From hydroplastic to brittle deformation: controls on fluid flow in fold and thrust belts. Insights from the Lower Pedraforca thrust sheet (SE Pyrenees)

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Abstract

We present a multidisciplinary study to decipher the controls of deformation on fluid flow regime in fold and thrust belts using the Lower Pedraforca thrust sheet in the SE Pyrenees as an example. We integrate field-based and petrographic observations and geochemical and geochronological data to differentiate seven types of fractures, eight types of calcite cement (Cc1 to Cc8) and two sets of stylolites during the deformation stretching the studied thrust sheet.

During syn-sedimentary hydroplastic normal faulting affecting poorly consolidated Upper Cretaceous and Eocene syn-orogenic sediments, calcite cement did not precipitate. During burial, bed-parallel stylolites formed and Cc1 and Cc2 precipitated from formation waters in a closed palaeohydrological system. During the layer-parallel shortening, Cc3 precipitated from formation waters (~+5.4 ‰ VSMOW) with $^{87}Sr/^{86}Sr$ ratios of 0.707922 and at ~70 ºC. Cc4 precipitated from formation waters recording different burial conditions, as the up to 4 ‰ dispersion in $\delta^{18}O$ of this cement suggests. Contrarily, during folding and thrusting, Cc5 to Cc7 precipitated in an open palaeohydrological system. Cc6

precipitated from formation waters (~+5 ‰ VSMOW), with $^{87}Sr/^{86}Sr$ ratios of 0.707817 and at ~75 ºC. These fluids carried hydrocarbons and probably interacted with Upper Triassic evaporites. An $^{87}Sr/^{86}Sr$ ratio of 0.708230 for Cc5 indicates that formation waters also interacted with clays within continental deposits. During this period, stylolites formed in relation to faulting, and previous hydroplastic normal faults reactivated as reverse and strike-slip faults allowing fluid flow. Cc7 precipitated after Cc6, also from fluids in isotopic disequilibrium with their adjacent host rock. The fluid system continued open during the Oligocene, when Cc8 precipitated in normal faults affecting syn-orogenic conglomerates deposited during the reactivation of the Lower Pedraforca thrust sheet.

The influence of deformation on fluid flow observed in the Lower Pedraforca thrust sheet is similar to that observed in other fractured areas worldwide.

Keywords: Hydroplastic and brittle deformation, fluid flow, U-Pb calcite dating, clumped isotopes, fold and thrust belts.

1. Introduction

The study of fracture-filling cement in fold and thrust belts reveals changes in the fluid regime and the evolution of fluid-rock interaction through time (Vandeginste et al., 2007, 2012; Breesch et al., 2009; Beaudoin et al., 2014; Crognier et al., 2018; Cantarero et al., 2018; Cruset et al., 2018). In the shallow crust, brittle deformation is responsible for the formation of fractures (Marrett and Allmendinger, 1990), which act as preferential conduits or seals for the migration of fluids (Missenard et al., 2014; Ogata et al., 2014; Maher et al., 2017). However, the conduit or barrier behaviour is not steady-state and it can evolve through time, especially due to: 1) variations in the stress field, forcing changes in the tectonic regime (Sibson, 1995; Wiprut and Zoback, 2000; Soumaya et al., 2015); 2) the increase of fluid pressure, which can produce seismically-induced slip and/or hydraulic fracturing (Aydin, 2000; Wiprut and Zoback, 2000; Rutqvist et al., 2013); 3) fracture sealing by cement due to fluid regime changes (temperature, pressure, composition; Benedicto et al., 2008; Beaudoin et al., 2014); and 4) a combination of these factors.

The reactivation of faults can increase the heterogeneity of fractured reservoirs and the uncertainty during reservoir analysis (Roure et al., 2005; Casini et al., 2011; Khosravi et al., 2012; Tavani et al., 2015). Moreover, these heterogeneities are also controlled by additional factors such as fault core composition and strain distribution during folding, which also affects fault permeability (Egholm et al., 2000; Dimmen et al., 2017; Watkins et al., 2018). The study of these factors in outcrop analogues is key to mitigate the uncertainties related to the evaluation of fractured reservoirs with bad accessibility and those that are under exploration or production stages.

The southern Pyrenees is an exceptionally well-preserved fold and thrust belt in which the complete sequence of thrust sheets and the age of their related syn-tectonic deposits are well known (e.g., Vergés et al., 2002). In this compressional belt, the relationships between fluid migration and deformation have been studied either in its Palaeozoic basement (McCaig et al., 1995, 2000; Trincal et al., 2017), cover thrust sheets constituted of Mesozoic and Palaeogene rocks (Travé et al., 1997, 1998; Beaudoin et al., 2015; Crognier et al., 2018; Cruset et al., 2018; Lacroix et al., 2014, 2018; Nardini et al., 2019) and in its foreland basin, constituted of Palaeogene rocks (Travé et al., 2000; Cruset et al., 2016). Other studies in the southern Pyrenees report the presence of fractures formed in hydroplastic (Soliva and Benedicto, 2004, 2005; Soliva et al., 2006, 2008) and brittle (Shackleton et al., 2005, 2011; Tavani et al., 2011; Gutmanis et al., 2017) regimes. However, the relationships between fluids and hydroplastic fractures, as well as their evolution through time, have not been studied yet in the southern Pyrenees.

In this contribution, we report a whole history of fluid flow evolution from syn-sedimentary hydroplastic deformation to later brittle fracturing in a section of a fold and thrust belt, which includes reactivation of pre-compressive structures. To deal with the aim of this study, we use the Lower Pedraforca thin-skinned thrust sheet in the SE Pyrenees as an example of a fractured reservoir that increases its heterogeneity during progressive folding. The exceptional outcrop exposures of this thrust sheet allowed to work on three meso-scale (metre-scale) fracture systems that are correlative through time: 1) hydroplastic normal faults (as defined by Petit and Beauchamp (1986) and Petit and Laville (1987); 2) background fracture systems, which consist of stratabound bed-perpendicular veins and bed-parallel slip surfaces; and 3) non-stratabound fracture systems formed of reverse, strike-slip and normal faults. The study of the evolution of these fracture systems is combined with petrographic observations and geochemical data (carbon, oxygen and strontium isotopes, clumped isotopes thermometry, elemental composition and U-Pb geochronology) of fracture-filling calcites, extending the fluid flow history reported previously by Cruset et al. (2018) for the Lower Pedraforca thrust sheet. The results obtained will be compared with other fractured areas worldwide.

2. Geological setting

The Pyrenees (Fig. 1A) formed due to the continental collision that resulted from the partial subduction of the Iberian plate beneath the Eurasian plate from Late Cretaceous to Miocene (Choukroune et al., 1989; Roure et al., 1989; Muñoz, 1992; Vergés et al., 2002). As a result, the previous Mesozoic rift basins were inverted, and an antiformal stack of thrust sheets constituted of basement units (the Axial Zone) developed along the internal zone of the Pyrenean doubly verging orogenic system (Fig. 1B), acting as a boundary between the north and south Pyrenean fold and thrust belts (e.g., Muñoz, 1992; Grool et al., 2018).

The south Pyrenean fold and thrust belt (Fig. 1B, C, and 2A) consists of a piggy-back sequence of south-verging thrusts (e.g., Puigdefàbregas et al., 1992), detached predominantly above Upper Triassic (Séguret, 1972) and Eocene evaporites deposited in the foreland basin (Vergés et al., 1992; Sans et al., 1996). In this work, we study the Lower Pedraforca thrust sheet (Fig. 1C and 2A), which emplaced from Lower to Middle Eocene using a detachment level located in the Upper Triassic Keuper facies

(Puigdefàbregas et al., 1986; Burbank et al., 1992a). The emplacement of this structural unit took place under marine foreland conditions, as attested by the syn-orogenic fan delta conglomerates of Queralt deposited at the thrust front (Vergés, 1993).

The complete stratigraphy of the Lower Pedraforca thrust sheet constitutes a sedimentary wedge of up to 2400 m in the northern imbricate and less than 500 m in the frontalmost thrust nappes (Vergés 1993; Fig. 1C). This stratigraphy ranges in age between the Upper Triassic and the Oligocene and consists of pre- to syn-orogenic sedimentary rocks (Fig. 2B). Pre-compressive stratigraphy consists of evaporites and red clays from the Keuper facies, Jurassic limestones and dolostones from the Bonansa Formation and Coniacian to Lower Santonian limestones from the Sant Corneli Formation (Mey et al., 1968; Simó, 1985; Calvet et al., 1993). Syn-orogenic deposits comprise Late Cretaceous, Eocene and Oligocene detrital rocks. Late Cretaceous rocks comprise upper Santonian to Campanian marine sandstones and limestones from the Vallcarga Formation, Campanian-Maastrichtian coastal deposits of the Areny Formation and Maastrichtian-Thanetian continental deposits from the Garumnian (Moeri, 1977; López-Martínez et al., 1999; Rosell et al., 2001; Oms et al., 2007). Eocene rocks comprise lower Ypresian limestones from the Cadí Formation, the upper Ypresian to Lutetian marine conglomerates of Queralt, and middle Lutetian to Bartonian conglomerates of the Coubet Formation (Solé Sugrañes and Clavell, 1973). Eocene-Oligocene continental conglomerates deposited during the reactivation of the northern margin of the Lower Pedraforca thrust sheet (Vergés, 1993).

3. Methodology

Five localities (Q, G1, PEG, G2 and EST) located in the southern (Q, G1) and the northern (G2, EST) margins and in the internal nappes forming the Lower Pedraforca thrust sheet (PEG) were chosen to study the structural controls on fluid flow during the development of this structure (Fig. 2).

Bedding and fractures were measured in the field, and their crosscutting relationships were recorded. The fracture analysis was carried out using the program Win-Tensor (v5.8.8.) (Delvaux and Sperner, 2003). Restoration of fracture data and associated stress orientations with respect to their adjacent bedding has been done using the same software. Each fracture system is plotted in Lower hemisphere Schmidt stereoplots, and their associated stresses are also calculated with the same software. Additionally, sampling of 58 fracture-filling calcite cement and related host rocks was undertaken for petrographic observations and geochemical analyses.

Petrographic observations of 57 polished thin sections made from six different host rocks and eight types of fracture-filling calcite cement were made using optical and cathodoluminescence microscopy. A CL Technosyn cathodoluminescence device Model 8200 MkII at 15-18 kV operating conditions and 350 μA gun current was used to distinguish the different types of cement.

The U-Pb dating method was applied to determine the absolute timing of fluid migration and fracturing. This method is similar to that previously described by Ring and Gerdes (2016) and Burisch et al. (2017). U-Pb dates were acquired using laser ablation-inductively coupled plasma mass spectrometry (LA-ICPMS) at FIERCE (Frankfurt Isotope and Element Research Center, Goethe Universität), applying a modified method of Gerdes and Zeh (2006, 2009). A ThermoScientific Element XR sector field ICPMS was coupled to a RESOlution 193nm ArF excimer laser (COMpexPro 102) equipped with a two-volume ablation cell (Laurin Technic S155). Samples were ablated in a helium atmosphere (300 mL/min) and mixed in the ablation funnel with 1100 mL/min argon and 5 mL/min nitrogen. Signal strength at the ICP-MS was tuned for maximum sensitivity, whereas keeping the oxide formation (monitored as $^{248}ThO/^{232}Th$) below 0.2% and no fractionation of the Th/U ratio. Static ablation used a spot size of 213 μm and a fluency of about 2 J/cm at 12 Hz. For NIST SRM 614 this yielded a depth penetration of ~0.6 μm/s and an average sensitivity of 380,000 cps/μg for ^{238}U. The detection limit for ^{206}Pb

and ^{238}U was ~0.2 and 0.03 ppb, respectively. Data were acquired in fully automated mode overnight in three sequences of 598 analyses each. Each analysis consisted of 18 s of background acquisition followed by 18 s of sample ablation and 25 s of washout. During 36 s of data acquisition, the signal of ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{232}Th, and ^{238}U was detected by peak jumping in pulse-counting and analog mode with a total integration time of ~0.1s, resulting in 370 mass scans. Prior to analysis, each spot was pre-ablated with 8 laser pulses to remove surface contamination. Soda-lime glass NIST SRM 614 was used as a primary reference together with three carbonate reference materials, which were bracketed in between the analysis of samples (see Table S4 for validation results). Raw data were corrected offline using an in-house VBA spreadsheet program (Gerdes and Zeh, 2006, 2009). Following background correction, outliers (±2σ) were rejected based on the time-resolved $^{207}Pb/^{206}Pb$ and $^{206}Pb/^{238}U$ ratios. The mean $^{207}Pb/^{206}Pb$ ratio of each analysis was corrected for mass bias 0.3% and the $^{206}Pb/^{238}U$ ratio for inter-element fractionation (~5%), including drift over the sequence time, using SRM 614. Due to the carbonate matrix, additional offset factors were applied (sequence 1: 1.06, sequence 2: 0.96 and sequence 3: 1.10), which were determined using WC-1 carbonate reference material (Roberts et al., 2017). The $^{206}Pb/^{238}U$ fractionation during 20s depth profiling was estimated to be 3%, based on the common Pb corrected WC-1 analyses, and was applied as an external correction to all carbonate analyses. Uncertainties were calculated by quadratic addition of the standard deviation of the mean of the considered isotopic ratios, the counting statistic uncertainties of each isotope, the uncertainty of the primary reference material after drift correction, and the decay constants uncertainties. The mean square of weighted deviates (MSWD) for the WC-1 lower intercept age of each analytical session was about 0.52 to 1.50. Thus, no carbonate matrix-related excess of variance was included in the uncertainty propagation. Reference material ASH15 (3.085 ± 0.044 and 3.005 ± 0.026 Ma; Vaks et al., 2003) was measured. In addition, a stromatolitic limestone from the Cambrian-Precambrian boundary in South-Namibia (here called NAMA) was analysed, and used as a secondary in-house RM for quality control (obtained ages agree with the U/Pb zircon age of 540.1 ± 0.1 Ma from the directly overlying ash layer, Spitskopf formation; Linnemann et al. 2018). Altogether the data imply an accuracy and repeatability of the method of ~2%. The analytical results are presented in Tables S3 and S4. Data were plotted in Tera-Wasserburg diagrams and ages were calculated as lower intercepts using Isoplot 3.71 (Ludwig, 2009). All uncertainties are reported at the 2σ level.

For carbon and oxygen stable isotope analysis of calcite cement and carbonate host rocks, a 400 µm-thick dental drill was employed to extract 60 ± 10 µg of carbonate powder from trims. The calcite powder was reacted with 100% phosphoric acid for 2 minutes at 70 °C. The resultant CO_2 was analysed using an automated Kiel Carbonate Device attached to a Thermal Ionization Mass Spectrometer Thermo Electron (Finnigan) MAT-252 following the method of McCrea (1950). The International Standard NBS-18 and the internal standard RC-1, traceable to the International Standard NBS-19, were used for calibration. The results were corrected using the standard technique from Craig and Gordon (1965) and Claypool et al. (1980), expressed in ‰ with respect to the VPDB (Vienna Pee Dee Belemnite) standard. Standard deviation is ±0.02 ‰ for $\delta^{13}C$ and ± 0.05 ‰ for $\delta^{18}O$.

Clumped isotope thermometry was applied to two fracture-filling calcites to calculate temperatures of cement precipitation as well as the $\delta^{18}O$ values of the fluids from which calcite cement precipitated. The two analysed samples (Q2 and Q24) are representative of calcite cement Cc3 and Cc6. To analyse them, 2–3 mg aliquots from each cement were measured with the Imperial Batch Extraction system (IBEX), an automated line developed at Imperial College of London. Each sample was dropped in 105% phosphoric acid at 90 ºC and reacted for 30 min. The reactant CO_2 was separated using a poropak-Q column and transferred into the elbows of a Thermo Scientific MAT 253 mass spectrometer (Thermo Fisher GmbH, Bremen, Germany). The characterization of a replicate consisted of 8 acquisitions in dual inlet mode with 7 cycles per acquisition. The post-acquisition processing was completed with a software for clumped isotope analysis named Easotope (John and Bowen, 2016). Δ_{47} values were corrected for isotope fractionation during phosphoric acid digestion employing a phosphoric acid correction of 0.069 ‰ at 90 ºC for calcite (Guo et al., 2009). The data were also corrected for non-linearity applying the heated gas method (Huntington et al., 2009) and projected into the absolute reference frame of Dennis et al. (2011). Carbonate $\delta^{18}O$ values were calculated with the acid fractionation factors of Kim et al. (1997). Samples were measured three times and the average result was converted to temperatures using the calibration method of Davies and John, (2019). Calculated $\delta^{18}O$ values of the fluid are expressed in ‰ with respect to the VSMOW standard (Vienna Standard Mean Ocean Water).

One sample of host limestones and three types of fracture-filling calcites were analysed for $^{87}Sr/^{86}Sr$ isotopes. 100% carbonate samples are dissolved in 5 ml of 10% acetic acid and introduced in an ultrasonic bath for 15 minutes. After this time, samples are dried after being centrifuged during 10 min at 4000 rpm. The remaining sample is digested in 1 ml of 3 M HNO_3 and dried. Finally, the resultant product is digested again in 3 ml of 3 M HNO_3 and introduced in chromatographic columns. The chromatographic separation of Sr was done using an extraction resin type SrResinTM (Trisken International) (crown-ether (4.4’ (5’)-di-t-butylcyclohexano-18-crown-6). The Sr is recovered with HNO_3 0.05 M as eluent. The fraction where Sr is concentrated is dried, charged on a Re single filament with 1 µl of H_3PO_4 1 M and 2 µl of Ta_2O_5 and analysed on a TIMS-Phoenix mass spectrometer. The method of acquisition of data consists of dynamic multicollection during 10 blocks of 16 cycles each one, with a beam intensity for the ^{88}Sr mass of 3 V. Analyses were corrected for possible interferences of ^{87}Rb. The $^{87}Sr/^{86}Sr$ ratios are normalized with respect to the measured mean value of the ratio $^{86}Sr/^{88}Sr$=0.1194 in order to correct possible mass fractionation during filament charge and instrumental analyses. During sample analysis, the isotopic standard NBS-987 was measured seven times obtaining a mean value of 0.710247 and a standard deviation 2σ of 0.000008.

These values have been used for the correction of the analysed values in the samples. The precision of the analytical standard error or internal precision is 0.000009. The analytical errors referred to 2σ confidence levels in the $^{87}Sr/^{86}Sr$ ratio are 0.000003.

Carbon-coated polished thin sections were used to analyse major, minor, and trace element concentrations on a CAMECA SX-50 electron microprobe. The microprobe was operated using 20 kV of excitation potential, 15 nA of current intensity and a beam diameter of 10 µm. Analytical standards included natural silicates, carbonates and oxides as follows: calcite (Ca), dolomite (Mg), Fe_2O_3 (Fe), rhodonite (Mn) and Celestite (Sr). The detection limits were 135 ppm for Mn, 127 ppm for Fe, 101 ppm for Ca, 146 ppm for Na, 180 ppm for Mg, and 390 ppm for Sr. Precision on major element analyses averaged 0.64% standard error at 2σ confidence levels.

4. Results

4.1. Locality description

The five studied localities (Q, G1, PEG, G2 and EST, from south to north) belong to the thrust system in the Lower Pedraforca thrust sheet (Fig. 1B and 2A). Fracture data interpretation and sampling were carried out in representative localities of each exposed thrust nappe.

The locality Q corresponds to the frontal part of the Lower Pedraforca thrust sheet, one km to the north of Berga city (Fig. 2A). The general structure of this locality consists of three imbricated thrust sheets constituted by the Upper Cretaceous Areny Formation and the Palaeocene Garumnian red beds (Fig. 1C). To the south, the front of the thrust system is unconformably overlain by the upper Ypresian to lower Lutetian conglomerates of Queralt, which define a growth strata. The syn-tectonic conglomerates of Queralt are unconformably overlain by the conglomerates of the Coubet Formation.

Localities G1 and PEG are located 3 km to the N and 10 km to the NW from Berga city, along the frontal region of the Lower Pedraforca thrust sheet (Fig. 1C and 2A). In locality

G1, the hangingwall of the thrust is constituted of the Upper Triassic Keuper facies, which gradually change upwards to the Lower Jurassic Bonansa Formation. These are unconformably overlain by the Upper Cretaceous Vallcarga Formation. The footwall of the thrust in locality G1 is formed by the Upper Cretaceous Vallcarga Formation. In the locality PEG, a thrust fault cuts across Palaeocene Garumnian limestones in both hangingwall and footwall (Fig. 1C and 2A).

The locality G2 is located in the northernmost part of the Lower Pedraforca thrust sheet, 1 km to the S of Bagà village (Fig. 1 and 2A). In this area the entire Lower Pedraforca thrust sheet is folded, during the younger emplacement of the Cadí thrust sheet, and dips south forming the northern flank of the Ripoll syncline (Fig. 1C). The locality G2 is located along the basal thrust of the Lower Pedraforca limiting with the underlying Cadí thrust sheet. The hangingwall of the basal thrust is formed by Upper Triassic Keuper facies overlain by Lower Jurassic limestones, whereas the footwall is constituted by middle Eocene Campdevànol Formation.

Finally, the locality EST is located 3 km to the NE of Gósol village (Fig. 1 and 2A). It consists of Oligocene conglomerates deposited along the northern sector of the Lower Pedraforca thrust sheet once eroded and latter thrusted to north during the thrust reactivation during progressive folding. These conglomerates are unconformably overlying the middle Eocene Armàncies Formation, belonging to the Cadí thrust sheet (Fig. 2B).

4.2. Host rocks

The Lower Pedraforca thrust sheet is constituted by a thick Jurassic, Upper Cretaceous, Palaeocene, Eocene, and Oligocene sedimentary successions.

The Jurassic Bonansa Formation consists of mudstones without skeletal components and with millimetre-thick sub-horizontal lamination. The Upper Cretaceous host rocks include the marine Vallcarga and Areny Formations. The Vallcarga Formation is formed of grainstones with up to 10% of detrital quartz. Microfauna includes *Orbitoides* and *Hemicyclammina,* indicating a late Santonian age (Pons and Caus, 1996). The Areny Formation is mainly composed of grainstones of peloids, miliolids and bryozoan and echinoid fragments and changes northwards to wackestones of gastropods and algae and scleractinian coral fragments. The Palaeocene Garumnian facies consist of continental detrital and carbonate rocks. Detrital rocks include red clays with orange and purple colorations, with abundant Microcodium that occasionally replaces the whole rock and suffer dissolution processes, as well as fine-grained sandstones formed of quartz (~10%) and carbonate clasts (~80-90%). These sandstones have an excellent sorting and are well-cemented. Regarding the Garumnian carbonate deposits, they are grey-brown mudstones and wackestones with charophytes. Middle Eocene syn-orogenic sediments deposited in the Lower Pedraforca thrust front are formed of well-cemented, medium-grained grey sandstones with a good sorting. Detrital components consist of Microcodium fragments from the Garumnian (~5-10%), limestone clasts (~70%), quartz (~10%), and Nummulites (~10%). Oligocene conglomerates are formed of centimetre- to metre-scale carbonate clasts supported by a matrix constituted of well-cemented and coarse-grained sandstones with a good sorting. Detrital components of the matrix are lithics derived from carbonates (>60%) and metamorphic rocks and quartz.

4.3. Fracture analysis

The Lower Pedraforca thrust sheet was affected by up to seven fracture sets (F1 to F7) summarized in chronological order in Fig. 3. Fracture classification has been done according to the type of fracture, crosscutting relationships, angular relationships with bedding and U-Pb dating of fracture-filling calcite cement (U-Pb dates will be described in detail in the geochemistry section).

After their restoration with respect to bedding, fracture set F1 consists of E-W stratabound normal faults affecting the Upper Cretaceous Areny Formation and Middle Eocene syn-orogenic sediments deposited in the thrust front (Fig. 3). These faults dip

45º to 80º either towards the north or south, have a length of up to 2 m with millimetre thickness and they show displacements up to 10 cm and soft, undulated grooves and striae sets (Fig. 4A and B). These features are indicative of hydroplastic deformation as defined by Petit and Beauchamp (1986) and Petit and Laville (1987) and are similar to those faults described in other areas of the Lower Pedraforca thrust sheet by Soliva and Benedicto (2004, 2005), Soliva et al. (2006, 2008). Calculated stress orientations indicate an N-S extension (Fig. 3). These fractures do not have calcite cement, although occasionally calcite veins with reverse striae sets have been observed, resulted from a later reactivation. Fracture set F1 has been observed in locality Q.

The second fracture set (F2) consists of bed-parallel slip surfaces formed occasionally at the contact between clays and more competent layers of the Areny Formation and Garumnian facies in locality Q (Figs. 3 and 4C). F2 fractures have a thickness of up to 0.5 cm and a length of a few centimetres.

Fracture set F3 consists of N-S, NNW-SSE, and NNE-SSW bed-perpendicular veins that often display en-échelon arrays (Fig. 3 and 4D and E). F3 is stratabound and show sub-vertical dips after restoring bedding to the horizontal. F3 shows openings of up to 2 cm and lengths of up to 30 cm. These fractures affect the Upper Cretaceous Areny Formation, the Palaeocene Garumnian facies and the Middle Eocene syn-orogenic sediments. Calculated stress orientations for F3 indicate a N-S strike-slip motion (Fig. 3). F3 has only been observed in locality Q.

Fracture set F4 is constituted of E-W, NNE-SSW, and NNW-SSE reverse fault zones and their associate veins affecting the Jurassic and Upper Cretaceous Bonansa, Areny and Vallcarga Formations (Fig. 3 and 5A). These faults dip between 15º and 75º towards the N and NW, are not stratabound, have a constant orientation regardless of bed dips, are filled with calcite and occasionally contain hydrocarbon seeps. Fault cores are formed of thick S-C zones with the development of pressure-solution cleavage (Fig. 5B) or thin discrete planes formed of up to 2 cm-thick shear veins. F4 shows lengths from a few centimetres to tens of meters. However, in thrust faults in which thick units of Upper Triassic evaporites act as a detachment, hydraulic fracturing is observed within the most competent limestones of the footwall (Fig. 5C). These fractured areas extend tens of meters away from the fault core. The calculated stress orientation for F4 indicates an N-S (localities G1, PEG and G2) and NW-SE (locality Q) reverse motion (Fig. 3). In locality Q, some of the reserve faults formed due to the reactivation of hydroplastic normal faults F1.

The fifth fracture set (F5) consists of N-S, NW-SE, NNW-SSE, and NE-SW strike-slip faults dipping between 45º and 90º that affect Upper Triassic, Jurassic, Upper Cretaceous, and Palaeocene rocks. Fault planes are discrete, formed of shear veins with a thickness of up to 2 cm and show striae sets indicating dextral and sinistral motion (Fig. 3 and 5D). F5 faults have lengths of up to 5 metres. Calculated stress orientations for F5 indicate NW-SE, N-S, and NE-SW strike-slip motion in localities Q, G1, G2, and EST, respectively (Fig. 3). Like F4, strike-slip faults have a constant angle regardless of bed dip.

Fractures F6 consists of 1 cm-wide and up to 5 cm-long N-S sub-vertical veins observed occasionally in thrust fault zones of the locality G1 (Fig. 3). These fractures affect folded Jurassic strata at a constant angle, indicating their late-folding formation. The stress orientation for F6 indicates NNW-SSE strike-slip motion (Fig. 3).

Fracture set F7 consists of normal faults affecting the Oligocene conglomerates related to the reactivation of the Lower Pedraforca thrust sheet studied in locality EST (Fig. 5E). These faults have an NNW-SSE strike, a dip between 60º and 80º either towards the SW and NE and show fault displacements from 1 to 2 m (Fig. 3). Fault planes are discrete, formed of up to 2 cm-thick extensional veins, and show lengths of up to 20 metres. Calculated stress orientations for F7 indicate an ENE-WSW extension.

4.4. Petrography

From petrographic observations and U-Pb geochronology, eight types of calcite cement filling fracture, vug and moldic porosity (Cc1 to Cc8 in chronological order) and two sets of stylolites (St1 and St2) have been identified in the Lower Pedraforca thrust sheet. Their main features and crosscutting relationships are summarized in Figs. 3, 6, and 7. Some of the collected samples are located in Fig. 5 for reference.

Calcite cement Cc1 and Cc2 are not fracture-related. Cc1 consists of non-luminescent microsparite precipitated in the intergranular and moldic porosity of grainstones from the Areny and Vallcarga Formations in localities Q and G1, respectively (Fig. 6A and B). Cc2 consists of blocky calcite crystals of more than 1 mm in size. This cement is non-luminescent and precipitated in vug porosity affecting the Garumnian facies in locality Q and in the intergranular porosity of breccias within the Jurassic limestones in locality G1 (Fig. 7). Cc3 precipitated in F2 and F3 fractures and vug porosity postdating Cc1 and Cc2 in locality Q (Fig. 6A, B, and 7). This cement is orange luminescent and consists of blocky calcite crystals ranging from 100 to 300 μm and fibrous calcite crystals parallel to fracture walls varying from 200 μm to 2 mm in length. Blocky crystals have been observed filling rhomb-shaped veinlets formed by crack-seal mechanism in F2 fractures. Cc4 consists of blocky and bladed crystals ranging between 250 μm and 2 mm and between 300 μm and 1 mm in length, respectively. This cement is dull-orange to orange luminescent and precipitated in reactivated F1 fractures and in F3 veins affecting Eocene syn-orogenic sediments in locality Q (Fig. 7). Cc5 consists of sparite crystals ranging from 100 to 700 μm. This cement is zoned, from non-luminescent to dull orange and precipitated in vug porosities within the Areny Formation and in some F4 fractures postdating the previous cement in locality Q (Fig. 6A and B). Cc6 consists of blocky microsparite and from 200 μm to 2 mm fibrous crystals arranged parallel and oblique to fracture walls. Blocky sparite has been also observed filling rhomb-shaped veinlets formed by crack-seal mechanism (Fig. 6C and D). Cc6 is dull-brown luminescent and precipitated in vug porosities within the Areny Formation and in F4 and F5 fractures postdating Cc2 and Cc5 (Fig. 7). Cc6 has been observed in localities Q, G1, G2, and PEG. Cc7 consists of locally zoned blocky calcite crystals ranging from 100 µm to 1mm and up to 1 mm fibrous crystals arranged perpendicular to fracture walls (Fig.7). This cement is dull to bright orange and precipitated in F6 fractures. Cc7 has only been observed in locality G1. Calcite cement Cc8 consists of blocky crystals ranging from 500 µm to more than 2 mm in size and shows orange luminescence (Fig. 6E and F). Cc8 has been only observed within normal faults F7 in locality EST.

Stylolites St1 consist of a set of bed-parallel stylolites affecting preferentially mudstones from the Jurassic Bonansa Formation and the Palaeocene Garumnian (Fig. 7). St1 are postdated by Cc3 precipitated in F3 veins and have been observed in Q, G1 and G2 localities (Fig. 3). St2 stylolites are arranged both parallel and perpendicular to the walls of F4 and F5 fractures containing Cc6. St2 stylolites occasionally affect internally Cc6 and occur at the contacts between this cement and its adjacent carbonate host rocks (Figs. 3 and 7). Close to F4 fractures, host carbonates display stylobreccia fabrics in Garumnian mudstones from locality PEG. Crosscutting relationships with Cc7 have not been observed. St2 stylolites have been observed in localities Q, G1, G2 and PEG.

4.5. Geochemistry

4.5.1. U-Pb geochronology

U-Pb dating was applied successfully to calcite cement Cc3, Cc4, Cc6, Cc7, and Cc8. The results are presented in Table 1 and Fig. 3. Concordia graphs and analytical data are presented in Table S1 and Fig. S1 from supplementary material, respectively.

Calcite cement Cc3, Cc4, Cc6, and Cc7 yielded Lutetian ages. For Cc3, dates of 47.3 ± 1 and 45.7 ± 1.9 Ma were obtained. However, the youngest date has a mean squared weighted deviate (MSWD) higher than 2, indicating either a mixing of dates, an underestimated analytical error, minor open-system behaviour, or an incomplete initial equilibration of the Pb isotopes (Rasbury and Cole, 2009). Consequently, this date must be interpreted with some caution. Cc4 has U-Pb dates of 47.9 ± 1.3 and 44.8 ± 1.4 Ma. For Cc6, U-Pb dates of 47.2 ± 0.7 Ma and 45.1 ± 1.2 were obtained, whereas Cc7 yielded two younger dates of 42.9 ± 0.9 and 42.3 ± 0.8 Ma. Finally, for Cc8, an Oligocene U-Pb date of 30.2 ± 2 Ma was obtained.

4.5.2. Carbon and oxygen stable isotopes

The carbon and oxygen stable isotopic composition of carbonate host rocks and calcite cement within the Lower Pedraforca thrust sheet is presented in Fig. 8A and Table S2. The comparison between $\delta^{18}O$ of the sampled calcite cement and their adjacent host carbonates is shown in Fig. 8B.

Lower Jurassic marine limestones have $\delta^{13}C$ ranging from -6.06 to +4 ‰ VPDB and $\delta^{18}O$ between -5.2 and -3.6 ‰ VPDB (Fig. 8A). Marine carbonates from the Upper Cretaceous Vallcarga Formation have values between +2.1 and +2.5 ‰ VPDB and $\delta^{18}O$ between -4.1 and -3.1 ‰ VPDB (Fig. 8A). Marine carbonates from the Upper Cretaceous Areny Formation have $\delta^{13}C$ between +1.5 and +1.7 ‰ VPDB and $\delta^{18}O$ between -4.5 and -3.2 ‰ VPDB (Fig. 8). Palaeocene palustrine limestones have $\delta^{13}C$ between -17.5 and -3.7 ‰ VPDB and $\delta^{18}O$ between -8.2 and -4.8 ‰ VPDB (Fig. 8A). A carbonate clast from Oligocene conglomerates has a $\delta^{13}C$ of +1.1 ‰ VPDB and a $\delta^{18}O$ of -2.8 ‰ VPDB (Fig. 8A).

Calcite cement Cc1 to Cc5 show $\delta^{13}C$ and $\delta^{18}O$ values similar to their adjacent host rocks (Fig. 8B). Cc1 has $\delta^{13}C$ of +1.5 ‰ VPDB and $\delta^{18}O$ of -5.2 ‰ VPDB (Fig. 8A). Cc2 has $\delta^{13}C$ values between -10.1 and -6.6 ‰ VPDB and $\delta^{18}O$ values between -6.5 and -5 ‰ VPDB (Fig. 8A). For Cc3, the $\delta^{13}C$ ranges between -10.8 and -0.4 ‰ VPDB and the $\delta^{18}O$ ranges between -6.4 and -3.9 ‰ VPDB (Fig. 8A). Cc4 has $\delta^{13}C$ values between -5.9 and -3.7 ‰ VPDB and $\delta^{18}O$ between -6.9 and -2.6 ‰ VPDB and Cc5 has $\delta^{13}C$ values between +0.8 and +1.6 ‰ VPDB and $\delta^{18}O$ ranging between -5.7 and -4.4 ‰ VPDB (Fig. 8A).

Calcite cement Cc6 to Cc8 show depleted $\delta^{18}O$ values with respect their adjacent host rocks (Fig. 8B). For Cc6, the $\delta^{13}C$ ranges between -8.9 and +3.7 ‰ VPDB and the $\delta^{18}O$ between -10.7 and -5.8 ‰ VPDB (Fig.8A). Cc7 has $\delta^{13}C$ values between -1.73 and -0.94 ‰ VPDB and $\delta^{18}O$ ranging between -11.3 and -9.58 ‰ VPDB (Fig. 8A). The $\delta^{13}C$ for Cc8 ranges between -0.3 and -0.2 ‰ VPDB and the $\delta^{18}O$ between -7.3 and -6.2 ‰ VPDB (Fig.8A).

4.5.3. Clumped isotopes thermometry

For this study, clumped isotopes thermometry has been applied to calcite cement Cc3 and Cc6. The results are presented in a $\delta^{18}O_{fluid}$ vs clumped temperature cross-plot (Fig. 9) and in Table 2. $\delta^{18}O_{fluid}$ in ‰ VSMOW of fluids are calculated from clumped temperatures using the equation of Friedman and O'Neil (1977).

For Cc3, the Δ_{47} is 0.579 ± 0.011 ‰, which translates into a temperature of 69.1 ± 5.3 ºC and a $\delta^{18}O_{fluid}$ of +5.4 ± 0.9 ‰ VSMOW. The analysed Δ_{47} for Cc6 is 0.579 ± 0.008 ‰, which translates into a temperature of 74.2 ± 4 ºC and a $\delta^{18}O_{fluid}$ of +5.1 ± 0.7 ‰ VSMOW.

4.5.4. Strontium isotopes

The Areny Formation limestone has an $^{87}Sr/^{86}Sr$ ratio of 0.707841 (Fig.9, Table S3). Only calcite cement Cc3, Cc5, and Cc6 could be sampled, obtaining $^{87}Sr/^{86}Sr$ ratios of 0.707922, 0.708230, and 0.707817, respectively (Fig.10, Table S3).

4.5.5. Elemental composition

The Fe, Mg, Sr, and Mn contents and Ca/Fe and Mg/Ca molar ratios of calcite cement Cc1, Cc3, Cc4, Cc5, and Cc6 are presented in table S4.

The elemental composition of calcite cement Cc1 shows values ranging from 172 to 1940 ppm in Fe and from 1096 to 6925 ppm in Mg, Sr, and Mn contents range from below the detection limit to 3592 and 361 ppm, respectively. Calcite cement Cc3 has values ranging from below the detection limit to 548 ppm in Fe and from 289 to 4169 ppm in Mg. The Sr and Mn contents range from below the detection limit to 879 and 477 ppm, respectively. In calcite cement Cc4, the Fe content is below the detection limit, whereas Mg shows values ranging from 801 to 4560 ppm. The Sr and Mn contents range from below the detection limit to 275 and 384 ppm, respectively. For calcite cement Cc5, Mg content ranges from 672 to 2765 ppm and the Fe, Sr and Mn contents range from below the detection limit to 3028, 1851, and 365 ppm, respectively. The Mg content of calcite cement Cc6 range from 679 to 4353 ppm whereas its Fe, Sr and Mn contents range from below the detection limit to 3021, 656, and 362 ppm, respectively.

The elemental composition of cement Cc1, Cc3, Cc4, Cc5 and Cc6 shows a good Mg/Fe and Mn/Fe correlation and a bad correlation with the Sr content. The distribution of the Mg/Fe and Mn/Fe results shows two different fields (Fig. 11A and B). The first field (light grey) includes calcite cement Cc1 and Cc3 and shows a wide range of Mg and Mn content and narrow range of Fe content, whereas the second one (dark grey) includes cement Cc5 and Cc6 and shows a wide range of Fe content and narrow range of Mg and Mn content.

Although the elemental composition in natural carbonates does not always reflect equilibrium partitioning (Reeder and Grams, 1987; Paquette and Reeder, 1995), precipitation in equilibrium is assumed in this study to differentiate between different types of fluids from which the studied calcites precipitated. Thus, molar ratios between Ca and Fe, Sr, Mn and Mg were calculated for Cc1, Cc3, Cc4, Cc5, and Cc6 since their values yield an estimation of the compositions of the former fluid (Table 3). Molar ratios were calculated using the formula of McIntire (1963) and using K_{Mg}=0.097 at 70 ºC (Katz, 1973), K_{Fe}=5 at 25 ºC (Tucker and Wright, 1990), K_{Mn}=8 at 25º C (Lorens, 1981), K_{Sr}=0.08 at 100ºC (Kinsman, 1969). The Ca/Fe molar ratio of cement Cc1, Cc3, Cc5 and Cc6 ranges from 1390 to 15903, from 4963 to 19934, from 836 to 6993 and from 880 to 3912, respectively. The Mg/Ca molar ratio ranges from 0.047 to 0.304 for Cc1, from 0.069 to 0.18 for Cc3, from 0.034 to 0.197 for Cc4, from 0.03 to 0.121 for Cc5 and from 0.044 to 0.195 for Cc6. The Ca/Fe and Mg/Ca ratios are plotted in Fig. 11C. The Sr/Ca molar ratios of cement Cc1, Cc3, Cc4, Cc5 and Cc6 range from 0.006 to 0.052, from 0.006 to 0.013, from 0.007 to 0.02, from 0.0052 to 0.027 and from 0.006 to 0.019, respectively. The Mn/Ca ratios range from 0.000032 to 0.000085 for Cc1, from 0.000032 to 0.00011 for Cc3, from 0.000033 to 0.000091 for Cc4, from 0.00025 to 0.000086 for Cc5 and from 0.000023 to 0.000083 for Cc6.

5. Discussion

5.1. Timing of fracture development

The sequence of fractures F1 to F7 documented in this work characterizes the evolution of deformation of the Lower Pedraforca thrust sheet.

The hydroplastic behaviour of F1 normal faults indicate that they were formed when the sediments were still poorly consolidated (Petit and Beauchamp,1986; Petit and Laville, 1987) and therefore, at shallow depths soon after deposition of the Upper Cretaceous Areny Formation and Middle Eocene syn-orogenic sediments. Similar fracture patterns also affecting the Areny Formation have been observed in other areas of the Lower Pedraforca thrust sheet (Soliva and Benedicto, 2004, 2005; Soliva et al., 2006, 2008) (Fig. 2A).

Fractures F2, F3, F4 and F6 have been dated using U-Pb geochronology of calcite cement Cc3, Cc4, Cc6 and Cc7. The obtained ages (from 47.9 ± 1.3 Ma to 42.3 ± 0.8 Ma) indicate that these fractures formed during the emplacement of the Lower Pedraforca thrust sheet during the Lutetian. Furthermore, crosscutting relationships between fractures and bedding allow differentiating stages of deformation during this emplacement. Thus, fracture systems F2 and F3 arranged parallel and perpendicular to bedding, respectively, probably formed at the same stage of deformation since they both contain calcite cement Cc3 (from 47.3 ± 1 Ma to 45.7 ± 1.9 Ma). These fracture systems formed during layer-parallel shortening, and are associated to the first stages of compression in many fold and thrust belts (Casini et al., 2011; Tavani et al., 2015). Fracture systems F4, F5, and F6 have a constant orientation regardless of the beds dip, indicating that they formed during the main or late stages of folding, once strata were already tilted (Casini et al., 2011). Considering crosscutting relationships between the different types of calcite cement (Fig. 7), F4 containing Cc5 probably formed prior to F5 containing Cc6. Contrarily, F4 containing Cc6 and F5 formed at the same time since they contain the same type of calcite cement (from 47.2 ± 0.7 Ma to 45.1 ± 1.2 Ma). The presence in the thrust front of hydroplastic normal faults F1 with Cc6 and striae sets showing a reverse motion indicate that they were reactivated during this stage. This reactivation has also been observed in other areas of the Lower Pedraforca thrust sheet (Fig. 2A), where they show oblique and strike-slip striae sets (Soliva and Benedicto, 2004, 2005). F1 hydroplastic normal faults were reactivated probably to accommodate tilting and changes in the orientation during folding due to a tectonically-induced fluid pressure increase or because they represent a weak surface that facilitates reactivation (Letouzey et al., 1990; Sibson, 1995; Aydin, 2000; Wiprut and Zoback, 2000; Chi et al., 2012; Cobbold et al., 2013; Rutqvist et al., 2013; Soumaya et al., 2015; Wisseall et al., 2018). The presence of hydraulic breccias in thrust fault zones and normal faults tilted to low angles, or 0º, can be accounted for by a combination of both processes. U-Pb dates of 42.9 ± 0.9 Ma and 42.3 ± 0.8 Ma obtained for calcite cement Cc7 in fractures F6 reveal that these fractures formed after F4 and F5.

Normal faults F7 affect well-cemented Eocene-Oligocene conglomerates. Their NNW-SSE orientation is not consistent with the E-W trend of the main south Pyrenean structures (Vergés and Muñoz, 1990). The U-Pb age obtained for cement Cc8 precipitated in F7 (30.2 ± 2 Ma) suggests that their formation could be related to an E-W local extension affecting the Eocene-Oligocene conglomerates, which were deposited during the reactivation of the Lower Pedraforca thrust sheet (Vergés, 1993).

5.2. Evolution of the palaeohydrological system

The evolution of the palaeohydrological system through time within the Lower Pedraforca thrust sheet is inferred from the geochemical data of calcite cement Cc1 to Cc8.

The $\delta^{13}C$ of most of the studied calcite cement is similar to their adjacent host rocks, indicating a high interaction between fluids and host rocks (Fig. 8). This similarity is not observed for Cc2 in locality G1, thus indicating the influence of soil-derived CO_2 or oxidation of organic matter within the host rocks (Irwin et al., 1977; Cerling et al., 1989). In the same locality, cement Cc6 postdating Cc2 is also in disequilibrium with their adjacent host rock whereas it has similar $\delta^{13}C$ to that of Cc2 (Fig. 8). This could indicate that the $\delta^{13}C$ of fluids from which Cc6 precipitated locally reequilibrated with Cc2 instead of with the host carbonates. The $\delta^{13}C$ and $\delta^{18}O$ of Cc2 suggest that this cement probably precipitated from meteoric waters (Veizer and Hoefs, 1976) (Fig. 8).

Regarding to the $\delta^{18}O$, values for calcite cement Cc1 to Cc5 are similar to their host carbonates (Fig. 8). This could indicate a relatively closed palaeohydrological system, in which fluid-host rock interaction was high enough to equilibrate the $\delta^{18}O$ of the host carbonates with that of the fluid (Banner and Hanson, 1990) but not high enough to modify the $\delta^{13}C$ signature of the host rock, as evidenced by the wide spread of values for each cement (Fig. 8). This different behaviour of the $\delta^{18}O$ and $\delta^{13}C$ may be related to the different concentrations of these isotopic species in the host rock, which require different fluid/rock ratios to be reequilibrated with fluids (Banner and Hanson, 1990). For calcite cement Cc6, Cc7 and Cc8, however, the $\delta^{18}O$ is progressively more depleted with respect to their adjacent host carbonates, suggesting an opening of the palaeohydrological system or higher temperature conditions during calcite precipitation (Fig. 8). In this setting, and in opposition with that for Cc1 to Cc5 calcite cement, fluid-host rock interaction was not sufficient to re-equilibrate the $\delta^{18}O$ of host rocks with that of fluids due to a lower water/host rock ratio. The opening of the palaeohydrological system could have been favoured by the development of fractures F4 to F7, which have a major length and width than that of F2 and F3. The development of longer and wider fractures increased the reservoir permeability and facilitated the opening of the system to external fluids and the decrease the water/host interaction (Travé et al., 2000; Hurai et al., 2015; Muñoz-López et al., 2020). The depletion in $\delta^{18}O$ of Cc6, Cc7, and Cc8 with respect to their host rocks could be due to the input of hotter fluids or mixing between formation and more diluted meteoric waters (Zheng and Hoefs, 1993; Travé et al., 1997; Immenhauser et al., 2007; Breesch et al., 2009; Vilasi, 2010; Vandeginste et al., 2012; Beaudoin et al., 2014; Lacroix et al., 2014; Cruset et al., 2016; 2018; Nardini et al., 2019). The presence of oil seeps trapped within Cc6 precipitated in F4 fractures also evidences an open fluid system. The origin of these hydrocarbons is unclear since the main source rock in the SE Pyrenees is the Armàncies Formation (Caja et al., 2006). This unit consists of lower Eocene carbonates in the footwall of the Lower Pedraforca thrust sheet below its main Upper Triassic detachment (Fig. 1C). However, in the western continuation of the Lower Pedraforca thrust sheet, the Montsec and Serres Marginals thrust units, Early Jurassic source rocks have been identified (Martínez-del Olmo, 2019). Therefore, a possible Jurassic origin for oil in the Lower Pedraforca thrust sheet cannot be ruled out. The low $\delta^{13}C$ value measured in one sample of Lower Jurassic limestones from locality G2 (-6.06 ‰ VPDB) could account for organic matter oxidation (Irwin et al., 1977). Contrarily, the $\delta^{13}C$ of the other measured Jurassic host rocks are within the range of Jurassic-Cretaceous marine carbonates (Veizer et al., 1999) (Fig. 8). In this scenario, F4 fractures, where Cc6 precipitated, may have facilitated interconnection between different hydrostratigraphic units and the migration of hydrocarbons to shallower areas.

The two fields observed in the Mn/Fe cross-plot (Fig. 11B) also indicate the behaviour of the palaeohydrological system during fluid migration within the Lower Pedraforca thrust sheet. Thus, as the distribution coefficient of Mn (K_{Mn}) is higher than the distribution coefficient of Fe (K_{Fe}), in a closed palaeohydrological system, the Mn content decreases faster than the Fe content in the fluid as calcite precipitates (Dromgoole and Walter, 1990). In contrast, if Fe content decreases faster than that of Mn during calcite precipitation, it will necessarily imply an open system. In the Lower Pedraforca thrust sheet, calcite cement Cc1 and Cc3 fall in the field with a faster decrease in Mn than in Fe (Fig. 11B), and thus, reflecting a relatively closed system and high fluid-rock interaction. Contrarily, cement Cc5 and Cc6 fall in the field with a faster Fe decrease than Mn and therefore, that they precipitated in a more open palaeohydrological fluid system in which fluid-rock interaction was low.

The elemental composition of the calcite cement also records the composition of fluids migrating within the Lower Pedraforca thrust sheet. The Mn/Ca and Sr/Ca molar ratios of fluids from which calcite cement Cc1, Cc3, Cc4, Cc5 and Cc6 precipitated range from 0.000231 to 0.000091 for Mn/Ca and from 0.0052 to 0.0522 for Sr/Ca. These values are similar to those of calcites precipitated from formation waters (McIntire, 1963; Howson et al., 1987; Tucker and Wright, 1990). The Mg/Ca and Ca/Fe ratios of calcite cement Cc1 and Cc3 (from 0.03 to 0.304 for Mg/Ca and from 1390 to 19934 for Ca/Fe) indicate the influence of marine, formation and meteoric waters (Tucker and Wright, 1990; Kolker and Chou, 1994; Steuber and Rauch, 2005; Ligi et al., 2013) (Fig. 11C), whereas in calcite cement Cc4, Cc5 and Cc6 (from 0.03 to 0.197 for Mg/Ca and from 836 to 6993 for Ca/Fe) these ratios suggest the presence of meteoric and formation waters (Howson et al., 1987; Tucker and Wright, 1990; Kolker and Chou, 1994). These results suggest that during the evolution of the fluid system, the influence of marine waters is stronger during the precipitation of cement Cc1 and Cc3, when the fluid system was relatively closed (Fig. 11C). In contrast, during the precipitation of calcite cement Cc5 and Cc6, the influence of meteoric waters was stronger, suggesting the opening of the fluid system to these fluids (Fig. 11C).

The $^{87}Sr/^{86}Sr$ ratios of calcite cement Cc3 (0.707922) and Cc5 (0.708230) are higher than expected for cement precipitated from Middle Eocene seawater (McArthur et al.,

2001) and thus, fluids had to interact with a more radiogenic source. The $^{87}Sr/^{86}Sr$ ratio of Cc3 falls within the range of the Upper Triassic evaporites from Keuper facies (Fig. 10), indicating that fluids from which this cement precipitated probably interacted with these evaporites. An alternative interpretation would imply fluids interacting with clay minerals such as illite and/or smectite (Katz and Bullen, 1996), indicated by the $^{87}Sr/^{86}Sr$ ratio of Cc5 higher than Upper Triassic evaporites (Fig. 10). The source of these minerals could be the Garumnian continental deposits. On the other hand, calcite cement Cc6 shows the lowest $^{87}Sr/^{86}Sr$ ratio (0.707817, Fig. 10), which could indicate the influence of either middle Eocene seawater or of brines from the Upper Triassic Keuper facies, which act as a detachment of the thrust system. The absence in Cc6 of any marine influence in the Ca/Fe and Mg/Ca ratios (Fig. 11C), together with its $\delta^{18}O_{fluid}$ of +5.1 ± 0.7 ‰ may support the influence of Upper Triassic evaporites rather than middle Eocene seawater.

5.3. Relationships between deformation style and fluid flow

A conceptual model divided in five stages showing the relationships between fluid flow and fracturing during the development of the Lower Pedraforca thrust sheet is presented (Fig. 12).

During the first stage (T1, Fig. 3 and 12A), hydroplastic normal faults F1 formed soon after the deposition of the Upper Cretaceous Areny Formation at shallow conditions. During this event, there was no cement precipitation within faults, probably because faulting occurred in poorly consolidated sediments with internal heterogeneities that act as zones of low permeability (Caine and Minor, 2009; Loveless et al., 2011), or because the fluid that migrated along fractures was undersaturated with respect to calcite.

During T2 (Fig. 12B), Cc1 and Cc2 precipitated in the intergranular, moldic and vug porosities within the Jurassic Bonansa and Upper Cretaceous Areny Formations and the Palaeocene Garumnian facies. Cc1 and Cc2 probably precipitated from formation and meteoric waters, respectively. These two types of cement precipitated before the Lutetian shortening event related to the emplacement of the Lower Pedraforca thrust sheet, as evidenced by crosscutting relationships between these types of cement and cement Cc3 (Fig. 6A and B and 7). Therefore, they probably precipitated during burial diagenesis of the Jurassic, Upper Cretaceous, and Palaeocene sediments. During this burial stage, bed-parallel stylolites St1 formed in carbonate rocks of the Bonansa and Areny Formations and Garumnian facies.

The Lower Pedraforca thrust sheet was emplaced during the Lutetian (stages T3 and T4). At stage T3, fractures F2 and F3 formed during layer-parallel shortening, and calcite cement Cc3 and Cc4 precipitated post-dating stylolites St1 (Fig. 3 and 12C). During this period, formation waters, possibly derived from Upper Triassic evaporites and in isotopic equilibrium with adjacent Upper Cretaceous and Palaeocene host rocks, migrated along fractures in a closed system. The precipitation temperature of ~70 ºC obtained for Cc3 is higher than expected by burial in the frontalmost part of the Lower Pedraforca thrust sheet, where the complete pile of sediments is less than 500 m (Vergés, 1993). Considering a linear geothermal gradient of 30 ºC, which is slightly high for foreland basins, the estimated burial depth is ~2.3 km. This thermal gradient was tested in the southern Pyrenean foreland basins by Vergés et al. (1998). This depth is consistent with the stratigraphic thickness of the northern imbricated Lower Pedraforca thrust sheet (Fig. 1C; Vergés 1993), fact that could indicate that formation waters migrated from the deeper parts of the thrust sheet to the shallow thrust front along F2 and F3 fractures. Rapid fluid flow would account for thermal disequilibrium with their adjacent host rocks (Bons et al., 2012; Beaudoin et al., 2014). During T3, fractures F3 cut hydroplastic normal faults F1 in the Upper Cretaceous Areny Formation. In the thrust front, however, hydroplastic normal faults developed within middle Eocene syn-orogenic sediments in Q. These faults were reactivated during progressive tilting of bedding and Cc4 precipitated. The dispersion in $\delta^{18}O$ of this cement (from -6.9 to -2.6 ‰ VPDB) could indicate different precipitation temperatures, probably related to different burial conditions during the progressive deposition of the syn-orogenic sediments.

The fourth stage (T4) is related to folding and thrusting when F4 reverse and F5 strike-slip faults and F6 veins formed (T4, Fig. 3 and 12D). During this event, recorded by cement Cc5, Cc6, and Cc7, the fluid system opened to formation waters carrying hydrocarbons (Fig. 8, 10 and 11C). These fluids probably interacted with Upper Triassic evaporites as indicated by the $^{87}Sr/^{86}Sr$ ratio of Cc6 (0.707817). This new input of formation waters was coupled with a progressive decrease of the water/host rock interaction, resulting in the precipitation of calcite cement Cc6 and Cc7, with $\delta^{18}O$ depleted with respect to their adjacent host rocks (Fig. 8). The temperature about 74 ºC obtained for Cc6 is also higher than expected by burial. Considering the geothermal gradient of 30 ºC, an estimated burial depth of ~2.4 km is obtained, which is consistent with the stratigraphic thickness of the northern imbricate Lower Pedraforca thrust sheet (Fig. 1C; Vergés 1993). The increase of temperature of Cc6 with respect to Cc3 could indicate an increase of burial during deposition of the Bellmunt Formation conglomerates, which buried the Lower Pedraforca thrust sheet during the Lutetian (Burbank et al., 1992a). As deformation progressed, St1 stylolites were passively rotated in the fold limbs and St2 stylolites postdating Cc6 formed parallel and orthogonal to F4 and F5 fractures. St2 formed due to shortening during the emplacement of the Lower Pedraforca imbricates. The preferential development of these stylolites in close relationship with F4 and F5 accounts for this scenario. During progressive folding, F1 hydroplastic normal faults in the Upper Cretaceous Areny Formation were reactivated as reverse faults in the thrust front, whereas in the central area of the Lower Pedraforca thrust sheet (Fig. 2A), they were reactivated as strike-slip faults, allowing fluid migration (Soliva and Benedicto, 2004, 2005; Soliva et al., 2006, 2008). Such reactivations increased the fracture reservoir heterogeneity and are interpreted to have been induced by fluid pressure build-up and/or reorientation of pre-existing fractures during folding, as reported in other fractured reservoirs worldwide (Letouzey et al., 1990; Sibson, 1995; Aydin, 2000; Wiprut and Zoback, 2000; Roure et al., 2005; Chi et al., 2012; Cobbold et al., 2013; Rutqvist et al., 2013; Soumaya et al., 2015; Wisseall et al., 2018). Fluids migrated along discrete fault planes or through hydraulic fracturing triggered by fluid overpressures in the footwall of thrusts displaced along Upper Triassic evaporites. According to Aydin (2000) in the Uinta basin (United states), hydraulic fractures act as preferential paths for fluids in areas with low permeability.

Finally, during the reactivation of the thrust system (T5, Fig. 3 and 12E) at the Oligocene, normal faults F7 formed and fluids also in disequilibrium with their adjacent host rocks migrated through fractures precipitating cement Cc8 in a relatively open system.

5.4. Pyrenees fluid flow comparison to other fold and thrust belts examples

The Lower Pedraforca corresponds to a single thrust sheet and its emplacement represents a short period of time of the whole south Pyrenean foreland basin evolution under marine conditions (Vergés et al., 1995). Despite these limited area and time scales, the fluid flow behaviour in the Lower Pedraforca thrust sheet is similar to that of in other Pyrenean transects as well as in larger scale fold and thrust belts (Fig. 13). In all cases, fluid-related processes are controlled by the evolution of deformation patterns, from layer-parallel shortening (Fig. 13A) to subsequent folding and thrusting (Fig. 13B). The Puig-reig anticline, in the south Pyrenean foreland basin, is located to the south of the frontal thrust and thus corresponding to a younger foreland region than that of the Lower Pedraforca thrust sheet. In this anticline, hydrothermal fluids migrated through early stratabound strike-slip faults and low angle thrusts. Subsequently, during folding and crestal graben development, the palaeohydrological system opened to the input of meteoric waters that mixed at depth with the hydrothermal fluids (Cruset et al., 2016). A similar opening of the fluid system through time is observed in other south Pyrenean structures developed at different periods of time and at different foreland domains than the Lower Pedraforca thrust sheet, such as the Vallfogona, l'Escala, l'Abocador, Larra-Eaux-Chaudes and Jaca thrusts (Lacroix et al., 2014; Crognier et al., 2018; Cruset et al., 2018). Elsewhere, in larger fold and thrust belts such as the Bighorn Basin in the Sevier thrust belt and in the Ionian fold belt of Albania, a closed palaeohydrological system prevailed during layer-parallel shortening, which opened to external fluids during fracturing associated to folding and thrusting (Vilasi et al., 2006; Beaudoin et al., 2013). Likewise, in the Mexican fold and thrust belt and in the central Appalachians, fluids were stratigraphically segregated during the early deformation, whereas the fluid system became interconnected during fold tightening (Ferket et al., 2000, 2003; Lefticariu et al., 2005; Fischer et al., 2009; Fitz-Diaz et al., 2011; Evans et al., 2012). In the Northern Oman Mountains, pre-burial fluids migrated through fractures in a rock-buffered system, and deep-sourced fluids migrated through thrust faults during the main stage of compression (Breesch et al., 2009). In this example of fold belt from Oman, main thrust faults acted as barriers for transversal fluid flow, since evidence of migration of fluids were not observed in the hangingwall carbonates. Finally, the anticlines from the Lurestan Province of Iran, in the Zagros fold belt, show a fracture pattern similar to that observed in the Lower Pedraforca thrust sheet, although the Iranian folds are located in a more external domain of the foreland basin. In this area, syn-sedimentary normal faults were passively rotated into the anticline limbs during the main and later stages of folding and were reactivated as reverse faults, where calcite cement containing hydrocarbons precipitated (Casini et al., 2011; 2018). Like in the Lower Pedraforca thrust sheet, the presence of hydrocarbons within fracture-filling calcites indicates the opening of the fluid system during this main stage of folding and the input of exotic fluids in contact with petroleum source rocks.

The changes of the fluid regime in compressional settings are also observed in extensional regimes such as the Neogene Vallès-Penedès (Baqués et al., 2010; Cantarero et al., 2014) and the Corinth rift (Benedicto et al., 2008) extensional systems.

In these examples, during the first stages of upward propagation of normal faults, the palaeohydrological system was relatively closed with high fluid-rock interaction, whereas during the final stages of normal faulting it changed to a more open one, with lower fluid-rock interaction.

6. Conclusions

The integration of field-based and petrographic observations, together with geochemical and geochronological data allowed to differentiate up to eight types of calcite cement (Cc1 to Cc8) and two sets of stylolites (St1 and St2) revealing the evolution of the palaeohydrological system during the emplacement of the Lower Pedraforca thrust sheet.

Relationships between calcite cement and fractures indicate that during hydroplastic deformation related to the pre-shortening stage within the Lower Pedraforca thrust sheet, there was no precipitation of calcite cement in fractures. During the progressive burial, calcite cement Cc1 and Cc2 precipitated from formation waters in isotopic equilibrium with their adjacent host rocks. Burial was also responsible for development of the bed-parallel stylolites St1.

During middle Eocene (Lutetian) layer-parallel shortening, calcite cement Cc3 and Cc4 precipitated from fluids in a relatively closed palaeohydrological system with high fluid-host rock interaction. Clumped isotopes thermometry indicates that calcite cement Cc3 precipitated from formation waters (~+5.4 ‰ VSMOW) at temperatures around 70 ºC. This temperature, together with an $^{87}Sr/^{86}Sr$ ratio of 0.707922, indicates that formation waters migrated forwards from the deeper domains in the Lower Pedraforca thrust sheet to the shallower thrust front and probably interacting with Upper Triassic evaporites at the base of the hangingwall succession. The $\delta^{18}O$ dispersion up to 4 ‰ VPDB of calcite cement Cc4 could indicate different precipitation temperatures during the progressive burial of syn-orogenic sediments deposited in the thrust front (Emery, 1987).

Progressive folding and thrusting, during Lutetian age, was coupled with tilting of St1 stylolites and precipitation of calcite cement Cc5 to Cc7. Clumped isotopes thermometry indicates that Cc6 cement precipitated from formation waters (~+5 ‰ VSMOW) at temperatures around 75 ºC, which are also interpreted as migrated from the deeper regions of the thrust sheet to the thrust front. The $\delta^{18}O$ depletion of calcite cement Cc6 and Cc7 with respect to their adjacent host rocks and the presence of hydrocarbons in Cc6 indicate an opening of the palaeohydrological system. The $^{87}Sr/^{86}Sr$ ratios of Cc5 (0.708230) and Cc6 (0.707817) suggests the influence of clay minerals, probably from the Garumnian continental deposits, and of Upper Triassic evaporites, respectively. During this period, stylolites St2 formed and previous hydroplastic fractures were reactivated as reverse and strike-slip faults facilitating fluid flow. Cc7, precipitated after Cc6 according to U-Pb geochronology, also precipitated from fluids in isotopic disequilibrium with their adjacent host rocks.

Finally, large-scale folding of the Lower Pedraforca thrust sheet due to the emplacement of younger thrust sheets below, induced the reactivation of its basal thrust during the Oligocene. During this period, fluids in isotopic disequilibrium with their adjacent host rocks migrated through local normal faults that cut Oligocene conglomerates in the footwall of the Lower Pedraforca basal thrust and Cc8 precipitated.

The progressive shortening and concomitant fracturing and fluid flow in the Lower Pedraforca thrust sheet share a common fluid evolution with other fold and thrust belt domains in the Pyrenees as well as elsewhere alike the Sevier, Appalachians, Bighorn basin, Ionian, Mexican, Zagros, and Oman fold and thrust belts

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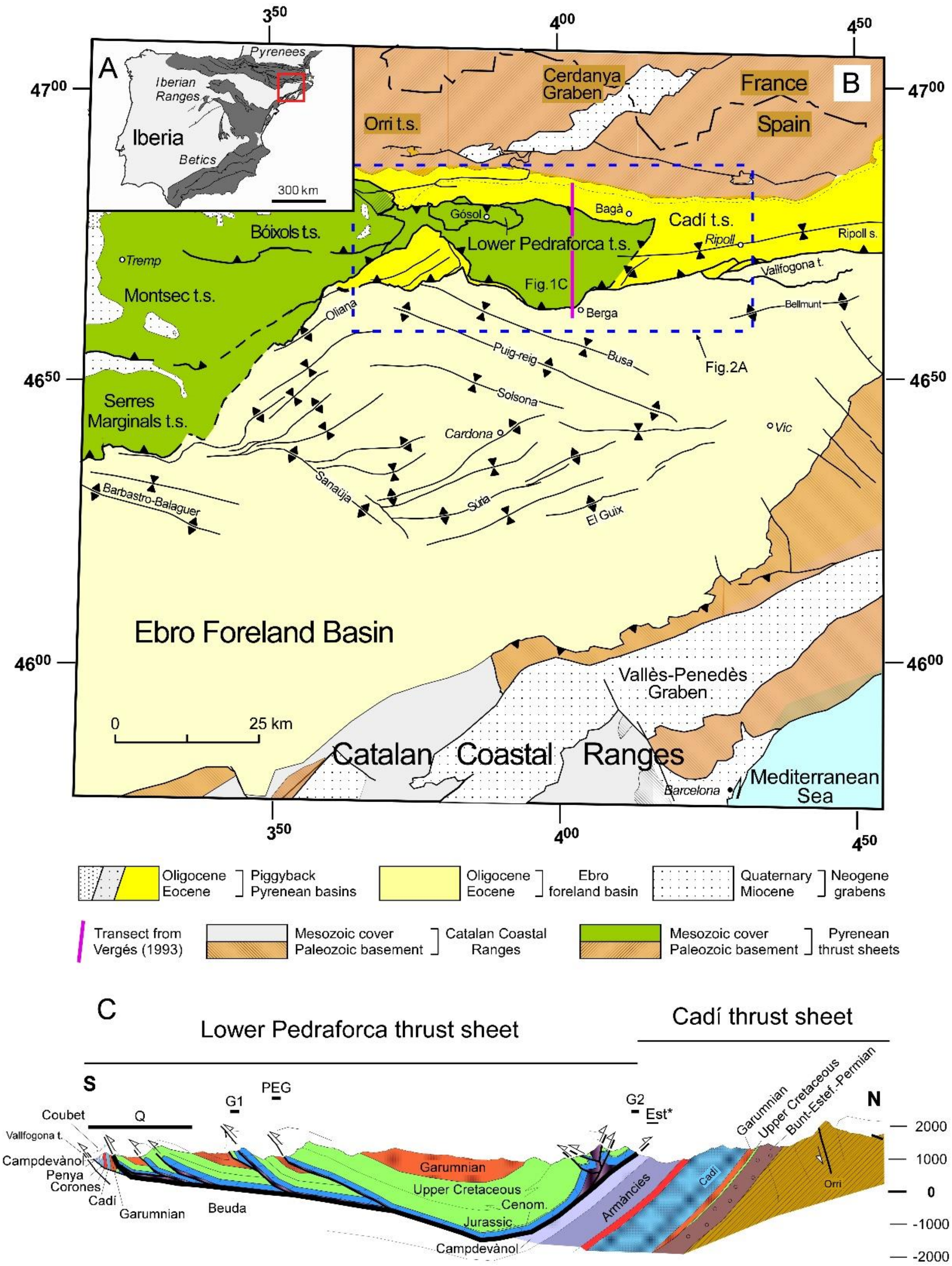

Fig. 1 A) Regional map of the Iberian Peninsula showing the location of the South Pyrenean fold and thrust belt (red box). B) Simplified geological map showing the main structural units forming the South Pyrenean fold and thrust belt (Vergés, 1993). The thick pink line indicates the location of the cross-section shown in Fig. 1C. The dashed blue box indicates the location of Fig. 2A. C) Geological cross-section of the Lower Pedraforca

thrust sheet from Vergés (1993) showing the structural position of the studied localities. Est*: projection of the position of this location.

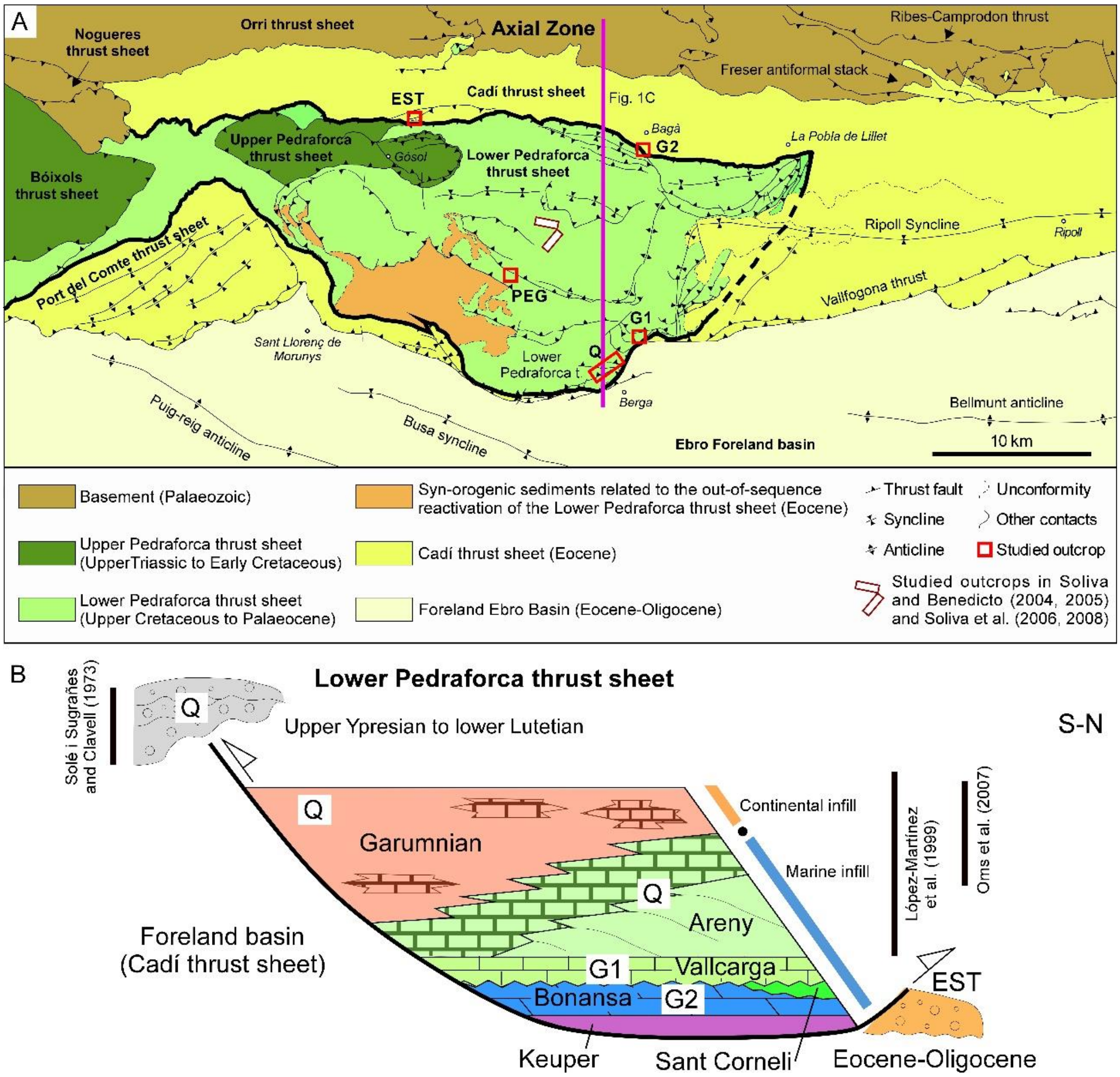

Fig. 2 A) Structural sketch of the studied area with locality locations. White boxes bounded by red lines indicate the areas studied by Soliva and Benedicto (2004, 2005) and Soliva et al. (2006, 2008) in the Lower Pedraforca thrust sheet. The thick pink line indicates the location of the cross-section shown in Fig. 1C. B) N-S stratigraphic panel of the Lower Pedraforca sheet. The age of sedimentary units has been defined according to Solé i Sugrañes and Clavell (1973), López-Martínez et al. (1999) and Oms et al. (2007).

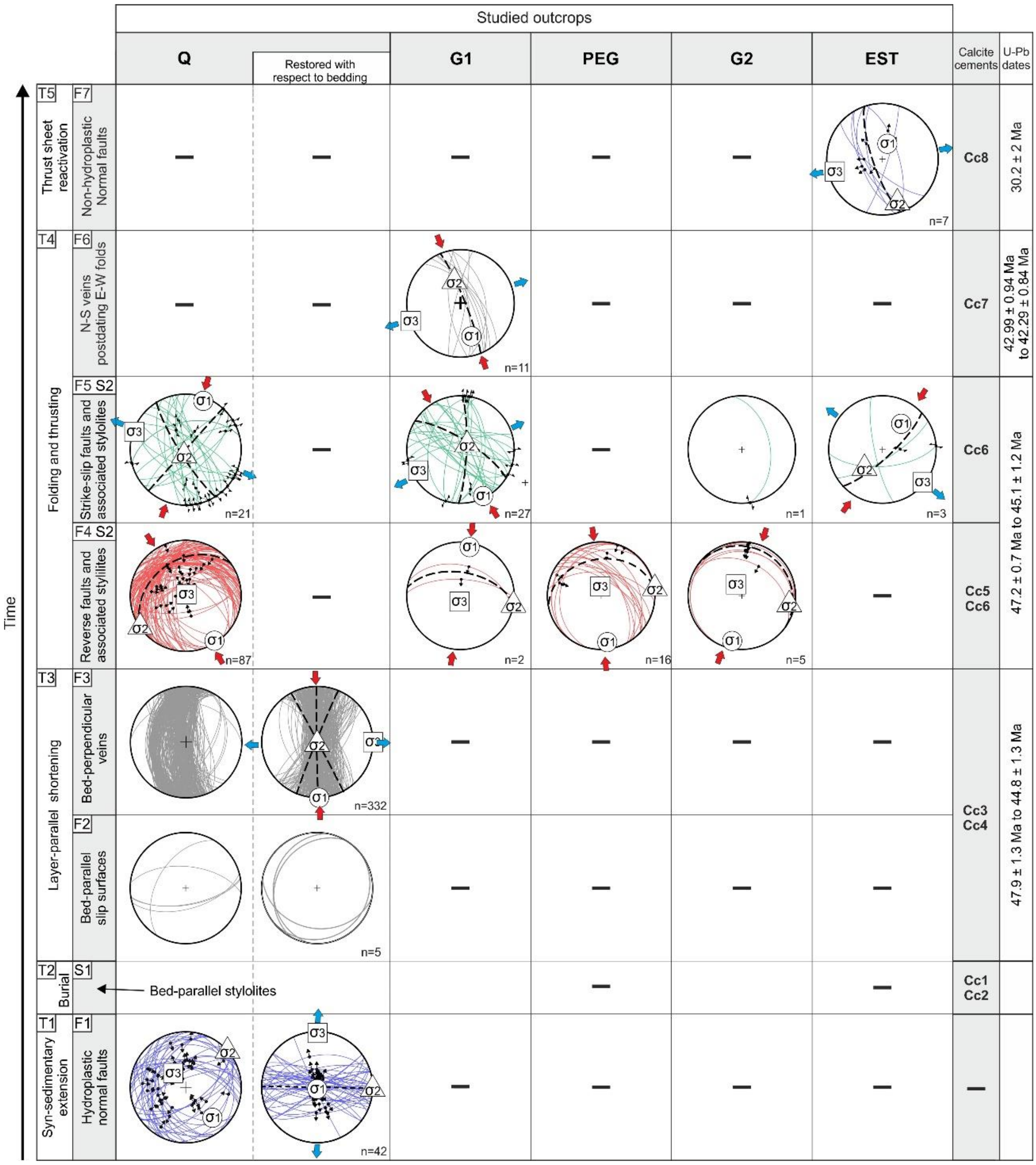

Fig. 3 Lower hemisphere Schmidt stereoplots representing fracture data from the different studied localities, their associated calcite cement and different stages of deformation and stylolitization. Fracture systems F1, F2 and F3 are presented at their current orientation and restored with respect to bedding. The grey boxes with references Q, G1, PEG, G2 and EST represent the studied localities in Figs. 1 and 2. Thick dashed black lines represent mean planes for each fracture system.

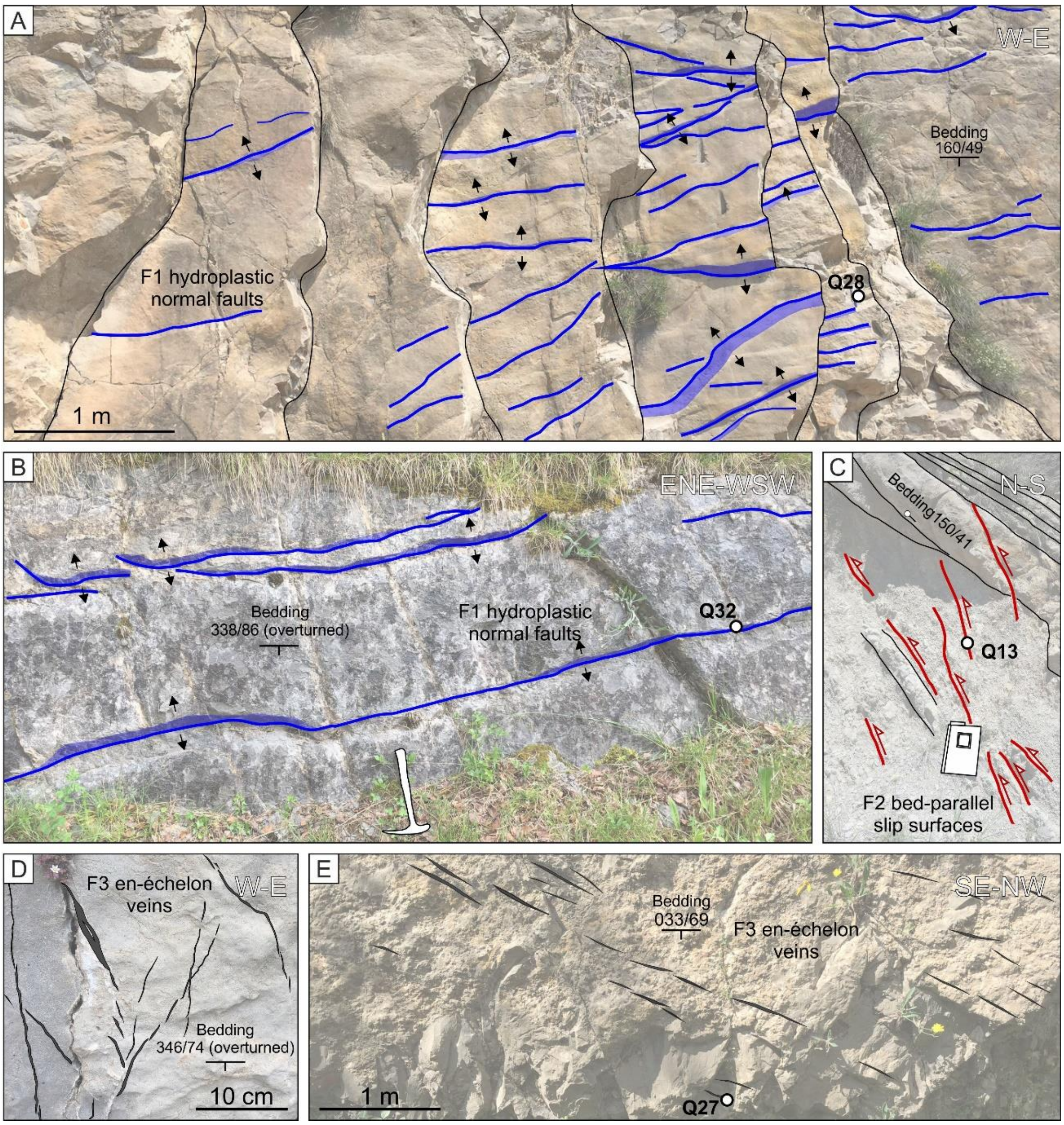

Fig. 4 Outcrop images showing the main features of fracture systems F1, F2 and F3 within the Lower Pedraforca thrust sheet. A-B) E-W hydroplastic normal faults F1 in the Upper Cretaceous Areny Formation and middle Eocene syn-orogenic sediments, respectively. C) Bed-parallel slip surfaces F2 affecting Palaeocene sediments. D-E) N-S, NNW-SSE and NNE-SSW en-échelon vein arrays F3 affecting middle Eocene syn-orogenic sediments and the Upper Cretaceous Areny Formation, respectively. Bed dip directions and dips are given. White points indicate sample location.

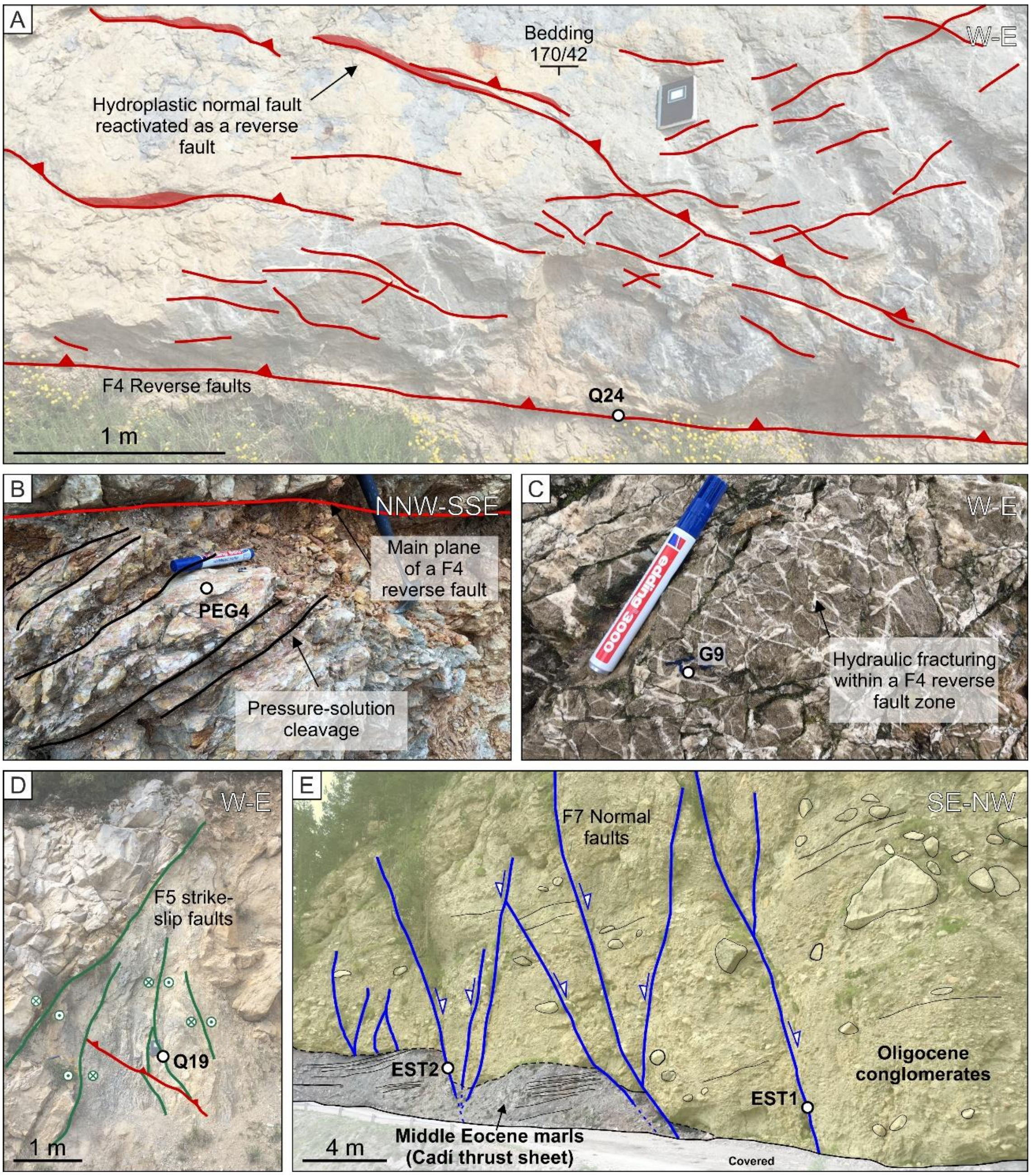

Fig. 5 Outcrop images showing the main features of fracture systems F4, F5 and F7 within the Lower Pedraforca thrust sheet. A) Reverse faults F4 and associated veins within the Upper Cretaceous Areny Formation. Bed dip direction and dip is given. B) Pressure solution cleavage formed in the core of a F4 thrust fault. C) Hydraulic fracturing formed in the damage zone of a F4 thrust fault. D) F5 strike-slip faults affecting the Upper Cretaceous Areny Formation. E) F7 normal faults affecting Oligocene conglomerates. White points indicate sample location.

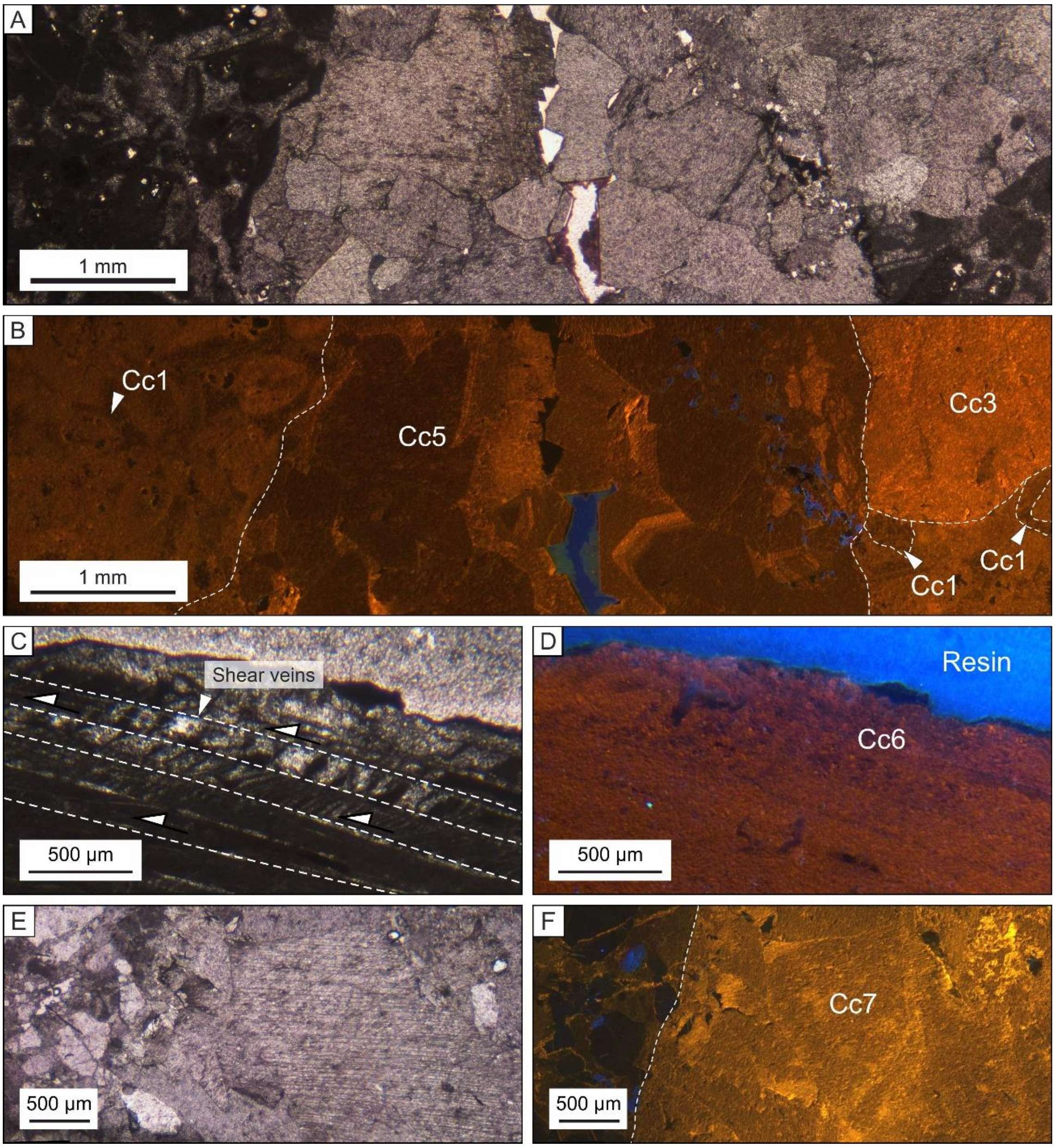

Fig. 6 Images from polarizing optical and cathodoluminescence (CL) microscopy of the main features of calcite cement and microstructures. A-B) Crosscutting relationships between intergranular porosity and veins filled with calcite cement Cc3 and Cc5. C-D) Image showing veins filled with calcite cement Cc6 in F4 reverse faults. E-F) Calcite cement Cc8 filling veins in F7 normal faults.

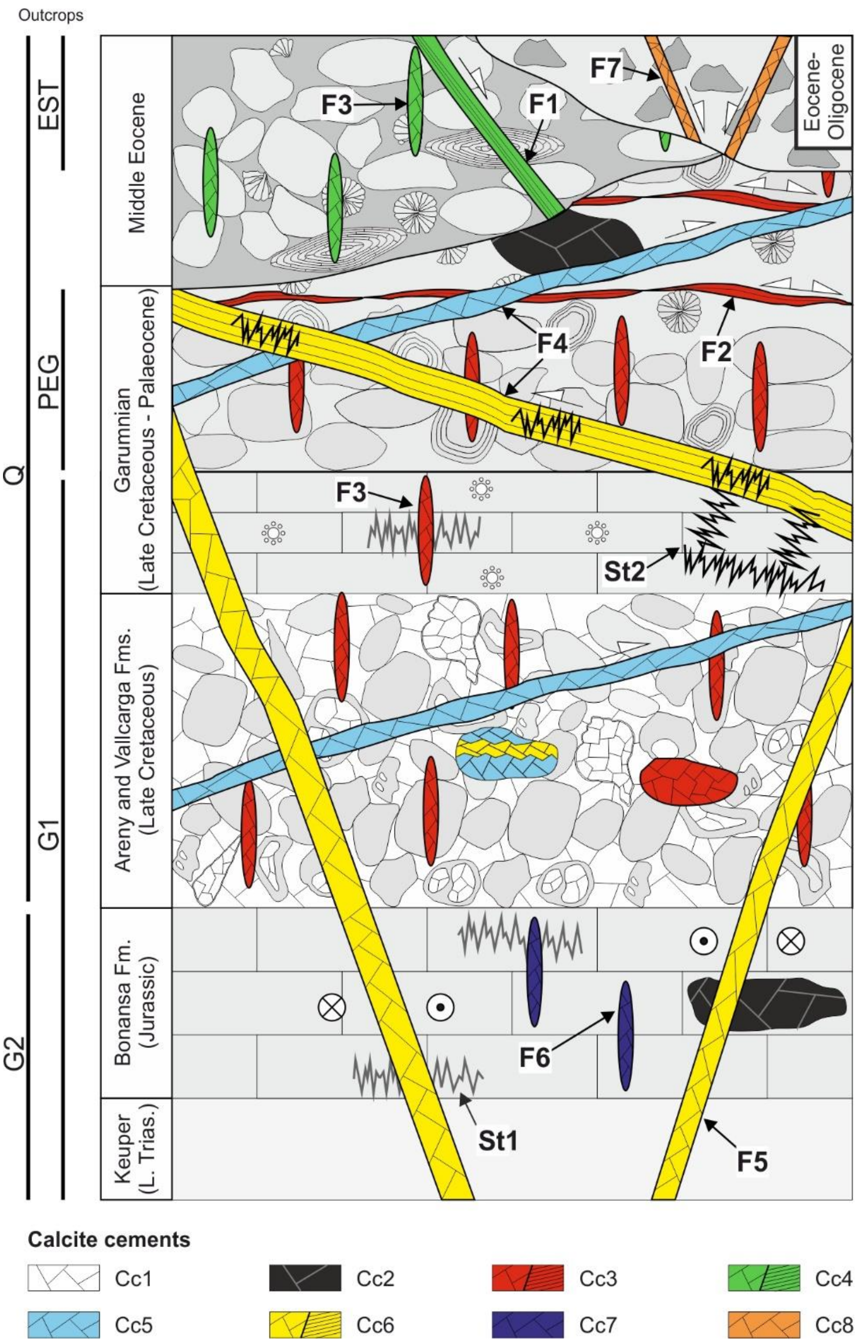

Fig. 7 Schematic representation of the crosscutting relationships between fractures, stylolites and related calcite cement in the Lower Pedraforca thrust sheet.

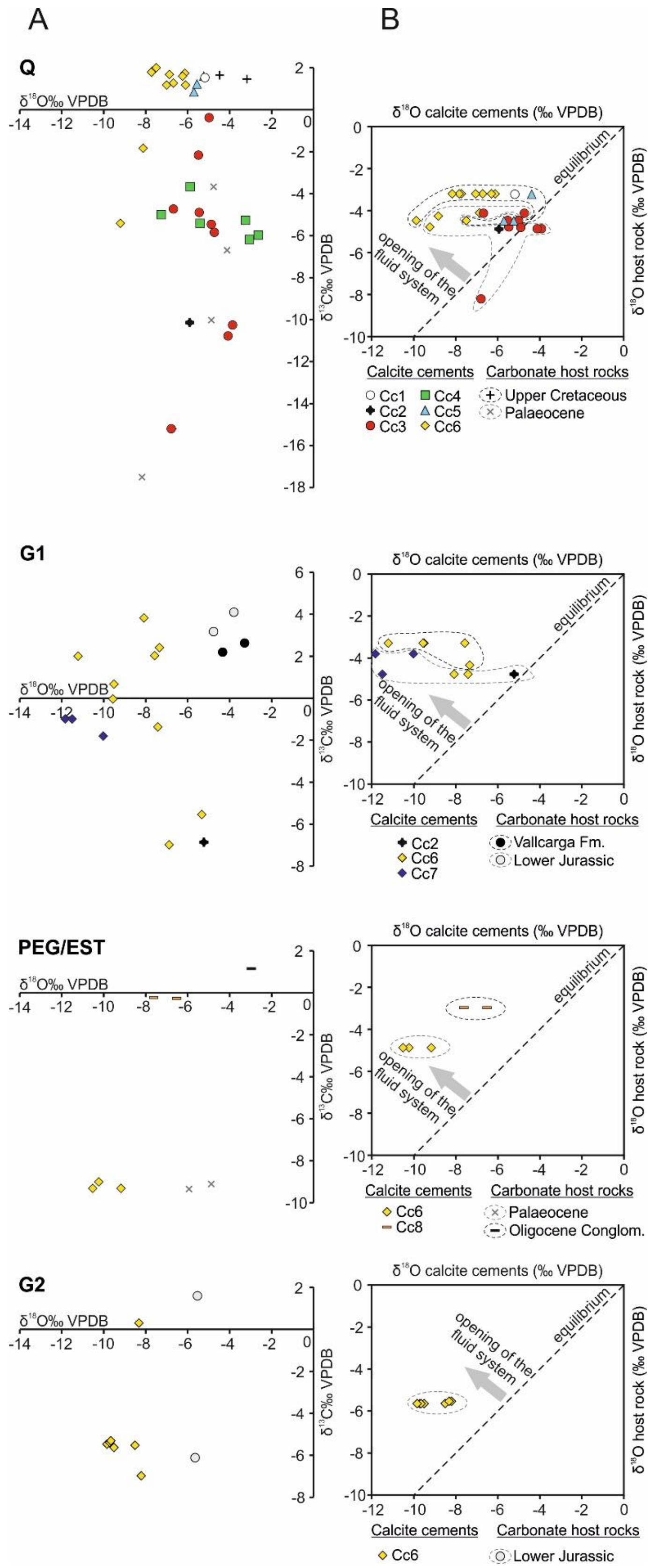

Fig. 8 A) δ18O vs δ13C from the Lower Pedraforca thrust sheet. B) Cross-plots comparing the δ18O of calcite cement with their adjacent host rocks. The dashed areas group

cement according to their adjacent host rocks. The dashed black line represents the equilibrium between calcite veins and their adjacent host rocks.

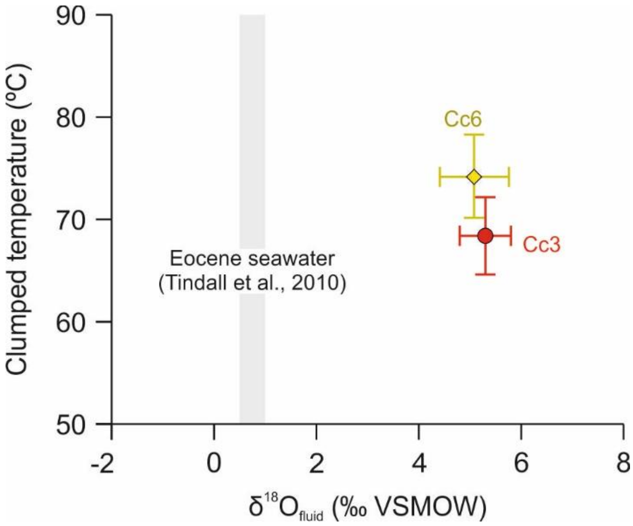

Fig. 9 Clumped isotope temperatures in ºC vs calculated $\delta^{18}O_{fluid}$ (‰ VSMOW) for calcite cement Cc3 and Cc6. $\delta^{18}O$ of Eocene seawater according to Tindall et al. (2010).

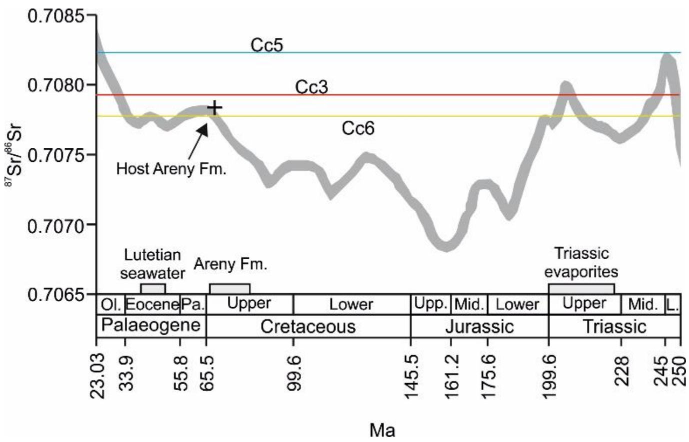

Fig. 10 $^{87}Sr/^{86}Sr$ composition of calcite cement and carbonate host rocks. The $^{87}Sr/^{86}Sr$ ratios of the LOWESS curve from McArthur et al. (2001) are also plotted. The grey area boxes indicate the $^{87}Sr/^{86}Sr$ ratio of middle Eocene and Upper Triassic seawater from McArthur et al. (2001).

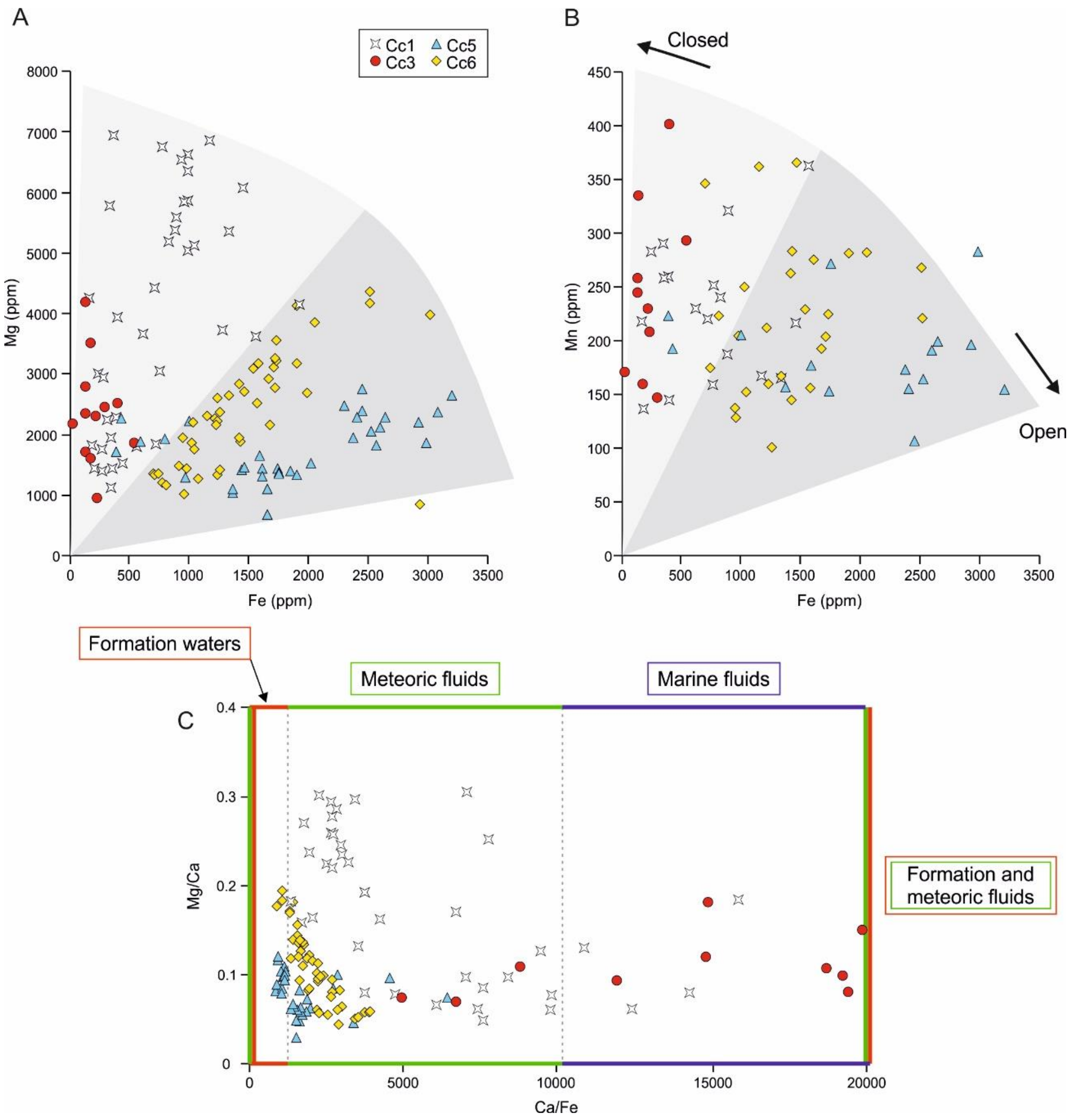

Fig. 11 Elemental composition of the calcite cement. A-B) Fe vs Mg and Fe vs Mn cross-plots of calcite cement Cc1, Cc3, Cc5 and Cc6. C) Ca/Fe vs Mn/Ca molar ratios cross-plot of calcite cement Cc1, Cc3, Cc5 and Cc6. Areas bounded by blue, green and red thick lines represent the composition of marine, meteoric and formation fluids, respectively. Fluid compositions are based on McIntire (1963), Howson et al. (1987), Tucker and Wright (1990), Kolker and Chou (1994), Steuber and Rauch (2005) and Ligi et al. (2013).

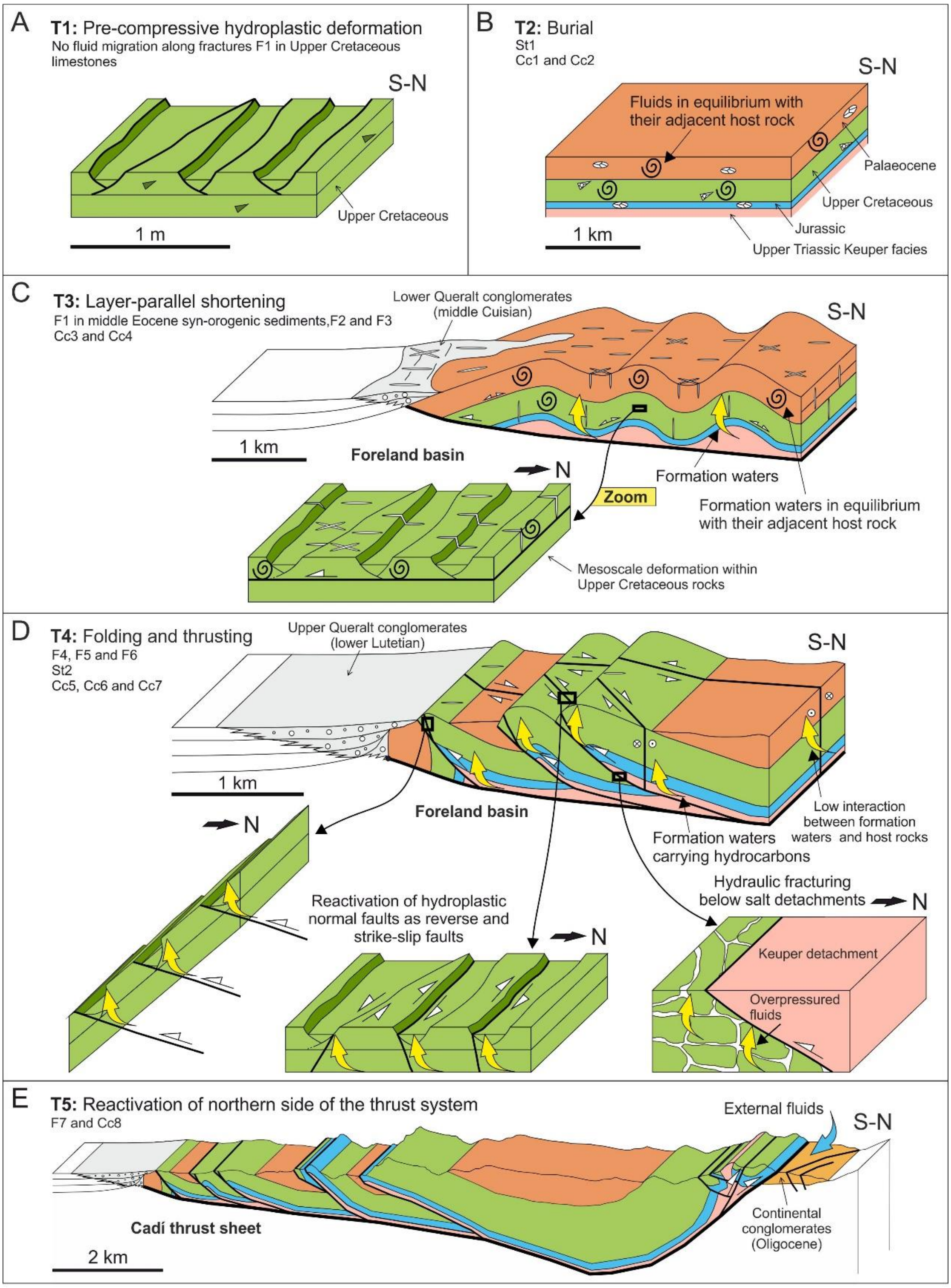

Fig. 12 Fluid flow evolution during the emplacement of the Lower Pedraforca thrust sheet. A) T1, pre-compressive hydroplastic deformation. B) T2, burial diagenesis. C) T3, layer-parallel shortening. D) T4, folding and thrusting. E) T5, reactivation of the northern sector of the thrust system. For each stage, the type of migrating fluids, associated calcite cement and fractures are given.

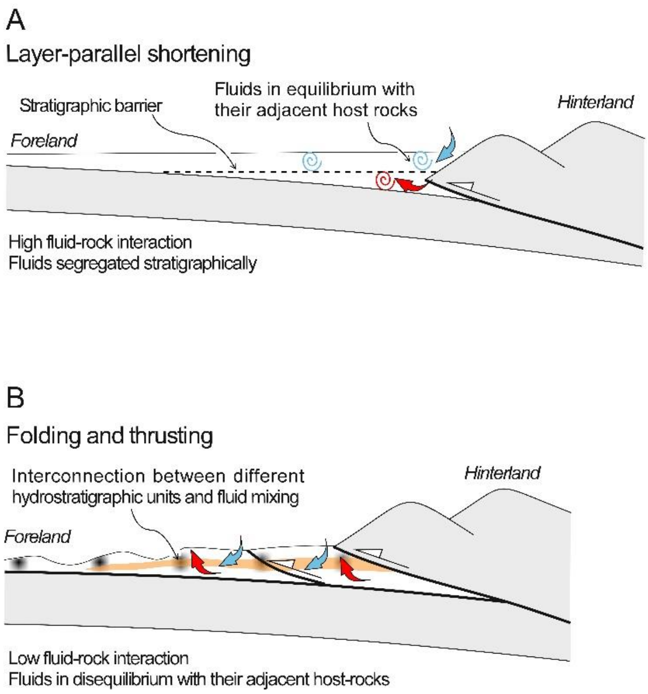

Fig. 13 Conceptual model of fluid flow in fold and thrust belts. A) Layer-parallel shortening stage. Fluids are in equilibrium with their adjacent host rock and fluid-host rock interaction is high. Fluids are segregated stratigraphically. B) Folding and thrusting stage. The paleohydrological system opens, allowing the interconnection between different hydrostratigraphic units and fluid mixing. The fluid-host rock interaction is low.

Table 1. U-Pb dates of calcite cement Cc3, Cc4, Cc6, Cc7 and Cc8.

Sample	Locality	Fracture set	Cement type	Age (Ma)	± 2σ	MSWD	$^{207}Pb/^{206}Pb$ Upper intercepts	± 2σ	Number of spots
Q27	Q	F3	Cc3	45.7	1.9	2.2	0.845	0.033	25
Q3-1	Q	F4	Cc3	47.3	1	1.3	0.879	0.036	24
Q11	Q	F3	Cc4	47.9	1.3	1.7	0.827	0.03	31
Q33	Q	F3	Cc4	44.8	1.3	1.4	0.8756	0.0062	23
Q24	Q	F4	Cc6	45.1	1.2	1.09	0.8327	0.0028	32
Q29	Q	F4	Cc6	47.2	0.7	1.4	0.829	0.013	27
G3	G1	F6	Cc7	42.9	0.9	1.8	0.705	0.004	32
G3b	G1	F6	Cc7	42.3	0.8	1.5	0.8091	0.0043	20
EST2	EST	F7	Cc8	30.2	2	1.8	0.843	0.011	21

Table 2. $\delta^{13}C$, $\delta^{18}O$, Δ_{47} and $\delta^{18}O_{fluid}$ of the calcite cement Cc3 and Cc6 within the Lower Pedraforca thrust sheet. n represents the number of analyses per sample.

Sample	Locality	Cement type	n	$\delta^{13}C$ ‰ VPDB[a]	$\delta^{18}O$ ‰ VPDB[a]	Δ_{47}[b]	T ºC	$\delta^{18}O_{fluid}$ ‰ VSMOW
Q2	Q	Cc3	4	+0.33 (0.01)	-5.02 (0.06)	0.579 ± 0.011	69.1 ± 5.3	+5.4 ± 0.9
Q24	Q	Cc6	3	+1.6 (0.04)	-6.1 (0.03)	0.569 ± 0.008	74.2 ± 4	+5.1 ± 0.7

[a] 1σ error for $\delta^{13}C$ and $\delta^{18}O$ of calcite cement.

[b] Error for Δ47 is presented as standard error and calculated by the replicate standard deviation divided by square root of n.

Table 3. Mg/Ca, Sr/Ca, Ca/Fe and Mn/Ca ratios for calcite cement Cc1, Cc3, Cc4, Cc5 and Cc6 precipitated in locality Q.

Cement type	Mg/Ca		Sr/Ca		Ca/Fe		Mn/Ca	
Cc1	Max.	0.304	Max.	0.052	Max.	15903	Max.	0.000085
	Min.	0.047	Min.	0.006	Min.	1390	Min.	0.000033
	Mean	0.175	Mean	0.014	Mean	5570	Mean	0.000053
Cc3	Max.	0.18	Max.	0.013	Max.	19934	Max.	0.000111
	Min.	0.069	Min.	0.006	Min.	4963	Min.	0.000032
	Mean	0.011	Mean	0.008	Mean	13357	Mean	0.000054
Cc4	Max.	0.197	Max.	0.020	Max.	-	Max.	0.000091
	Min.	0.034	Min.	0.007	Min.	-	Min.	0.000033
	Mean	0.104	Mean	0.01	Mean	-	Mean	0.000048
Cc5	Max.	0.121	Max.	0.027	Max.	6993	Max.	0.000086
	Min.	0.03	Min.	0.005	Min.	836	Min.	0.000025
	Mean	0.078	Mean	0.015	Mean	1916	Mean	0.000051
Cc6	Max.	0.194	Max.	0.019	Max.	3912	Max.	0.000083
	Min.	0.044	Min.	0.006	Min.	880	Min.	0.000023
	Mean	0.107	Mean	0.011	Mean	2149	Mean	0.000049