 1 Simplified geological map of the St. Florent area with an inset map of Corsica. Modified from Fournier *et al.* (1991).

tion as shear strain gradients locally can be observed along fault-vein margins, and some veins are partly overprinted by ductile fabrics (Fig. 2b). A colour banding defined by variable size and/or content of porphyroclasts and commonly convoluted by folds is present in many veins. Textural and mineralogical characteristics of the veins and their wall-rocks are given in Table 1. The gabbro-hosted veins locally display intricate dendrites

(Figs 2c and 3b,c) of fassaitic pyroxene (Table 2). Veins 0.2–1 cm across have a central part with 10 µm euhedral pyroxene crystals, some of which have cores of diopside (Fig. 3c). The vein margins are characterized by dendrites and spherulites (Fig. 3c,d). The dendrites branch outward from orthopyroxene clasts that are partly replaced by talc (Fig. 3d). The hydration of orthopyroxene to talc cannot have occurred after the growth of the

Fig. 2 (a) Multiple-generation fault-breccia of gabbro with network of pseudotachylyte veins. Notice pull-apart with fragments of wall-rock (top and bottom) filled with pseudotachylyte. (b) Pseudotachylyte vein along right-lateral fault, showing a shear-strain gradient defined by the foliation in the gabbro wall-rock highlighted by dotted white lines in the figure. (c) BSE image (Cor30) of spherulitic texture in pseudotachylyte, with epidote, dendritic fassaite and plagioclase.

dendrite as this would have destroyed the delicate texture. Acicular epidote grains locally form spherulites. The clasts and wall-rock minerals are similar in composition, suggesting that they are locally derived. The fassaitic pyroxene contains up to 18 wt% Al_2O_3 as jadeite, Ca-tschermak and in the most Al-rich pyroxenes up to 15 mol.% Ca-Eskola component. Fassaitic pyroxenes with similar composition have been reported from pseudotachylytes in the Musgrave range, Central Australia (Wenk and Weiss, 1982). Wenk and Weiss (1982) pointed out that the high Al-pyroxene was similar to pyroxenes from eclogites and kimberlites that formed at 30 kbar and argued that the high pressure represented dynamic stresses released during catastrophic brittle failure. Fassaitic pyroxenes have also

Fig. 3 (a) Pseudotachylyte vein containing fassaitic cpx, boulder (sample Cor30) from the beach at Sole du Marine (all mineral abbreviations after Kretz, 1983). (b) Back-scattered electron (BSE) image from pseudotachylyte, showing dendrite of fassaitic cpx. (c) BSE image showing centre (right) to rim (left) of pseudotachylyte vein (Cor30). The centre contains euhedral crystals of fassaitic cpx locally surrounding clasts of cpx (cpx-1). The rim of the vein is characterized by dendrites of fassaitic cpx. (d) BSE image from pseudotachylyte vein (Cor30), showing dendrite of fassaitic cpx that has grown out from clasts consisting of relict opx partly replaced by talc. Talc must have formed before the faulting. (e) BSE image of pseudotachylyte vein transecting peridotite. Note that serpentinization stops at the margin of the vein. (f) BSE image of pseudotachylyte vein showing serpentine with overgrowth of younger olivine. Note also clast of Cr-diopside.

been produced during frictional melting experiments at 10 kbar conducted to simulate earthquakes at amphibolite facies conditions (Spray, 1988). Some of the gabbro-hosted veins contain blueschist facies parageneses including 10–20 µm sodic amphibole grains that are typically zoned from edenitic cores to glaucophane rims (Table 2) or from actinolite to edenite. Pumpellyite, albite, epidote and titanite typically coexist with amphibole (Table 2).

The peridotite contains remnants of primary olivine (Fo₉₁), chromediopside (Wo₄₆En₅₁Fs₄), orthopyroxene (En₈₈) and a Cr-rich spinel. Such minerals are typical for spinel lherzolites of mantle origin. Ultrafine-grained, millimetre- to centimetre-thick injection and fault veins of pseudotachylyte containing clasts of Cr-diopside and olivine transect the peridotite (Fig. 3e). Olivine close to the vein is granulated and locally contains injection veins. A characteristic and intriguing feature observed in pseudotachylyte-like veins are serpentine inclusions partly surrounded by neoblastic olivine (Fo₉₀) (Fig. 3f). The interpretation of these textures is not clear, but the dehydration reaction $\text{serpentine} = \text{olivine} + \text{H}_2\text{O}$ may have occurred. The replacement of serpentine by olivine requires a minimum temperature of *c.* 450 °C at a pressure of 10 kbar (Bucher and Frey, 1994). Because the dehydration textures have not been observed outside the vein it is suggested that the dehydration occurred as a response to shear heating and not to a regional temperature increase. The serpentine

Table 1 Petrography of pseudotachylyte veins and their wall rocks

Sample	Vein			Wallrock			
	Clast	Neolith	Texture	Primary minerals	Secondary minerals	Textures	Rock type
Cor29a	di, ol, srp	ol	ol growth on srp clasts	ol, cpx, opx, spl	srp, chl, mt	chl rims on mt	peridotite
Cor30	di, pl, srp, tc + opx	fst, zo, pl, tre	dend, sphe, opx growth on tlc	di, pl, hbl, ol/opx	tlc, ep, pl	ol/opx replaced by tc, plag	gb
Cor32	di, pl	act, ep, ab, chl		di, pl, ol/opx	tlc, ep, pl	strong alteration	gb
Cor36	pl + ep, chl	pmp, amph, ep	zoned amph(ed-act)	pl, cpx/ol/opx	chl, epid, alb, amph	strong hydration	gb
Cor48c	ep	gln, Pmp, pl, spn	zoned amph(gln-act)	cpx, pl	ep, ab	plag altered to alb + ep	gb
Cor47	di	amph		cpx, pl		kb and db in cpx, pl altered to zo + alb	gb
Cor62	di, aug, pl	fst, pl, amph	fst growth on di clasts	cpx, pl	ep, ab	kb and db in cpx	gb/do

Mineral abbreviations after Kretz (1983).

Additional abbreviations: gabbro, gb; dolerite, do; dendrite, dend; spherulite, sphe; kink bands, Kb; deformation bands, db.

Table 2 Compositions of pyroxenes and amphiboles from pseudotachylyte veins and their wallrock

Sample Texture Mineral	Cor30 dend. fst	Cor30 clast di	Cor30 dend. fst	Cor30 neolith fst	Cor30 dend. fst	Cor62 neolith fst	Cor29 pri. min. cr-di	Cor29 pri. min. opx	Cor30 clast opx	Cor36 core ktp	Cor36 rim tr	Cor48C core bar	Cor48C rim bar	Cor48C core gln
SiO ₂	50.7	50.71	50.6	48.39	50.84	49.72	50.88	53.88	54.33	45.26	57.81	44.64	57.37	57.58
TiO ₂	0.49	1.19	0.39	0.32	0.32	0.34	0.28	0.14	0.29	1.19	0.04	0.28	0	0
Al ₂ O ₃	16.21	3.7	12.93	14.05	18.54	10.94	5.5	5.89	1.38	10.63	1.22	13.86	11.39	11.37
FeO	5.28	8.03	5.65	5.17	4.93	4.92	2.15	6.67	13.64	16.57	5.42	10.01	8.46	8.16
MnO	0.19	0.14	0.19	0.14	0.16	0.11	0.03	0.14	0.32	0.44	0.15	0.04	0.07	0.04
MgO	11.04	14.24	15.32	15.99	9.88	16.86	17.42	32.35	28.35	10.96	19.84	15.12	11.78	11.46
CaO	13.93	20.77	13.26	14.63	13.85	16.48	21.89	0.71	1.22	8.05	12.84	8.91	2.72	2.28
Na ₂ O	2.37	0.52	1.63	0.97	2.69	0.8	0.76	0.06	0.05	4.2	0.38	4.02	6.18	6.41
K ₂ O	0	0	0	0	0	0	0	0	0	0.03	0	0	0	0.12
Cr ₂ O ₃	0	0.35	0.14	0.16	0.09	0.12	1.22	0.63	0.13	0	0.04	0.01	0.01	0.01
Total	100.21	99.65	100.11	99.82	101.3	100.29	100.13	100.47	99.71	97.33	97.74	96.89	97.98	97.43
Structural formula based on 6(O) and 23(O) for pyroxene and amphiboles, respectively														
Si	1.799	1.89	1.804	1.737	1.779	1.785	1.852	1.862	1.953	Si	6.743	7.998	6.474	7.886
Al ^{IV}	0.201	0.11	0.196	0.263	0.221	0.215	0.148	0.138	0.047					
Al ^{VI}	0.477	0.053	0.347	0.331	0.544	0.248	0.88	0.102	0.005	Al	1.866	0.199	2.369	1.791
Ti	0.013	0.033	0.01	0.009	0.008	0.009	0.008	0.004	0.008	Ti	0.133	0.004	0.031	0
Cr ³⁺	0	0.012	0.005	0.006	0.002	0.003	0.029	0.016	0.003	Cr	0	0.001	0	0
Fe	0.157	0.25	0.168	0.155	0.144	0.148	0.065	0.193	0.41	Fe	2.064	0.627	1.214	0.944
Mn	0.006	0.004	0.006	0.004	0.005	0.003	0.001	0.004	0.01	Mn	0.056	0.018	0.005	0.008
Mg	0.584	0.791	0.814	0.856	0.515	0.902	0.945	1.667	1.519	Mg	2.434	4.092	3.269	2.861
Ca	0.53	0.829	0.506	0.563	0.519	0.634	0.854	0.026	0.047	Ca	1.285	1.903	1.384	0.389
Na	0.163	0.038	0.113	0.067	0.183	0.056	0.054	0.004	0.003	Na	1.213	0.102	1.13	1.599
										K	0.006	0	0	0.021
Sum cations	3.93	4.011	3.97	3.99	3.921	4.002	4.044	4.015	4.011		15.794	14.944	15.875	15.247
Na(Mg,Ti)0.5Si ₂ O ₆	0.03		0.02	0.02	0.02									
Jd	0.14		0.09	0.05	0.17									
CaEs	0.14		0.06	0.02	0.16									
CaTs	0.2		0.2	0.26	0.22									
Aug	0.06		0.08	0.03	0									
Opx	0.34		0.45	0.49	0.33									

End-members calculated for pyroxene with sum cations < 4 according to Katayama *et al.* (2000).

Cor30, 36, 48 and 62: gabbro. Cor29: peridotite. Abbreviations as in footnotes to Table 1.

indicates that some hydrous minerals were present prior to faulting.

The gabbro wall-rock is variably hydrated. Plagioclase is typically altered to epidote and albite. Clinopyroxene is locally replaced by actinolite and chlorite. Orthopyroxene is altered to aggregates of quartz, chlorite and actinolite or replaced by talc. Olivine in the peridotite is locally replaced by serpentine and magnetite, the latter often along fractures. Cr-spinel is rimmed by chlorite. Although some hydration must have taken place prior to faulting, as demonstrated by clasts of serpentine and talc, the hydration also continued after faulting as veins in the peridotite are replaced by serpentine and magnetite along fractures and locally are totally overprinted by serpentine.

The contacts with wall-rocks in both gabbro- and peridotite-hosted veins are sharp, and the wall-rock is

transected by microfractures. Although clinopyroxenes locally have well-developed kink bands and deformation lamellae, the gabbro preserves the subophitic texture. An origin of frictional melts as a plastic instability (Hobbs and Ord, 1988) in a deforming shear zone seems to be incompatible with our observations. The textures found in the pseudotachylyte are typical of frictional melts formed during seismic faulting (Magloughlin, 1992). The change from euhedral crystals in the vein centre to dendrite at the vein rims suggests that the fassaitic pyroxene crystallized directly from the melt. Thus the dendritic texture supports the structural observations, which demonstrate that the veins are the result of faulting and represent true frictional melts. The spherulitic/dendritic textures shown in Figs 2(c) and 3(b–d) are similar to those produced during quenching of melt in experiments.

Discussion

The pseudotachylytes described occur in a blueschist facies terrain that experienced maximum metamorphic conditions of 550 ± 50 °C and 15–20 kbar, corresponding to subduction at a depth of 45 km or more. Although we cannot provide quantitative depth estimates for the faulting, the veins contain neoblasts and parageneses characteristic of blueschist facies metamorphism (glaucofan and other high-pressure amphiboles such as barroisite). The composition of the dendritic pyroxene with a high CaEs component is in accordance with pyroxene formed at 10 kbar (Spray, 1988) and further supports the idea that the seismic faulting occurred at considerable depth. Occurrence of pseudotachylyte at HP–LT conditions in the eclogite facies has previously been documented

from the orogenic root zone of the Caledonides in Western Norway (Austrheim and Boundy, 1994; Lund and Austrheim, 2003). These pseudotachylytes occur in dry Precambrian granulites and gabbros and it was argued that seismicity was an integral part of the fluid-driven Caledonian (420 Ma) eclogitization of the root zone by assisting fluid transport (Bjornerud *et al.*, 2002). These observations have recently been taken to support models of a dry, strong and seismically active lower crust beneath the Himalayas (Jackson, 2002). The Alpine example reported here has several analogies with the Caledonian HP–LT pseudotachylytes. The complex is partly metamorphosed to HP–LT assemblages and pseudotachylytes have been identified in rocks that partly preserve their previous mineralogy and textures. This suggests that dry strong rocks are a prerequisite for the faulting that produces pseudotachylyte. However, clasts of talc and inclusions of globular serpentine may give support for some hydration prior to faulting. A detailed search for dehydration textures on a regional scale is required to test whether the dehydration reaction represented by serpentine to olivine is related to a regional heating event and therefore supports existing models for subduction zone earthquakes (Hacker *et al.*, 2003) or if the dehydration took place during shear heating as suggested here. Pseudotachylytes have recently also been described from the Shiman-to accretionary complex in Japan by Ikesawa *et al.* (2003). The finding of palaeo-seismic fault zones in subduction complexes is exciting and represents a new source of information on subduction earthquakes. We anticipate that similar relationships will be found in other subduction complexes and blueshist terrains, which will open a new avenue for research towards a

better understanding of subduction zone processes.

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