EVIDENCE OF FRICTIONAL MELTS IN WEAK CARBONATE ROCKS-EXAMPLES FROM THE CUISA FAULT, ALTA GUAJIRA/NORTHERN COLOMBIA

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Abstract

Along the strike-slip Cuisa fault, in the Jurassic Cuisa Shale Formation of the Guajira-Falcon Composite Terrain, Alta Guajira region, Northern Colombia, discrete carbonate-filled fractures, blebs and veins are documented. Some discrete carbonate-filled veins are formed by repeated crack-seal processes. In addition, in a small notch beside the crack-seal zones, calcite nodules of the same composition of the crack-seal calcites occur. They are embedded in a fine-grained matrix of calcite of significant different composition, which is rich in MgO and poor in FeO. We discuss their origin by frictional melting during (seismic?) extremely rapid shear in which the nodules represent clasts of former coarse-grained carbonate veins. The fine-grained matrix derives from rapidly cooled melts, which devitrified later. Therefore, an interpretation as preserved carbonaceous pseudotachylytes is presented.

Key Words: Carbonate-filled veins, carbonaceous pseudotachylytes, crack-seal processes, Cuisa fault, Guajira

Resumen

A lo largo de la falla de deslizamiento en rumbo de Cuisa, en la Formación Shale de Cuisa del terreno compuesto Guajira-Falcon, región de la Alta Guajira, Colombia, son documentadas fracturas rellenas de carbonato, vesículas y venas. Algunas venas discretas rellenas por carbonato son formadas por procesos repetidos de ruptura-sello. Adicionalmente, en pequeñas muescas ubicadas a ambos lados de las zonas de ruptura-sello, ocurren nódulos de calcita de la misma composición que la que se encuentra presente en las zonas de ruptura-sello. Ellas están embebidas en una matriz de calcita de tamaño de grano fino de composición significativamente diferente, rica en MgO y pobre en FeO. Nosotros discutimos su origen por fusión friccional durante un cizallamiento extremadamente rápido (sísmico?) en el cual los nódulos representan clastos de las venas de carbonato de tamaño de grano grueso primarias. La matriz de tamaño de grano fino se deriva de los fundidos rápidamente enfriados, los cuales son posteriormente desvitrificados. Por lo tanto, se interpretan como pseudotaquilitas calcáreas preservadas.

Palabras clave: Venas rellenas por carbonato, pseudotaquilitas calcáreas, procesos de ruptura-sello, Falla de Cuisa, Guajira.

INTRODUCTION

Pseudotachylytes (Pst) represent fossil frictional melts and are the petrological evidence of earthquake hypocenters. As the product results of seismic failure, they are most important constraints of paleo-seismicity in exhumed rocks. They consist of fine-grained rocks, formed by frictional melting, and often rounded protolith clasts (Shand 1916). Melting follows seismic failure and brittle grain size reduction (e.g. Sibson 2003, Magloughlin 1992; Magloughlin and Spray 1992; Lin 1994; Hetzel et al. 1996), or hydro-fracturing (Austrheim and Boundy 1994; Lund and Austrheim 2003). During seismic failure most of the released energy dissipates as heat. Consequently, only a minor component is radiated as seismic energy (Sibson 2003). Pseudotachylyte generation is a complex thermally activated fault weakening process initiated by an abrupt increase of frictional strength during rapid shear (e.g. Rice 2006), melt generation, rapid cooling (quenching) and subsequent deformation. Quenching often produces glass and fine-grained neograins. Most examples are preserved, often devitrified, from the brittle upper crust. However, Pst can form also during upper mantle (subduction of continental lithosphere, Austrheim and Boundy 1994; Lund and Austrheim 2003; John and Schenk 2006) and mid-crustal seismic events (e.g. Lin 1994; Handy and Brun 2004). Few are known from meteoric impacts (e.g. Martini 1992) and giant landslides (Mash et al. 1985).

Pseudotachylytes are almost exclusively described from silicate rocks. Their formation in carbonate rocks is thought to be unlikely due to the ductile flow in carbonates, which inhibits high differential stresses (Passchier and Trouw 2005) and the dissociation at temperatures > 900°C. Han et al. (2007) reported that at seismic slip velocities calcite will be decomposed to CO_2 + lime. In contrast classical phase diagrams reveal that melting of carbonates at pressures > 1kbar is possible. However, here we present evidence of pseudotachylyte relics in carbonates, hosted in a large-scale brittle fault zone, in the Alta Guajira, Northern of Colombia.

GEOLOGICAL SETTING AND SAMPLE LOCATION

The northern margin of South America is generated by the complex interaction of the Nazca, Caribbean and South American Plates. Collision and subduction processes are responsible for the development of a set of discrete blocks or micro plates, which move independently from each other. These blocks are composed of different lithostratigraphic units and are separated by strike-slip faults (Figure 1a).

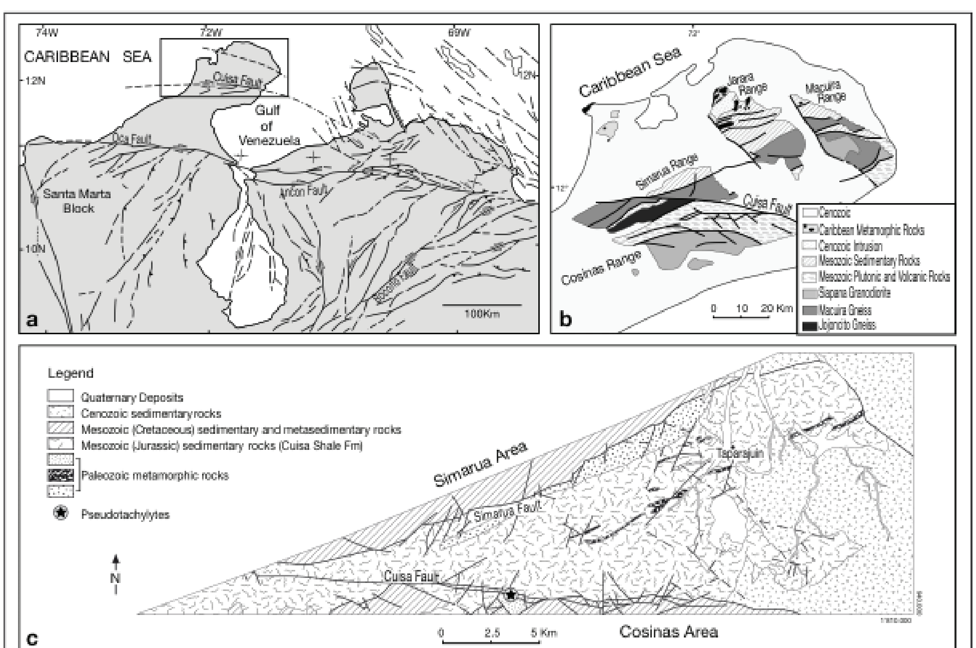

Figure 1 a. Neotectonic map of the Caribbean and the northern part of South America (Taboada et al. 2000; Audemard and Audemard, 2002, Gómez et al., 2007). b. Generalized geological map of the Alta Guajira Region, Colombia (Audemard, 1996). c. Geological map from the Simarúa area (modified of Cardona et al. 2006 ; Zuluaga et al. 2009), showing sample location.

The study area in the Alta Guajira (Figure 1a,b,c) is part of the Guajira-Falcon Composite Terrain striking from northwestern Colombia to northern Venezuela and consisting of fragments of Proterozoic and Paleozoic continental crust, Jurassic sediments and Cretaceous oceanic crust (Cediel et al. 2003; Taboada et al. 2000; Mann et al. 2007; Audemard 2003).

The lithostratigraphic units of the Alta Guajira region (Figure 1b) include high-grade gneisses of Mesoproterozoic age, which record Grenvillian metamorphic ages (Rodríguez & and Londoño 2002; Cardona et al. 2006). In other areas medium- to high grade metamorphic rocks as well as low-grade metamorphic metasediments of Paleozoic age occur (Lockwood 1965). Conglomerates, arenites, limestones and shales as well as quartzdioritic and granodioritic plutons (MacDonald 1964) and rhyodacitic lavas (Radelli, 1960) make up the Jurassic units (Renz 1956; Rollins, 1965). Cretaceous rocks are represented by clastic sediments, low-grade metamorphic rocks and plutonic rocks (Radelli, 1960; MacDonald, 1964; Rollins, 1965; Lockwood, 1965; Álvarez 1967 Rodríguez and Londoño 2002). Most major rock units have tectonic contacts.

This study focuses on carbonate veins, hosted in the Cuisa Fault zone, which forms a large-scale brittle fault zone, transecting the Mesozoic rock suite (Figure 1c). The veins are located in calcareous rocks of the Cuisa Shale Formation of Jurassic age, which are overprinted by a weak foliation. The origin of the weak foliation is still unknown. However, the parallel orientation of the foliation and the Cuisa fault makes a genetic relation likely. The Cuisa Fault is considered to have been active from Late Eocene to Early Miocene as a strike-slip fault (Raasveldt 1956, Macellari 1995; Gómez 2001). The lateral displacement reaches up to 25Km (Alberding 1957; MacDonald 1964; Álvarez 1967, Krause 1971).

During the Miocene (22 Ma) the displacement pattern of the Cuisa Fault changed to normal faulting with a small vertical throw (<200 m) associated with the relative uplift of the southern block (Rollins 1965, Álvarez 1967; Gómez 2001). A reactivation occurred during late Miocene and later times (7-0 Ma), as a prominent set of NW trending faults with dextral kinematics (Renz 1960; Hosie 1994; Gomez 2001).

ANALYTICAL PROCEDURES

Major elements, Cr and Sr concentrations were determined with wavelength dispersive spectrometry using Cameca SX50 electron microprobe (EMS) at the GeoForschungsZentrum Potsdam. The operation conditions are an acceleration voltage of 15 kV and a beam current of 20 nA for whole rock, opaques and silicate phases; respectively 15kV acceleration voltage, 10 nA probe current and 20 µm beam size for carbonates (calcite). Whole rock analyses of the fine-grained marls are determined by ca. 200 point analyses in a 10x10mm area, using a 5 µm beam near to the carbonate veins. BSE pictures are taken by the Jeol 8400 EMS at the University Potsdam.

STRUCTURES AND COMPOSITION

The studied outcrop is composed of very fine-grained silicious marls of the Cuisa formation (Figure 2). Grain-sizes are mostly ≤ 20 µm. Optical microscopy reveals carbonate grains, Fe-oxide- or Fe-hydroxide-coated finer grained particles or particle aggregates, quartz, clay minerals or micas. However, the small grain size anticipates a more precise identification. In order to obtain more details of the petrographic and geochemical composition of the very fine-grained rock analyses by electron microprobe have been performed. Whole rock chemical analyses, yields up to ca. 24 wt.% SiO_2, 32 wt.% CaO and 7.6 wt.% FeO (Table 1). Clay minerals are suggested by Al_2O_3 concentrations of about 4.4 wt.% in the whole rock analyses and by up to 16 wt% Al_2O_3 combined with 6 wt.% K_2O in single points by electron microprobe scans. The marls are transected by numerous grey to black, up to 10cm thick, discrete carbonate veins (Figure 2.a,b), carbonate blebs and veins with angular to rounded clasts of the wall rock and veins with apophyses (Figure 2c). The macro-fabrics of the outcrops and especially the occurrence of clasts in the veins indicate that the dark carbonate veins may be interpreted as deformation-related rocks. In thin section different types of micro-fabrics characterize the dark carbonate veins:

1. Layers of columnar calcite crystals separated by thin sutured zones, showing modal composition similar to the wall rocks (Fig.2.d,e; Table 1). The calcite crystals are up to 0.9 mm in length in "thick" carbonate veins and up to 0.6 mm in thin veins (Figure 2d.). In the latter ones smaller grain sizes (0.08-0.15 mm) occur at the rim of the veins. In the analyzed samples the long axes of calcite have grown perpendicular to the vein margin. Up to six layers, parallel to the vein margins, are located in single vein. In some places fine-grained quartz and rarely small euhedral albite crystallized between the large calcite crystals.

2. A small-scale notch at the boundary between carbonate veins and the marls are filled by rounded, nodular single crystals of calcite (Figure 2e, f). They are embedded in very a fine-grained matrix of

Table 1. Chemical composition of the bulk composition of the wall rocks and minerals. U.d.l: under detection limit. U.d.l. of Al_2O_3 in opaques:ca. 500ppm)

		calcites			opaques		feldspars
	wall rock	vein	embayment (Pst)		embayment		dark veins
		core	nodules	matrix	core	rim	feldspar
SiO_2	22.78	0.01	0.02	0.01			69.38
TiO_2	0.14	0.00	0.00	u.d.l.	0.67	0.27	0.01
Al_2O_3	4.37				u.d.l.	u.d.l.	19.73
FeO	7.66	1.28	1.16	0.18	77,56	80.087	0.07
MgO	0.87	0.43	0.31	0.74	0.60	0.66	
MnO	0.15	0.10	0.04	0.03	0.04	0.04	
CaO	32.28	55.95	56.02	55.88			0.10
Na_2O	0.26						12.32
K2O	0.89						0.01
Cr_2O_3	0.01			0.00	0.01	0.02	
Sr		0.08	0.10	0.18			
Cl	0.05	0.01	u.d.l.	0.03			
SO_4					0.10	0.06	
Sum	68.42	57.77	57.54	56.84	78.98	81.14	101.62

calcite (Figure 2e, f, 3a). The nodules show in some cases embayments resembling magmatic resorption textures (Figure 3b). The nodules are in the range from 0.28-0.23 to 0.32-0.24 mm. The grain sizes of the rim calcites are less than 10 µm. The nodules and the matrix have different characteristics in back-scattered electron images (BSE, Figure 3a), indicating different compositions. Rare plagioclase grains, altered to albite plus epidote, occur between the calcite nodules and in direct contact with the nodules (Figure 3c). In addition, anhedral and slightly zoned opaque or very weakly transparent minerals occur.

The structural differences of the calcites coincide with significant geochemical differences.

The vein-hosted calcites (v) have a similar composition as the nodules (n) with mean FeO_{tot} concentrations of about 1.3 (v) to 1.2 (n) wt.% and have about 0.3 (n) to 0.4 (v) wt.% MgO. Both have Sr concentrations of about 800 – 1,000 ppm (Tab.1). In contrast, the matrix has significant lower FeO_{tot} concentrations (0.18 wt.%,) than the nodules and the calcites of the veins. Furthermore, the matrix has MgO contents of ca. 0.74 wt.%, which is more than two times the concentration of the nodules. Sr concentrations are nearly twice the concentrations of the nodules and vein calcites (Table 1).

The opaque minerals have FeO_{tot} concentrations between 78 wt.% suggesting the presence of FeOOH-minerals like lepidocrocite (γ-FeO(OH)) or a very fine-grained mixture of magnetite and hematite. They have a rim with higher FeO_{tot} and lower TiO_2 concentrations than the core (Table 1).

INTERPRETATION

The veins characterized by the repetition of zones of calcites growing perpendicular to the wall rocks as well as the remnants of small wall rock slices clearly indicate the episodic fracturing and precipitation of carbonates into open spaces during tectonic activity. Such calcite zones were considered to have been formed by a `crack- seal' mechanism, as originally proposed by Ramsay (1980) to explain multiple precipitation and re-cracking episodes

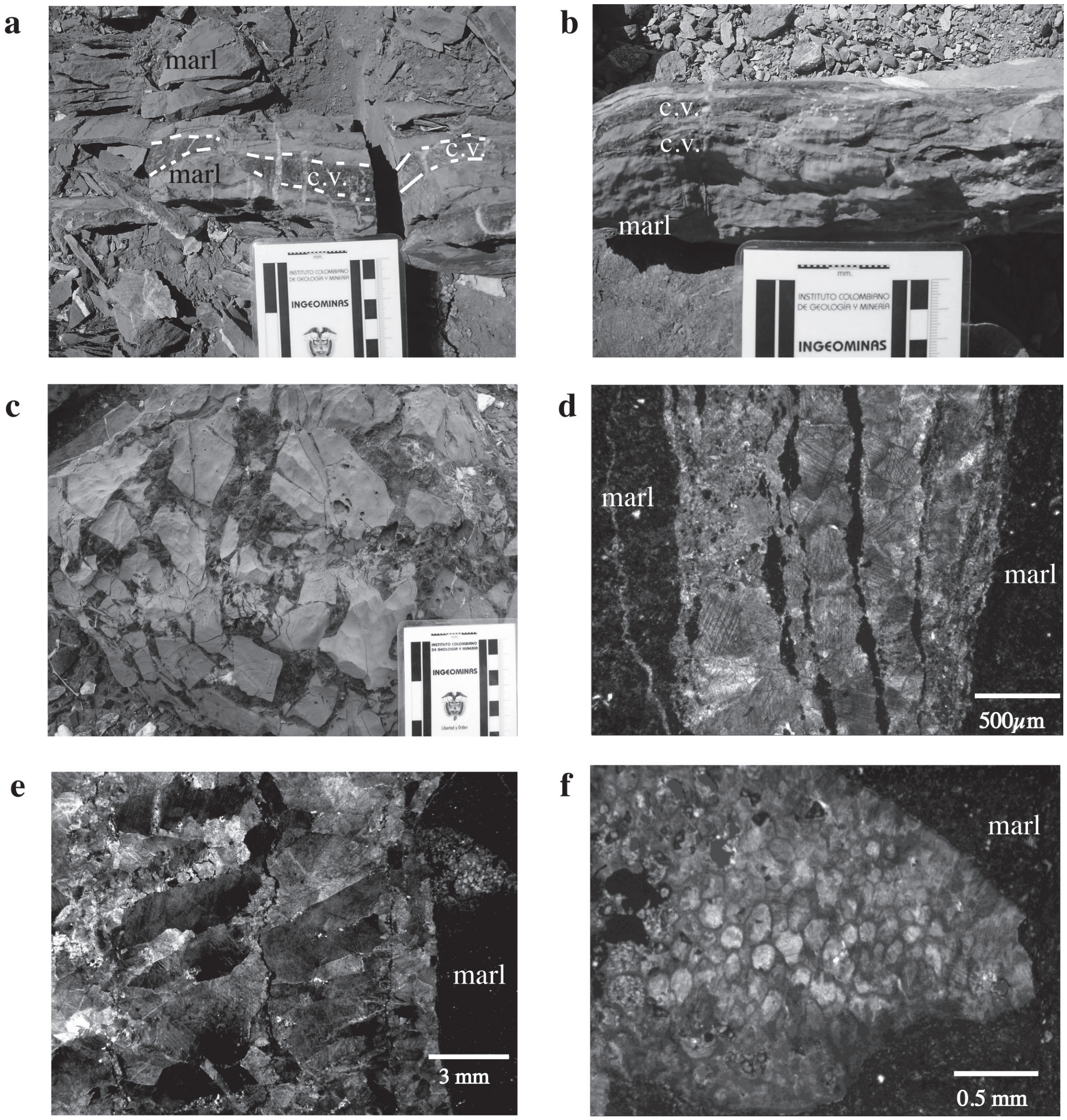

Figure 2 a, b. Carbonate veins (dark, cv), partly deformed and transected by steep and younger carbonate veins (light color). c. Irregular, non-parallel carbonate veins and blebs with angular to rounded clasts of the wall rock. d. Different zones of calcite in carbonate vein with long axes perpendicular to the wall rock. Zones are separated by thin relics of the wall rock (marl). Crossed nicols. e. Different zones of calcite in carbonate vein with long axes perpendicular to the wall rock and a notch in the wall rock with carbonate nodules, fine-grained carbonate matrix and opaques. Crossed nicols. f. Enlargement of notch in e.

in mode I fractures cutting limestones and sandstones with antitaxial fiber growth. Similar calcite crack and seal episodes in dilatational jogs of faults, with a slip component during or before seal, have been discussed e.g. by Davison (1995) and Petit et al. (1999).

However, the notches filled with nodular single crystal calcites or aggregates of "large" calcite crystals in a very fine-grained calcite matrix of significantly different chemical composition has to be explained by a different mode of formation. Two facts, one related to composition and the other to fabrics, are the key to interpret the filling of the notches:

I. The calcite nodules are single crystals or part of groups of large single crystals, partly with embayments, interpreted as corrosion textures formed during frictional melting.

II. The composition of the nodules is very similar to the calcites in the crack-seal zone, whereas the fine-grained calcites in the matrix clearly differ in composition with respect to the nodules as well as to the vein calcites.

Therefore, we suppose the following model for the formation of the nodule-rim association in the notch:

The nodules are relics of formerly greater single crystals or crystal aggregates, originally formed in open spaces like the columnar crystals in the crack-seal zones. After formation in a crack-seal environment, the columnar calcites are fractured by brittle and rapid deformation, as well as rounded by subsequent melting. Brittle deformation forming fine-grained particles with an increased total surface enhances subsequent melting; this is well known from silicate pseudotachylytes in silicate rocks (Hetzel et al. 1996). However, the multiple reactivation and precipitation in the crack-seal veins, post-dating the embayment filling, shows a very limited differences in chemical composition of the newly formed calcites. Therefore, a simple solution and reprecipitation model of the fine-grained carbonates would imply a similar chemical composition of the fine-grained second calcite generation, assuming unchanged pressure-temperature conditions and source rock composition. This suggests that the calcite clasts and the calcites of the crack-and-seal veins geochemically roughly reflect the nearly unchanged low-temperature conditions of the upper crust before and after seismic failure. In contrast, the very fine grain size of calcites of the matrix points to a very rapid crystallization or recrystallization from glass. The MgO-rich composition of the matrix may indicate higher temperature during crystallization or solidification in contrast to the low-temperature and low-Mg calcites in the crack-seal veins. Generally, the concentration of Mg in calcite reflects crystallization temperatures (e.g. Harker and Tuttle 1955; Powell et al. 1984; Anovitz and Essene 1987; Farver and Yund 1996). However, the use of the Mg concentration as a thermometer is based on the calcite-dolomite solvus in thermodynamic equilibrium. Therefore, the use of the thermometer in absence of dolomite is problematic since it provides only minimum temperatures. In the described veins and embayments we cannot prove dolomite. The rough estimate by the Mg in calcite thermometer calibrated by Powell et al. (1984) would result in temperatures about 200°C higher for the matrix (□500°C) than compared to the nodules.

However, the main argument for a pseudotachylyte origin is a structural one that is the preservation of rounded clasts in a fine-grained, chemically different matrix representing a previous melt. Fast crystallization under higher temperatures could be explained by fast cooling of a carbonate melt. The embayments in the clasts are interpreted as resorption phenomenon occurring between melt and solid, similar to those described in silicate systems. It is well described from pseudotachylytes in silicate rocks, too (e.g. Lin 2008). The local and small-volume preservation of the melt in wall rock, notches, besides the coarse-grained calcites, is best explained by a multi-stage evolution (Figure 3d):

1. Tectonically induced extensional cracks at the Cuisa fault are filled by a single phase of calcite growth or by multiple generations of columnar calcites, formed by the crack-seal mechanism, perpendicular to sigma 1 (Figure 3, step I,).

2. During rapid shear after seismic failure the deformation is concentrated along previously formed calcite veins. The energy released is dissipated as heat, activating partial (frictional) melting of the carbonate veins (Figure 3d, step II). The frictional melt contains a large fraction of not molten clasts. The clasts maintain their original chemical composition comparable to the vein calcites. The rare plagioclase grains and the opaques can be interpreted as clasts, too. The increase in FeO in the rim of the opaques is probably due to the higher temperatures leading to dehydration of FeOOH.

3. Rapid cooling (quenching) of the melt, due to extreme temperature contrasts between melts and upper crustal wall rocks forms MgO-rich and FeO-poor carbonate glasses and/or extremely fine-grained carbonate crystals. There is no direct proof of this glass-stage. However, coherently with pseudotachylytes in silicate rocks rapid cooling of melts in upper crustal regions forms glasses. Glass often devitrifies later on (Figure 3, stage II).

4. Later (aseismic) fracturing, multiple cracking, solution and reprecepitation overprint the pre-existing fault zones. Crack-seal involves disruption and solution processes. Therefore, the formerly generated pseudotachylytes are preserved at only few mechanically favored places as notches in the wall rock (Figure 3, stage III).

The lack of restitic parts in the marls, like FeO- and Al_2O_3- rich zones makes an in-situ melting of the marls, as the source for a clast-loaded melt, unlikely.

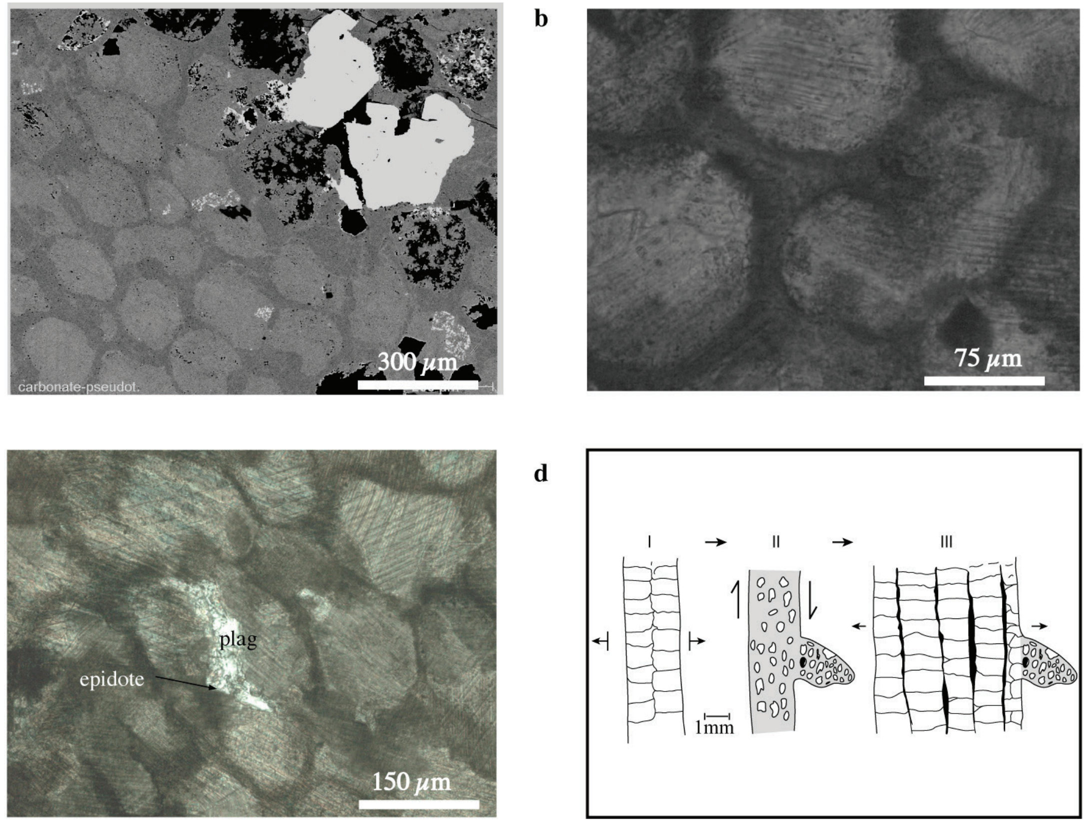

Figure 3 a. Back-scattered (BSE) image of carbonate nodules (light grey) in carbonate matrix (dark grey). The different colors indicate (slightly) different composition. Opaques are white-colored. b. Thin section photomicrograph of calcite nodules with resorption structures (arrow). Plane polarizer. c. Thin section photomicrograph of plagioclase with epidote as alteration product at the grain boundaries between two carbonate nodules. d. Model of the evolution of the studied carbonate pseudotachylyte.

DISCUSSION AND CONCLUSION

At a first view, melting of carbonates during deformation is an unlikely process. Plastic flow and dynamic recrystallization of weak calcite, as a shape-changing process, starts at low strain rates at temperatures above 250°C (Burkhard 1993). However, the framework-structure mineral calcite is relatively strong, following Byerlee's Law (friction coefficient μ = .85, (Morrow et al. 2000). Comparable to qtz-rich rocks, the extreme rapid deformation and specific temperature conditions in seismic zones do not favor crystal-plastic processes or chemical reactions like the calcite dissociation. The extreme physical environment favours the non-eutectic (non equilibrium) melting of polyphase rocks or monomineralic aggregates at the specific melting point. The preserved small-scale clast-matrix aggregates reflect original clasts formed through brittle processes with additional melt-enhanced rounding enclosed in fine-grained recrystallized carbonate glass. The high clast/matrix ratio indicates just the start of melting or the loss of melt to injection veins, as often described in silicate pseudotachylytes. Pure $CaCO_3$ melts at temperature conditions of about 1330°C at pressures > 0.04 GPa (Irving and Wyllie 1973). Since the classical experiments of Wyllie and Tuttle (1959, 1960) it is well known that water as an essential constituent lowers the melting temperatures significantly. At 740°C/0.10 GPa the onset of partial melting of $CaCO_3$ is observed. In these conditions only 3 wt. % of water is necessary for 25 % vol. % melt. The temperature estimates of frictional melts in silicate rocks are often significantly higher than 1200°C (e.g. Lin 2008); the studied carbonate example indicates minimum temperature of "only" 740 °C.

We suggest partial frictional melting of coarse-grained carbonate veins during extremely rapid shear, followed by rapid cooling and later devitrification as the most probable process in the described noch. The pseudotachylyte was formed between two phases of crack-seal extensional veins. Consequently, we interpret these structures as pseudotachylytes. The rareness of carbonate pseudotachylytes is probably a problem of conservation (solution and reprecipitation), not of formation.

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