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Fault gouge dating in the Spanish Pyrenees: Fault ages, thrust propagation sequence, wall-rock provenance, and thermal constraints

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Abstract

Dating brittle faults by the growth of authigenic illite in fault gouge allows for direct testing of kinematic models of orogenic evolution, such as in-sequence vs. out-of-sequence thrusting, and the presence of orogenic ‘pulses’ of deformation on multiple thrusts simultaneously. We present illite gouge ages from 5 thrust faults along the Ter and Freser rivers in the south-eastern Pyrenees fold-and-thrust belt dated by Ar-Ar methods. The ages show in-sequence thrusting for the south-eastern Pyrenees fold-thrust belt during the Eocene and early Oligocene, ranging from 49.5 ± 4.4 Ma for the inboard Freser Antiformal Stack to 31.9 ± 3.9 Ma for the frontal L’Escala Thrust. Foreland progression of ages is preserved, although overlapping of ages of the frontal thrusts permits the interpretation of a period of more rapid fault displacement around 35 Ma. Shortening rates for the Ter-Freser section range from 1.2 – 2.7 km/my, with strain rates ranging from $7.0 \times 10^{-16} \text{ s}^{-1}$ to $1.6 \times 10^{-15} \text{ s}^{-1}$. The latest Paleozoic ages of the cataclastically-derived component inferred from the gouge dating methodology are shown to be pooled $2M_1$ illite/mica ages of wall rock sediments and have geological meaning. These inferred mica ages of the thrust wallrocks in the southeastern Pyrenees indicate Hercynian-age micas were deposited in the Southern Pyrenean foreland basin as early as the late Cretaceous. Previous thermochronometer and Δ_{47} temperatures from syn-faulting calcite veins constrain temperature of clay gouge formation in the Ter-Freser section at 50 - 210°C, with most likely temperatures of 50 - 160°C, consistent with previous studies.

Key points:

Main point #1: (140 character limit including spaces)
SE Pyrenees fold-thrust belt propagated in-sequence

Main point #2: (140 character limit including spaces)
Clay gouge minerals grew at temperature of 50 - 210°C, most likely 50 - 160°C.

Main point #3: (140 character limit including spaces)
Age of detrital component from gouge dating is shown to be geologically meaningful, and here is a pooled age of foreland basin micas

Plain Language Summary:

Mountain belts are generally thought to grow from the center out towards their margins over geological time. In this model, the oldest faults are at the interior of the range, while the youngest faults are near the edges of the belt. However, observations from several mountain belts worldwide show something different, that mountain belts have many faults of the same age suggesting 'pulses' of mountain belt growth lasting a few millions of years, separated by periods of relative quiet. We test this idea by directly dating clay minerals inside the fault rock of several thrust faults in the southeastern Pyrenees mountain belt in Spain. We find that the SE Pyrenees grew like the model predictions, from the inside out, and not like the series of 'pulses' observed in other mountain belts such as the Canadian and America Rockies. We also identify the temperature at which these fault gouge clays, most likely 50 - 160°C.

1.0 - Introduction

1.1 - Introduction

The absolute timing of thrusts has important mechanical and regional implications for the evolution of fold-thrust belts. Analogue models of fold-thrust belts predict a forward younging progression of thrusts (e.g., Caudell, 1888; Liu et al., 1992; Lathrop and Burberry, 2017), often referred to as ‘in-sequence thrusting’ (McClay, 1992: Figure 1a). The observation that thrusts in a fold-thrust belt are typically younger towards the foreland has long been recognized (e.g., Armstrong & Oriel, 1965; Wiltschko and Dorr, 1983) and has been interpreted in terms of a forward-propagating, critically tapered orogenic wedge (e.g. Chapple, 1978; Davis et al., 1983; DeCelles & Mitra, 1995). However, thrusting can also occur on faults inboard of frontal thrusts, referred to as ‘out of-sequence thrusting’ (e.g. Morley, 1988, Figure 1b), which may indicate that the mechanical properties of the deforming orogenic wedge have changed, such that the wedge is deforming internally to regain critical taper (Dahlen, 1990). Fold-thrust belts with reliable age constraints on individual thrusts also indicate that deformation appears to occur in one or more ‘pulses’, which are temporally discrete periods lasting a few million years in which multiple faults overlap in age (e.g., van der Pluijm et al., 2006; Foster and Gray, 2007, Macquarie et al., 2014, Figure 1c). These periods of rapid fault activity and exhumation, suggestive of orogenic wedge realignment, have been suggested to indicate larger orogen-scale processes, such as possible delamination of a deep crustal root beneath Cordilleran-style orogens such as the Andes and the Canadian Rockies (e.g. Garzoni et al., 2006; DeCelles et al., 2009), or the development of a midcrustal duplex system (e.g. McQuarrie et al., 2014).

2.0 – Fault dating

2.1 - Fault gouge dating

The timing of movement of brittle faults in fold and thrust belts has traditionally been dated by ‘bracketing’ the age from events that preceded and followed fault motion (e.g. Armstrong & Oriel, 1965, Williams, 1985, Puigdefàbregas & Souquet, 1986, Farrell et al., 1987), by inferences from seismic lines (e.g. Ardèvol et al., 2000), by biostratigraphic and paleomagnetic data from syntectonic sediments (e.g. Labaume et al., 1985; Puigdefàbregas and Souquet, 1986; Burbank et al., 1992a, 1992b, Meigs et al., 1996, Meigs, 1997, Sussman et al., 2004; Carrigan et al., 2016) or by U-Pb dating of calcite vein systems (Cruset et al., 2020). Frequently, the constraints are not well defined when syntectonic sedimentary basins lack detailed biostratigraphic or magnetostratigraphic constraints or are lost to subsequent erosion. Dating of authigenic clay mineralization in fault gouges (van der Pluijm et al., 2001) offers an approach that determines the age of faulting directly (Figure 2). The growth of authigenic clays in the brittle regime ($<200^{\circ}\text{C}$), particularly the low-temperature 1M_d polytype of illite, has been recognized as a common process in clay-rich gouges (Haines and van der Pluijm, 2012). Identifying the age of the authigenic illite by dating multiple (3 or more) size fractions of a gouge and characterizing the relative abundances of the low-temperature (authigenic) 1M_d polytype and the high-temperature (cataclastically-derived) 2M_1 polytype of illite in each size fractions is used to reliably date faults from a variety of geologic settings (Ylagan, 2002; Solum et al., 2005; van der Pluijm et al., 2006; Solum & van der Pluijm, 2007; Haines & van der Pluijm, 2008, Rahl et al., 2011; Vrolijk et al., 2018). An age of the cataclastically-derived component is also

determined by the analysis. This age has been interpreted as a pooled age of all the cataclastically-derived $2M_1$ grains in the gouge (Pevear, 1999; van der Pluijm et al., 2001), although previous dating efforts have largely ignored any geological significance of the detrital age (e.g. van der Pluijm et al., 2001; 2006).

Figure 2 shows the sample preparation, X-ray characterization and Ar dating steps. As the kinetics for the growth of large clay crystallites at low temperatures are unfavourable, authigenic clays in gouges are typically very fine-grained ($< 1\mu\text{m}$) and thus tend to concentrate in the finest size fraction. Each dated size fraction of clay from a single gouge sample is treated as a point on a binary mixing line between the Ar-Ar age of the $2M_1$ (detrital) component (derived from the wall rock during slip) and the Ar-Ar age of the $1M_d$ (authigenic) component that grows during faulting. The percentage of detrital illite in each size fraction is established by quantitative modeling of XRD patterns using synthetic XRD patterns generated with WILDFIRE© (Reynolds, 1994), a program that calculates XRD patterns for illitic clays with a variety of crystallographic variables. WILDFIRE-generated modelled XRD patterns for $2M_1$ and $1M_d$ components are mixed and matched to the sample XRD pattern in an Excel spreadsheet until the lowest variance fit between the modelled patterns and the sample pattern is obtained. The percentage of detrital illite is then plotted against the Ar-Ar age for each size fraction, and the ages of the authigenic and detrital endmember components are obtained by extrapolation. Errors are quantified by York regression where X (clay quantification, $\pm 2-3\%$ error, Haines and van der Pluijm, 2008) and Y (Ar age, $<<1\%$ error) are independent (York, 1969).

In this contribution, we directly date thrust faults from the southeastern Pyrenees with three goals. 1) Provide direct age constraints on thrusts and test thrust propagation models in the eastern reach of the southern Pyrenean fold-thrust belt, which is less well known compared to the extensively studied central portion of the range. 2) Interpret the age of the cataclastically-derived component in fault gouge, so the provenance of the Ebro Basin wall rock can also be determined, providing additional insights into the Pyrenean exhumation history. 3) Determine the temperature constraints for the growth of 1M_d illite in fault gouge by integrating gouge ages with published burial and thermochronometric constraints.

3.0 – Pyrenees geological setting

3.1 – Pyrenees introduction

The Pyrenees, which straddle the border between France and Spain in Europe, are the westernmost expression of the Alpine-Himalayan orogen (Figure 3). The range is about 600 km long, including the Basque-Cantabrian Range to the west, and approximately 150 km wide. The Pyrenees formed as the result of interactions between the Iberian, African and European plates during the late Mesozoic and Cenozoic (Muñoz, 2019). Collision of the Iberian microplate with the European plate occurred from the late Cretaceous to the earliest Miocene, as the Iberian microplate collided with, and was partially subducted under the European plate (Choukroune, 1989; Muñoz, 1992; Teixell, 2018). The orogen consists of a roughly east-west striking central Paleozoic core, commonly referred to as the Axial Zone, with predominantly Carboniferous (Hercynian, 320 – 290 Ma) metamorphic and magmatic cooling ages (McCaig and Miller, 1986; Denele et al., 2014), although some younger mica ages are also reported, attributed to a mid-Cretaceous thermal event (Maurel

et al., 2007). The Axial Zone is flanked on both the north and south by paired fold-thrust belts (North and South Pyrenean fold-thrust belts) and associated foreland basins, the Aquitanian Basin to the north, and the Ebro Basin to the south (Figure 3) filled with Jurassic to Tertiary strata. Jurassic and Cretaceous strata are only locally present in the foreland basins, with their deposition controlled by geometries inherited from a complex Mesozoic rifting episode related to the opening of the North Atlantic (e.g. Jammes et al., 2009; Lagabrie et al., 2010; Ducoux et al., 2021).

The range is asymmetrical with the south verging thrust belt being wider than the northern belt (Muñoz, 1992; Vergés, 2002; Teixell et al., 2018). The foreland fold-and-thrust belts, especially along its southern (pro-wedge) outboard margin, have exceptional preservation of syn-orogenic strata, which has permitted timing of structural events in the foreland (e.g. Puigdefábregas et al., 1986; Burbank et al., 1992a, Sussman et al., 2004), and permitted previous estimations of rates of shortening processes (Burbank et al., 1992b; Vergés et al., 1995, 1998; Meigs et al., 1996; Carrigan et al., 2016; Labaume et al., 2016b; Cruset et al., 2020).

Along strike, the Pyrenees can be separated into three distinct regions. The western segment has a ~40 km wide southern fold-thrust belt and has limited exposure of Paleozoic Axial Zone rocks deformed during the Hercynian orogeny in the core of the segment (Teixell, 1996; Teixell et al., 2018). Range-scale balanced cross section reconstructions based on the Ansó-Arzacq deep seismic indicate that the western portion of the range experienced 75-80 km of total shortening (Teixell, 1998). The central segment has a

relatively wide (70 km) southern foreland fold and thrust belt, and significant exposure of Axial Zone rocks. Balanced section reconstructions based on the ECORS deep seismic profile variably suggest 90 - 150 km of shortening across the central portion of the range (Muñoz, 1992; Mouthereau et al., 2014; Teixell et al., 2018). By contrast, the eastern segment has a relatively narrow (20 km) southern foreland fold-and-thrust belt, and yet similar extensive exposure of Paleozoic rocks in the core of the range (Muñoz, 2019). Range-scale balanced cross section reconstructions suggest the eastern portion experienced ~125 km of total shortening (Vergés et al., 1995), similar to the central region, and greater than in the western reaches of the range. The interior portion of the eastern Axial Zone has been affected by Neogene extensional faulting during the opening of the Gulf of Lyon, but the foreland fold-thrust belt remains unaffected except at its easternmost end (Maurel et al., 2007). The northern (retrowedge) flank of the Pyrenees has a relatively narrow 10 – 40 km-wide fold-thrust belt (Baby, 1998; Mouthereau et al., 2014; Teixell et al., 2018; Ternois et al., 2019).

The narrow southeastern fold-thrust belt is propagated through primarily syn-orogenic Upper Cretaceous to earliest Oligocene strata of the flexural foreland Ebro basin (Muñoz et al., 1988; Vergés, 1995; Verges et al., 1998; Tavani et al., 2020) (Figure 4). The oldest synorogenic sediments found in the eastern portion of the Ebro basin, found only at the northern margin of the basin, are Maastrichtian-Paleocene Garumnian-facies continental siltstones and shallow marine carbonates. The older Eocene (Ypresian and lower Lutetian) units primarily marine, limestones, marls, and turbidites, while the middle Lutetian and younger sediments are primarily continental sandstones and siltstones (Figure 4). The

transition between the marine-dominated lower Eocene and continental-dominated units in the upper Eocene occurs in the mid-Lutetian, and is marked by the ~46 Ma Beuda evaporites, which also serves as an upper decollement for the outer half of the eastern fold-thrust belt. The basal decollement in the eastern portion of the range is the early Eocene marls of the Sagnari formation and the top of the Beuda evaporite (Puigdefàbregas and Sourquet, 1986; Vergés, 1993) (Figure 4). A distinctive feature of the SE Pyrenees is the Freser antiformal stack, a kilometer-scale structure of repeated south-dipping latest Cretaceous-Paleocene (Garrumnian) limestones, separated by south-dipping faults, which appear to be normal faults in the field, but are interpreted as an overturned thrust duplex linked to the now south-dipping Serra Cavallera thrust (Muñoz, et al., 1986; Puigdefàbregas et al., 1986; Figure 4). Each thrust sheet is ~500 m thick and is comprised of Paleozoic basement lithologies and their Garumnian-to-Eocene cover sediments (Muñoz et al., 1986; Vergés et al., 2002). South of the duplex, the section features several south-vergent thrusts, from N to S: the Vallfogona, Abocador and L'Escala thrusts, and the frontal Bellmunt anticline. Whereas the timing of thrusting events in the Pyrenees has been estimated using paleomagnetic and biostratigraphic correlations, close evaluation indicates that constraints of the period of activity on many thrusts remain quite broad. The ability to date shallow fault rocks in the brittle regime has made direct testing of geometric and kinematic scenarios of regional thrusting possible (e.g., van der Pluijm et al., 2006, Haines and van der Pluijm, 2008), and offers a powerful technique to test the validity of previous (often inferred) ages of thrusts, especially where other field constraints are absent.

3.2 - Sample locations

The fault gouges sampled for this study are taken from faults along a transect across the southern fold-and-thrust belt in the eastern Pyrenees along the Ter and Freser rivers north of Barcelona (Figure 3 and 4). The Ter-Freser section is that of Muñoz et al., 1986, Muñoz et al., 1988, and 15 km west of Section J-1 of Vergés, 1993 (Figure 4). Gouges were sampled from the L'Escala, Abocador, and Vallfogona thrusts, a minor thrust in the N limb of the Ripoll syncline, and a thrust within the Freser antiformal stack. Outcrop photos are shown in Figure 5, and sample locations are given in Table 1.

3.2.1 - L'Escala thrust

The L'Escala thrust is exposed in a highway roadcut (currently a bike path) on the west side of Route C-17, about 7 km south of the village of Ripoll (N 42.145487°, E 2.20535°, Figure 4), where the fault plane locally strikes NW-SE and dips 35° northwest. About 10 cm of firm clayey gouge is developed along the fault surface. The thrust is developed at the tip of a breached anticline, likely a fault propagation fold, and places reddish sandstones and siltstones of the middle Eocene (Lutetian) Bellmunt formation over grey sandstones of the middle Eocene (Bartonian) Puigsacalm formation (Figure 5a). The exact magnitude of displacement is uncertain but is likely on the order of 100's of meters, due to stratigraphic constraints (Muñoz et al., 1988).

3.2.2 - Abocador thrust

The Abocador thrust is exposed in roadcuts along both sides of Route C-17, about 6 km south of the village of Ripoll (N. 42.151304°, E 2.200726°, Figures 4 and 5d), where the fault plane strikes ENE-WSW and dips 40° north. The fault core is locally 0.5 – 2 m thick, with 10-50 cm of hard clayey gouge locally developed along the fault surface (Figure 5d).

The thrust places reddish sandstones and siltstones of the middle Eocene (Lutetian) Bellmunt formation over grey sandstones of the middle Eocene (Bartonian) Puigsacalm formation, with about 1 km of displacement (Vergés, 1993). A splay is also found in the same roadcut 100 m to the north of the main exposure, self-juxtaposing the Bellmunt siltstones.

3.2.3 - Vallfogona thrust

The Vallfogona thrust was sampled at a roadcut on Route C-26 near km 154.4, (N. 42.13018°, E. 1.900189°, Figures 4 and 5b), located 5.5 km northeast of Berga and 2.5 km southwest of Vilada. Locally the fault strikes WNW-ESE, and dips vertically, and is readily discernable from a change in colour of the drift (Fig 5b). About 10 cm of firm clayey gouge is preserved along the fault contact upon excavation with a shovel. The hanging wall is comprised of steeply north-dipping turbidites of the Campdevánol Formation that are lower-middle Eocene in age (49 – 46 Ma, upper Ypresian – lower Lutetian, Vergés et al., 1998). The footwall consists of steeply south-dipping carbonate-dominated conglomerates of the upper Eocene (Priabonian) to lower Oligocene in age >2000 m thick Berga formation, although the Berga is locally granite-clast dominated (Mato and Saula, 1991; Burbank, 1992; Saula et al., 2009; Figure 5b). Stratigraphic constraints and paleomagnetic

data (Burbank et al., 1992a) require that the fault was active in the late Eocene to the earliest Oligocene.

3.2.4 – Colonia Pernau thrust – Ripoll syncline

The northern limb of the Ripoll syncline consists of strata ranging from upper Cretaceous carbonates to the middle Eocene Bellmunt formation. Within it, lower Eocene (Ypresian) slope marls and turbidites of the Armàncies formation which are cut by numerous 10's of meters to 100's of meters sub-map-scale ENE-WSW-striking thrusts and folds are well exposed in a railway embankment 0.5 km west of the village of Colonia Pernau, 3.5 km south of the leading edge of the Freser antiformal stack (Figure 4, N. 42.2388°, E. 2.16445°, Muñoz et al., 1988). At outcrop, the sampled thrust dips 40 degrees WNW, while local bedding in the Armancies dips 50 degrees SSW. Gouge from an unfolded north-dipping thrust in the marls was sampled from a 10 cm thick gouge layer. The amount of offset could not be determined in the field, but is likely on the order of 10's to at most 100's of meters, as both hanging wall and footwall are lower Eocene Armancies formation. Due to self-juxtaposition of the Armancies, the age of faulting is not constrained by field relations beyond being post-Ypresian (<47.8 Ma).

3.2.5 - Freser antiformal stack

The antiformal stack is partially exposed in a cliff face at the north end of the Pont de les Coves bridge on the Freser River, approximately 5 km south of the village of Ribes de Freser along Route N-152/N-260 (N. 42.26965°, E. 2.159135°). The cliff face exposes

middle and upper Garumnian (Maastrichtian - Paleocene) silty lacustrine limestones, self-juxtaposed by several gently south-dipping (overturned) thrusts, many with well-developed clayey gouges. 10-20 cm of firm clayey gouge was sampled from one of the thrusts, locally striking E-W and dipping 10° S, exposed at road level, immediately above the horse-bounding thrust (Figure 5c). The thrust sampled is at the base of the fourth (highest preserved) thrust sheet diagrammed in Muñoz, et al., 1988. Prior age constraints for the timing of thrusting are only the depositional age of the Garumnian (latest Cretaceous – Paleocene) and cross-cutting of the rear of the antiformal stack by a poorly-exposed north-dipping, south-vergent, out-of-sequence thrust (Ribes-Camprodon thrust). The Ribes-Camprodon thrust is undated, but is interpreted to post-date the Freser antiformal stack on the basis of cross-cutting field relationships (Muñoz et al., 1986). The Ribes-Camprodon thrust sheet is thought to be the source of basement-derived clasts that appear with increasing frequency in upper Eocene syn-tectonic conglomerates and sandstones of the Bellmunt and Puigsacalm formations to the south, perhaps recording tectonic exhumation along the Ribes-Camprodon thrust (Puigdefàbregas et al., 1986).

4.0 - Methods

4.1 - Gouge sample preparation

All XRD work was performed on a Scintag X1 Θ - Θ powder diffractometer, with a Cu K α source, an accelerating voltage of 40.0 kV, and a filament current of 35.0 mA. To characterize the main clay minerals that are present in each fault exposure, oriented clay slurry mounts of the <2 μ m fraction are first used. Samples are scanned from 2-35° 2 Θ (Cu-K α) at a scan rate of 1°/minute both air dried and after ethelene glycol salvation for periods of 24 hours to 7 days (Figure xa-d, xf). Once the principal clay minerals are

identified, gouges where the primary clay mineral is illitic are then selected for polytypism analysis and centrifuged into three size fractions, 2.0 – 0.5 μm ('coarse'), 0.5 – 0.05 μm ('medium') and <0.05 μm ('fine') (Figures 2, 6e, 7, and Table 2). The Vallfogona sample was split into 4 size fractions, the coarse fraction was split into a 2.0 – 1.0 μm sample ('very coarse') and a 1.0 – 0.5 μm sample ('coarse'), while the fine and medium fractions are the same size as our other samples. As polytype-specific peaks used to establish the polytypism of illite are non-00 l peaks and are suppressed by the oriented mounts used to identify the main clay minerals present, random sample mounts of the separated size fractions prepared in a side-loaded sample packer (Moore & Reynolds, 1997) are used to accentuate the non-00 l peaks for each size fraction. Samples were step-scanned from 16–44° 2 Θ with a step size of 0.05° and a count time of 40 seconds per step (Figure 6).

4.2 - WILDFIRE modeling

To determine the relative abundance of the two polytypes of illite (2M₁ and 1M_d) in each size fraction of gouge, diffraction patterns obtained from random XRD scans were modeled in a spreadsheet using calculated XRD patterns generated by WILDFIRE[®] (Reynolds, 1993). WILDFIRE[®] calculates three-dimensional X-ray diffraction patterns for randomly oriented grains and allows the user to experiment with many mineralogic variables to fully capture the variability of structure ordering in illite, along with allowing the user to vary thickness of the diffracting crystallites, randomness of the sample (also known as the Dollase factor), percentage of interlayered smectite, its hydration state and any ordering of the illite/smectite (Reichweite). This multitude of options allows for optimal matching of real powder patterns, relative to early approaches that used empirical ratios of peak areas

derived from a single set of standards (e.g. Velde & Hower, 1963). The precision of the polytype modeling is 2-3 % (Haines & van der Pluijm, 2008), so we use a 1σ range of 2% for the subsequent illite age analysis. This approach has similar uncertainty to the Rietveld-based approach of Boles et al. (2018).

4.3 - Ar-Ar dating

A total of 16 size fractions from 5 faults were dated by Ar-Ar methods at the University of Michigan. To avoid the problem of argon recoil in fine-grained material, the samples were packaged into fused silica vials and sealed prior to irradiation (van der Pluijm et al., 2001). Thus, the ^{39}Ar expelled from the crystallites during irradiation is retained for analysis (see Dong et al., 1995 for a treatment of the issue). The sample vials were broken open, the initial gas was analyzed, and the vials were then step-heated under a defocused laser until sample fusion occurred. The total gas age obtained from the vacuum-encapsulated sample is equivalent to a conventional K-Ar age (Dong, 1995, 1997).

5.0 – Results

5.1 – XRD characterization of gouge clays

Characterization of oriented mounts of clay-size material ($<2\text{ }\mu\text{m}$ Stokes Law settling velocity equivalent) shows most samples contain some combination of illite, chlorite, quartz, calcite, and/or dolomite in the coarse and medium fractions, but are essentially illitic in the finest size fraction (Table 2). All samples also contain significant amounts of chlorite in the $2.0 - 0.4\text{ }\mu\text{m}$ Stokes equivalent (‘coarse’) and $0.4 - 0.05\text{ }\mu\text{m}$ (‘medium’) size fractions. Illite is the only clay mineral in the $<0.05\text{ }\mu\text{m}$ (‘fine’) size fraction in all samples,

except for Vallfogona. The Vallfogona sample, in addition to neoformed illite, contains some essentially pure smectite in all fractions, as well as small amounts of kaolinite in the very coarse and coarse size fraction, evidenced by a subtle (002) peak at $24.9^{\circ} 2\Theta$, differentiating it from the chlorite (004) peak at $25.1^{\circ} 2\Theta$ (Figure 6e). Evaporite minerals, halite and bertherine are present in some size fractions in minor amounts possibly an artifact of sample preparation. Illite in some samples exhibits some swelling upon glycolation, especially on the low-angle side of the illite (001) reflection at $8.8^{\circ} 2\Theta$, suggestive of the presence of some smectite layers, but glycolation does not measurably change the position of the illite (002) peak from 17.7° ($5 \text{ \AA}$, Figures 6a-d, 6f), so the percentage of smectite interlayers in most samples is $<10\%$ (Moore and Reynolds, 1997). The Vallfogona $<0.05 \mu\text{m}$ sample is the only sample that contained a illite-rich illite-smectite as the authigenic phase, evidenced by the shift in the illite (002) reflection from 17.7° to $17.2^{\circ} 2\Theta$ in the finest fraction upon glycolation (Figure 6e), suggestive of $\sim 80\%$ illite in illite/smectite (R_0) (Moore & Reynolds, 1997). This sample also contained some discrete smectite in the finest fraction, evidenced by a broad hump in the region between $5 - 6^{\circ} 2\Theta$ (Figure 6e).

The chlorite found in our samples ranges from an unaltered chlorite composition with peak intensity of the chlorite (001) $<$ chlorite (002), as at Abocador (Figure 6b), but most samples have XRD powder patterns where chlorite (001) peak height $>$ chlorite (002) peak height (figures 6a, 6c, 6e) suggesting alteration to a disorganized chlorite-smectite or partial alteration to a vermiculite-like composition, similar to chlorites found in natural fault gouges elsewhere (Haines and van der Pluijm, 2012). Chlorite in some samples also

exhibits minor swelling upon glycolation, suggestive of alteration to a chlorite-rich chlorite-smectite, but only the Vallfogona sample showed any change in the 2 - 3° 2 Θ range upon glycolation, suggestive of minor amounts of R1 chlorite/smectite ordering (corrensite, Figure 6e). Such chlorite/smectite or chlorite/vermiculite phases can form either during initial weathering prior to deposition, or during near-surface weathering at the time of exposure (Haines and van der Pluijm, 2012).

Our XRD modeling of random mounts using Wildfire-generated patterns of the various size fractions from each gouge shows that all samples along both transects display a change in polytypism from relatively 2M₁-rich (detrital polytype) in the coarse size fractions to relatively 1M_d-rich (authigenic polytype) in the finest size fractions of the gouge (Table 2). A typical polytype quantification is shown in Figure 7. The transformation from 2M₁ to 1M_d illite is consistent with authigenic illite growth in fault gouge from the breakdown of cataclastically-derived wall rock mica and 2M₁ illite (Haines and van der Pluijm, 2012).

5.2 – Ar/Ar dating

Ar/Ar ages for all samples are reported in Table 2, and spectra are shown in Figure 8. The Ar-release spectra for each size fraction do not have plateaus, because they are composed of mixtures of grains of different ages and grain sizes and due to the effect of Ar recoil. All the spectra have an initial near-zero-age component, representing ³⁹Ar released during irradiation due to recoil (Figure 8). The percentage of ³⁹Ar released during the initial ‘recoil’ fraction increases with progressively finer size fractions. ³⁹Ar released as recoil from the 2.0 – 0.4 μ m size fractions ranges from 13 - 20%, while ³⁹Ar released as recoil

from the $<0.05\ \mu\text{m}$ fractions ranges from 30 – 46% (Table 2). The increasing percentage of ^{39}Ar released as recoil is consistent with finer-grained clays having a higher surface-to-volume area and thus more potential for ^{39}Ar loss during irradiation. Illite Age Analysis plots of the % detrital (2M_1 polytype) versus the total gas Ar-Ar age of each size fraction are shown in Figure 9 and are shown together in Figure 10.

5.3 - Pyrenees fault ages

Gouge ages show that thrusts at several different structural positions in the south-central and south-eastern Pyrenees were active in the mid-to-late Eocene, consistent with the Pyrenees as a critically tapered orogenic wedge during Alpine-Himalayan orogeny at that time. Dating of individual thrusts shows a general progression of in-sequence thrusting that is younger towards the foreland and the direction of hangingwall displacement. Ages of the detrital component reflect the older, Hercynian history of the area.

5.3.1 - L'Escala thrust

The L'Escala thrust is the most outboard structure in the transect through the southeastern Pyrenean fold and thrust belt along the Ter and Freser rivers. Previous age constraints for displacement are unclear, but must be younger than the Bartonian (40.4 – 37.2 Ma) age of the footwall, and slip had been assigned to the Middle Eocene (Travé et al., 2007), although the grounds for such timing are unclear. Authigenic illite in fault gouge is 31.9 ± 3.9 Ma (Figure 9), giving an earliest Oligocene age for the L'Escala thrust, indicating that thrusting probably remained active as the L'Escala anticline grew in the earliest Oligocene. The gouge age also indicates that the L'Escala thrust is the youngest and most outboard

emergent thrust in the Ter-Freser section. The pooled age of the detrital material is 234.8 +/- 9.6 Ma, somewhat younger than the age of the detrital component for the same units for the Abocador thrust, which we interpret as a mixture of Hercynian micas and younger material.

5.3.2 - *Abocador thrust*

The Abocador thrust is a small thrust outboard of the Vallfogona thrust with an outcrop trace of ~25 km. Stratigraphic age constraints for thrust movement are scarce, except that it must have formed shortly after deposition of the footwall Bartonian Puigsacalm sandstones (Travé et al., 2007). The age of authigenic illite in the fault gouge is 36.1 +/- 4.8 Ma, indicating a Priabonian age for fault slip (Figure 9). The pooled age of the detrital component is 279.3 +/- 30.1 Ma, consistent with the presence of detrital micas in the wall rocks that cooled below the closure temperature for Ar diffusion (375 +/- 25 °C, Hodges, 2003) during the Hercynian orogeny.

5.3.3 - *Vallfogona thrust*

The Vallfogona thrust at outcrop juxtaposes early to middle Eocene (Ypresian - Lutetian) turbidites and gypseferous shales against Bartonian to, perhaps, Oligocene (40.4 – 33.9 Ma) sandstones and conglomerates and is found at the base of the south limb of the Ripoll syncline. Stratigraphic constraints and paleomagnetic data require that the fault was active in the middle Eocene to the earliest Oligocene, based on cross-cutting relationships 10 km west along strike (Burbank et al., 1992a). Three periods of activity on the Vallfogona thrust were inferred by Burbank et al. (1992a), 44-42.5 Ma, 41.5 – 40.5 and <39 Ma, based on

magnetostratigraphy and sedimentary relations in the Ripoll syncline and hangingwall conglomerates. The age of authigenic illite in fault gouge from the Vallfogona thrust is 38.9 +/- 5.8 Ma, consistent with the age of the final period of thrust activity inferred by Burbank et al., (1992a; Figure 9). A progressive unconformity in the lower Oligocene Berga conglomerates in the footwall 30 km to the west along strike has been used to argue that the Vallfogona thrust was active until at least 36 Ma and possibly as late as 31 Ma (Vergés & Burbank, 1996, Carrigan et al., 2016). The pooled age of the detrital component of the gouge is 269 +/- 10.1 Ma, consistent with the 2M₁ illite and detrital micas in both the Campdevanol turbidites and Berga conglomerates being Hercynian in age (Figure 9).

5.3.4 - Colonia Pernau thrust

The thrust exposed in the railway cut at Colonia Pernau is a minor thrust within the Ypresian Armàncies marls in the north limb of the Ripoll syncline, south of the Freser antiformal stack, and juxtaposes two different levels within the Armàncies marls. The age of faulting is not constrained by field relations, beyond being post-Ypresian (<47.8 Ma). The age of authigenic illite in fault gouge at Colonia Pernau is 40.9 +/- 7.2 Ma, dating the tightening of the north limb of the Ripoll syncline, and only slightly older than the Vallfogona thrust immediately to the south (see previous section; Figure 9). The gouge date likely records the timing of shortening of the Ripoll syncline. The age is both broadly contemporaneous with the first phase of activity on the Vallfogona thrust to the south (38.6 +/- 5.8 Ma), and overlaps partially with our gouge age from the Freser antiformal stack of 49.5 +/- 4.4 Ma (Figures 9, 11). The pooled age of the detrital illite in the gouge is 324.7 +/- 12.0 Ma, suggesting Hercynian-age detrital clays and micas in the Armàncies marls.

5.3.5 - *Freser antiformal stack*

The Freser antiformal stack (Puigdefàbregas et al., 1986, Muñoz, et al., 1986) is a kilometer-scale duplex structure of south-dipping, overturned, thin thrust sheets. The thrust sampled is at the base of the fourth (highest preserved) thrust sheet (diagrammed in Muñoz, et al., 1988). Prior age constraints for the timing of thrusting are only the depositional age of the Garumnian (latest Cretaceous – Paleocene) and cross-cutting of the antiformal stack by a north-dipping, south-vergent, out-of-sequence thrust (Ribes-Camprodon thrust), which carries Axial Zone rocks of Cambrian and Ordovician age (Muñoz, et al., 1986). The age of authigenic illite in the fault gouge from one of the higher slices in the antiformal stack is 49.5 ± 4.3 Ma (Figure 9) recording an early Eocene age for the earlier stages of the evolution of the stack, assuming the thrust stack evolved with older (higher) thrusts being passively back-rotated by subsequent (lower) thrusts as envisaged by Muñoz et al., (1986). This back-rotation overturned the duplex to its present-day south-facing orientation during the Upper Eocene, perhaps causing the shortening of the north limb of the Ripoll syncline, dated at 40.9 ± 7.2 Ma at Colonia Pernau. The rear portion of the antiformal stack was then cut by the later, undated, out-of-sequence Ribes-Camprodon thrust based on field relations. The pooled age of the detrital component of the gouge is 256.1 ± 19.6 Ma, again recording the primarily Hercynian age for source phyllosilicates contained within the silty Garumnian limestone.

6.0 - Discussion

6.1.1 – Southeast Pyrenees thrust propagation

The ages of faults of the Ter-Freser transect is consistent with forward younging, in-sequence thrusting (Figures 10B, Figure 11). Fault ages decrease systematically from north to south, ranging from 49.5 +/- 4.4 Ma for the northernmost Freser Stack deformation to 31.9 +/- 3.9 Ma for the southernmost L'Escala Thrust. However, although the overall age progression of the thrusts in the Ter-Freser section is clear, four of the five thrusts (L'Escala, Abocador, Vallfogona, and Colonia Pernau) have error bars that overlap a period between 35.8 and 33.7 Ma, suggestive of a 'pulse' of deformation. Ten km to the south (outboard) of the L'Escala thrust is the exposed Bellmunt anticline, which is cored by strongly tilted Bartonian rocks unconformably overlain by weakly folded Priabonian Berga Conglomerates (Institut Cartogràfic i Geològic de Catalunya, 2018), suggesting significant folding occurred somewhere between the Bartonian and the Priabonian (from ~40 Ma to <34 Ma).

Elsewhere in the Pyrenees, multiple thrusts have also been shown to be active during the Eocene. Gouge from the internal Gavarnie thrust in the central portion of the range was dated as 36.5 +/- 1.4 Ma (Rahl et al., 2011), and a footwall splay of the Gavarnie thrust, the Pic de Port Vieux thrust has neoformed muscovite in the pressure-solution-dominated fault rocks dating to 36.9 +/- 0.2 Ma (Abd Elmola et al., 2018). In the south-central portion of the range, the Serres Marginals and Montsec thrusts were also active (Meigs and Burbank, 1997), while thrusting from the northern side of the Pyrenees similarly dates from this time interval (Fischer, 1984; Bosch et al., 2016; Grool et al., 2018; Parizot et al., 2021).

The coeval ages of thrusting on many faults in multiple regions of the Pyrenees during the Middle and Late Eocene demonstrate that the range effectively behaved as a doubly tapered critical wedge, analogous to the no-backstop critical wedge model (sensu Dahlen et al., 1984). Contemporaneously, normal faulting in the eastern end of the Axial Zone began at 35 Ma, further suggesting a latest Eocene shift in the dynamics of the range (Milesi et al., 2022). The eastern end of the range records localized extension within the Axial Zone, related to the opening of the Gulf of Lyon, evidenced by modelling of 43 – 18 Ma apatite (U-Th)/He cooling ages sampled across the Têt normal nault (Milesi et al., 2022). No similar late Eocene extension has been documented in the central or western portions of the range.

Although the detached cover in the south-central portion of the range began in the late Cretaceous, with slip on the Boixols thrust, shortening in the detached cover in the Ter-Freser area only began around 50 Ma (Ypresian - early Eocene). This relatively late onset of shortening, over 20 Ma later than the south-central portion of the range, suggests that other faults in the system, such as the Pedraforca Nappe system, 20 km to the west of the Ter-Freser section were dominant in taking up convergence earlier in the eastern region's evolution. The Upper Pedraforca Nappe was emplaced between the latest Cretaceous and the middle Ypresian (Vergés et al., 2002, Cruset et al., 2020). The end of the emplacement of the Lower Pedraforca Nappe (Ypreseian-Lutetian) overlaps with the onset of shortening in the Freser antiformal stack (also Ypresian – Lutetian), suggesting an along-strike shift

of shortening in the detached cover to the east, perhaps in relation to along-strike variations in foreland basin stratigraphic architecture (discussed further in section 6.3.7).

6.1.2 – Ter-Freser bulk shortening and strain rates

The J-1 cross section along the Ter-Freser section has 31 km of shortening over a that restores to a 55 km length (57% shortening) over a previously-reported time interval between 47 and 34 Ma, indicating a minimum shortening rate of ~2.5 km/my (Vergés, 1993). Those age constraints for thrusting were determined biostratigraphically from growth strata. Our direct fault dating age results along the J-1 section indicates thrusting occurred over a longer time interval (49.5 +/- 4.4 to 31.9 +/- 3.9 Ma) than previously reported, with a resulting range of shortening rate from 1.2 – 2.7 km/my. If thrusting occurred during the maximum duration of all errors from the fault dating, (53.9 to 28.0 Ma), the resulting shortening rate would be 1.2 km/Ma; (Figure 11b). If the rate is calculated using the youngest age at which all frontal thrusts all overlapped within error (33.8 Ma), and using the age at the minimum error of the Freser antiformal stack (45.1 Ma), the resulting shortening rate would be 2.7 km/my, similar to the 3 km/my shortening rate reported by Vergés et al. (1995) (Figure 11b). In particular, our 49.5 +/- 4.4 Ma for the oldest thrust in the section, 5 Ma older than the previous age based on biotratigraphical constraints (Vergés, 1993), highlights the advantage of direct fault dating to constrain the onset of thrusting, which is challenging when reliant on the limited growth strata preservation in the internal portions of the range. Strain rates range from $7.0 \times 10^{-16} \text{ s}^{-1}$ for the 1.2 km/my case, to $1.6 \times 10^{-15} \text{ s}^{-1}$ for the 2.7 km/my case. Vergés et al., (1995; 2002) had independently calculated shortening rates for the same area of the southeastern

Pyrenees through time and derived a range from 0.5 km/my for Late Cretaceous and Paleocene times, with an acceleration to 4.5 km/my in early to mid-Eocene times, then shortening by 2 km/my after 47 Ma until 28 Ma. Cruset et al., (2020) reported similar shortening rates of 0.6 – 1.1 km/my on several thrusts in the Pedraforca nappe stack, 40 km to the west of the Ter-Freser section, documenting broadly in-sequence thrusting since 71 Ma using U-Pb ages of syn-tectonic calcite veins in fault zones. Shortening rates elsewhere across the Pyrenees fold-thrust belt are similar, with 1.7 – 2.6 km/ma reported for the shortening of the Jaca Basin in the central portion of the range (Labaume et al., 2016b). Pyrenean shortening rates are thus relatively consistent along strike (~1 – 4 km/ma), but are low compared to those in larger continental-scale orogens, such as the US-Canadian Rockies and the Himalaya where shortening rates of 5 – 20 km/my have been reported (Mugnier et al., 2004; Hirschmiller et al., 2014; Pana et al., 2015)

6.2 - Detrital ages and their interpretation

6.2.1 – Terr-Freser section detrital ages

The age extrapolated for the detrital component of fault gouge is a ‘pooled’ age of a mixture of grains derived from both the footwall and hanging wall (Figures 2 and 10a). In the Ter-Freser section, all the wall rocks are latest Cretaceous to earliest Oligocene in depositional age, and, based on paleocurrent analyses, are derived from the exhuming Pyrenees range to the north (Puigdefabrigas et al., 1992). Although a single age detrital age extrapolated from illite age analysis is a mixture of both footwall-derived and hanging wall-derived grains, the consistency of the 234-330 Ma ages of the detrital component from wall rocks of the five faults in the Ter-Freser transect argues that detrital clays in the wall rocks in

both the Garumnian and Eocene units in the eastern Ebro Basin are predominantly Hercynian in origin (Figures 10a, 12). Muscovite, Biotite, and K-feldspar Ar-Ar ages in the Central Pyrenees range from 320 to 280 Ma (Metcalf et al., 2009; Denele et al., 2014), and muscovite Ar-Ar ages from schists in the eastern Axial zone in Andorra range from 290 to 250 Ma (McCaig & Miller, 1986). Single-grain laser probe ages from muscovites in the Canigou Massif north of our field area yield discordant ages from 88 to 300 Ma, interpreted to be Hercynian ages micas partially exhumed during the early Cretaceous (Maurel et al., 2008). Detrital U-Pb ages from Paleocene to Oligocene sediments in the eastern Ebro basin, including the hanging wall of the Vallfogona Thrust near our Vallfogona gouge sample, similarly indicate that the youngest significant zircon population in sediments of the eastern Ebro basin is Hercynian (Odlum et al., 2019), suggesting a primarily Hercynian sediment source.

The age of the oldest Ar-Ar degassing step in each of our Ar analysis for the ‘coarse’ size fraction (2.0 – 0.2 μm) ranges from 236 to 285 Ma, while the oldest degassing step in each medium fraction analysis (0.2 – 0.05 μm) similarly ranges from 235 – 285 Ma (Figure 8). Taking into account that some ^{39}Ar may have been lost from even the coarse (<2.0 μm) micas during irradiation, both the oldest ages from each degassing step and the pooled ages from the illite dating are consistent with the detrital micas formed or reset during the Hercynian orogeny, and were exhumed to the surface by the late Cretaceous, or perhaps during the initial Permo-Triassic exhumation of the range. The 234 – 325 Ma detrital ages are pooled ages of micas and 2M_1 illite that experienced exhumation during the Hercynian Orogeny with a volumetrically minor contribution of micas that formed and cooled during

subsequent early Cretaceous or early Pyrenean orogenic events (Maurel et al., 2008; Ternois et al., 2019). The detrital ages from illite dating constrain the source regions of wall rock sediments, and serve as an internal check on the quality of the quantifications and the geologic meaning of authigenic ages.

6.2.2 – Previous interpretations of detrital ages from gouge dating

Other fault gouge dating studies have deduced different interpretations for the age of the $2M_1$ component in other geological settings. Two studies report fault gouge ages from brittle faults in high-grade metamorphic rocks in the Alps (Zwingmann and Mancktelow, 2004; Zwingmann. et al., 2010). These studies reported late Miocene ages for the $1M_d$ component, while the $2M_1$ component yielded a mid-late Miocene age. In those cases, wall rock mica and feldspar Ar-Ar ages indicated that wall rock ages were 16 – 19 Ma, ~10 Ma older than the inferred 9 Ma age for the $2M_1$ component. In those cases neoformation of $2M_1$ illite in the fault gouge, in addition to neoformation of $1M_d$ illite, was suggested on the basis of illite crystallinity measurements and SEM images to explain the difference in age between the $2M_1$ age deduced from the fault gouge, and the apparent equivalent $2M_1$ age of wall rock micas and feldspars. Similarly, three fault gouge dating studies from high-grade metamorphic rocks in SW Norway report apparent $2M_1$ component ages 10's of Ma to ~100 Ma younger than Ar/Ar or K-Ar ages of similar phases from wallrocks (Viola et al., 2016, Scheiber et al., 2018, Scheiber et al., 2019). Again, neoformation of $2M_1$ illite in the fault gouge in addition to $1M_d$ illite was suggested on the basis of SEM and TEM images, and illite crystallinity measurements. Abd Elmola et al. (2018) similarly report apparently neoformed $2M_1$ from the Pic de Port Vieux thrust, a lower branch of the Gavarnie Thrust in the Central Pyrenees, a greenschist facies fault zone dominated by

pressure-solution processes, although hot basinal fluids migrating up the fault may have played a significant role on thermal conditions inside the fault zone relative to wall rocks. See below.

The main branch of the Gavarnie thrust, where fault rocks are both pressure-solution-dominated carbonate fault rocks (Figures 13b, 13c, 13d), suggestive of temperatures of 150 – 250°C and clayey shales with authigenic 1M_d illite entrained in the fault zone formed at lower temperatures (50 – 180°C, Haines & van der Pluijm, 2012, Figure 13), is an unusual case. Although the hanging wall rocks are Devonian phyllites, field relations require that the phyllites at Plan de Larri, through which the Gavarnie thrust propagated, have been mostly within 3 km of the Earth's surface since the late Cretaceous. The fault zone exposure is found only 400 m down-dip of a Cretaceous unconformity where the phyllites are unconformably overlain by micritic limestones of Coniacian – Santonian age (89 – 83 Ma, Figure 13a). The overlying Santonian-to-Eocene stratigraphic section was approximately 2 – 2.5 km thick (Rios Argues et al., 1987), suggesting maximum wall rock ambient temperatures of 85°C (2.5 km burial at an assumed geotherm of 30°C/km + a minimum sea bottom temperature of 10°C). As the various Cretaceous limestones in both the hanging wall and footwall preserve primary sedimentary textures beyond 10 meters from the fault plane, heating of the whole interval by tectonic burial during emplacement of the overlying Noguères thrust sheet during the Paleocene and Eocene must have been minor. Although the surrounding wall rock temperatures are likely to have been similar to those along thrusts along the Ter-Freser section, the fault rocks are dramatically different. At the outcrop shown in Figure 13b, the fault rocks are predominantly protomylonitic carbonate fault

rocks (Figures 13c, 13d), with clayey shales only locally entrained in the fault zone developed near the contact with the hanging wall (Figure 13b). In hand specimen and thin section, the carbonate-rich fault rocks evidence clear crystal-plastic deformation of carbonate but brittle fracture of quartz grains in the carbonate matrix (Figure 13d). These textures require deformation at temperatures ($150^{\circ}\text{C} < \text{deformation} < 250^{\circ}\text{C}$, Passchier & Trouw, 2005) temperatures far higher than would be predicted from the stratigraphic limitations described above. As the conditions for the formation of 2M_1 micas are generally held to be $>250^{\circ}\text{C}$ (Sroden & Ebri, 1984), the 69.3 ± 0.7 Ma age of 2M_1 mica that apparently cooled below its blocking temperature while in a fault zone with local temperatures of $150 - 250^{\circ}\text{C}$ must instead be the result of the passage of high-temperature Sr-rich basinal fluids up the Gavarnie Thrust fault as described by McCaig et al., (1995). Whether the 69.3 ± 0.7 Ma detrital age actually dates an early pulse of fluid migration on a proto-Gavarnie thrust, or is a result of partially resetting the Ar-Ar system of wall rock micas with original Hercynian Ar-Ar ages by a pulse of hot fluids during the Eocene(?) is unclear.

By contrast, fault gouge ages from metamorphic core complexes, where wall rocks are amphibolite-facies metamorphic rocks, extrapolated 2M_1 component ages are essentially coeval with observed muscovite or feldspar Ar/Ar ages of wall rocks, suggesting a purely cataclastic origin for the 2M_1 component in those gouges (Haines and van der Pluijm, 2008, 2010). Several previous clay gouge dating studies from the American Cordillera and Appalachians with sedimentary wall rocks report 2M_1 component ages significantly older than depositional ages for wall rock sediments, sometimes by 100's of Ma (van der Pluijm

et al., 2001; 2006; Solum et al., 2005; Solum and van der Pluijm, 2007; Fitz-Diaz et al., 2014; Hnat and van der Pluijm, 2014; Pana et al., 2015). Those ages are consistent with a purely cataclastic origin for the $2M_1$ in these faults, although the polyorogenic history of western North America makes a precise interpretation of each detrital gouge age challenging, as thermal histories of wall rock micas may be complex. The age of the $2M_1$ component extrapolated during fault gouge dating is thus context-specific and needs to be examined together with the deposition or crystallization age of wall rocks and subsequent cooling history for its geological meaning to become clear.

6.3 – *Temperature of Pyrenees gouge formation*

The temperature interval over which authigenic $1M_d$ illite forms in clay gouges was previously estimated at 50 – 180 °C, based on integrating gouges ages with constraints from thermochronometers such as apatite fission track (AFT), zircon fission-track (ZFT) and apatite (U/Th)/He ages (AHe) from hanging wall or footwall rocks (Haines and van der Pluijm, 2012). Vrolijk and van der Pluijm (1999) estimated a temperature of 115 – 180°C for gouges from the Canadian Rockies (based on apatite fission track ages and vitrinite reflectance measurements). Zwingmann and Mancktelow (2004) estimated the temperature of clay gouge illite formation at between the closure temperatures of the ZFT and AFT systems, between 110 and 220°C. For the Ter-Freser section, apatite fission-track ages have been reported for the immediate hanging wall of the Freser antiformal stack and the Vallfogona thrust (Rushlow et al., 2013) (Figure 14a). We also note that all outcrops along the Ter-Freser show no visible evidence for late hydrothermal alteration, in contrast with the Gavarnie exposure described above.

6.3.1 – *Freser antiformal stack*

Stratigraphic constraints require that the hanging wall Garumnian sandstones were buried to depths of 1.5 – 3.0 km (Vergés, 1993), suggesting a background wall rock temperature of 40 - 85°C at the time of gouge formation, assuming a geothermal gradient of 20-25°C/km and a mean annual surface temperature of 10°C (Vergés et al., 1995). Rushlow et al. (2013) reported an apatite fission track age of 22.9 +/- 2.6 Ma from hanging wall sandstones, which they report as partially-reset, based on track length distributions. This 22.9 Ma AFT age is significantly younger than the gouge age of 49.5 +/- 4 Ma, indicating that fault gouge formation preceded rapid, likely tectonic, exhumation through the apatite fission-track partial annealing zone (PAZ = 60 - 110°C) at 25 to 20 Ma by ~15 Ma (Figure 13a). The preferred modelled temperature range of the hanging wall rocks at the possible time of gouge formation (53.9 – 45.1 Ma) is 50 - 110°C (Rushlow et al., 2013). Thrusting occurred during basin subsidence, and prior to peak burial from 35 to 28 Ma at ~130°C. A formation temperature interval anywhere from 40 to 170 °C is permissible from a combination of the minimum temperature from a 1.5 km burial depth, and the maximum temperature from the maximum of the modelled AFT history. A temperature range of 50 - 110°C is most likely for the Freser antiformal stack gouge, using the most likely modelled time-temperature history of Rushlow et al. (2013), although temperatures in the fault zone itself could have been somewhat higher (see below). It should be noted that the time-temperature history of Rushlow et al. (2013) only extends from 0 to 50 Ma and does not include the interval between 70 and 56 Ma (deposition of the Garumnian) and 50 Ma. Their model also permits unusually high temperatures (up to 180°C) for rocks only buried to depths of <3 km (Figure 13a).

6.3.2 – Colonia Pernau thrust

The Colonia Pernau thrust gouge lacks any fission-track constraints, but a 1-D burial model and vitrinite reflectance data from the wallrock Armancies marls indicate that the Armancies was buried to depths <3 km (Vergés et al., 1995), suggesting a background wall rock temperature range of 70 – 85°C, assuming a geotherm of 20 – 25°C/km. These temperatures would be within previous estimates of temperatures of neoformed clay growth of 60 - 180°C (Haines and van der Pluijm, 2012).

6.3.3 – Vallfogona thrust

An AFT sample from the hanging wall of the Vallfogona thrust at the same locality as our Vallfogona gouge sample yielded a fully-reset age of 30.0 +/- 4.6 Ma, suggesting that the 38.6 +/- 5.8 Ma neoformed gouge formed before the fault passed through the 110°C isotherm for AFT closure (Rushlow et al., 2013). The modelled time-temperature history of the Vallfogona hanging wall for the time period over which the gouge might have formed (44.4 – 32.8 Ma) is quite variable, ranging from 30 to 180°C, with a maximum temperature of ~180°C near 38 Ma, immediately before slow cooling through the apatite PAZ from 38 to 24 Ma (Figure 13b; Rushlow et al., 2013). The minimum wall rock temperature from stratigraphic constraints, assuming maximum 4 km burial of the Campdenavol turbidites (Vergès, 1993), a 20 – 25 °C geotherm and a 10 °C surface temperature is 90 °C. In addition, Cruset et al., (2018) reported temperatures from syntectonic calcite veins calculated using carbonate clumped isotope thermometry (Δ_{47}) for both the Vallfogona thrust hanging wall and Abocador thrust at the same localities as we sampled for gouge dating. For the Vallfogona thrust, pre-faulting bedding-parallel calcite

veins in wall rock indicate a Δ_{47} temperature of $154 \pm 2^\circ\text{C}$, while syn-faulting calcite veins precipitating along the fault plane yield temperatures of $101 \pm 6^\circ\text{C}$ and $105 \pm 14^\circ\text{C}$ (Figure 10b; Cruset et al., 2018). Thus, for the Vallfogona thrust, a temperature range of $90 - 160^\circ\text{C}$ is the best estimate for authigenic illite growth, honoring the pre- and syn-faulting Δ_{47} temperatures.

6.3.4 – Abocador thrust

For the Abocador thrust, Cruset et al., (2018) reported a single Δ_{47} temperature from calcite veins of $177 \pm 40^\circ\text{C}$, significantly higher than the <2 km maximum burial depth at the time of thrusting might suggest ($50 - 60^\circ\text{C}$) (Vergés, 1993) (Figure 13c). Cruset et al., (2018) describe the Abocador measurement as “preliminary”, in contrast to the other 8 measurements they report, and it has a temperature error $>2\times$ larger than the other 8 measurements. In that study, Cruset et al. (2018) presented a model of early $\delta^{18}\text{O}$ -enriched, basin-derived brine circulation sourced from the Beuda evaporites (the stratigraphic interval the Abocador thrust is detached on) being variably diluted by later meteoric fluids that enter the system when the southern Pyrenees margin transitions from being predominantly marine to continental, and thus open to some meteoric fluid recharge and circulation at ~ 37 Ma. We note that the relationship of the vein to the clay gouge is not described, and that the uncertainty of the measurement is consistent with the temperature ranges surmised for the other faults along the transect. We also note that the fault rocks at Abocador are not visibly different from those of the other faults we have sampled, both along the Ter-Freser section and in a previous study in the central Pyrenees (Rahl et al., 2011). The $177 \pm 40^\circ\text{C}$ Δ_{47} temperature is therefore considered an upper bound to the

temperature interval at which authigenic illite in gouge formed, but a lower bound cannot be established beyond a likely minimum temperature of 50°C, based on a maximum of 2 km burial of the juxtaposed units.

6.3.5 – *L'Escala thrust*

Like the Colonia Pernau thrust, the L'Escala thrust has no independent constraints on paleotemperature. The paleodepth of the juxtaposed wall rock units at the time of thrusting is <2 km, which is similar to the Abocador thrust 1 km to the north. The fluid flow history derived from $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ isotopic measurements from syn-tectonic calcite veins was interpreted to suggest warm basinal fluids early in the thrust's history, followed by basinal fluids mixed with meteoric fluids later in the fault's history (Trave et al., 2007). This interpreted fluid flow history is more similar to the Vallfogona thrust than to the Abocador thrust (Cruset et al., 2018), and it is thus possible that the L'Escala fault gouge formed at similar temperatures to the Vallfogona (90 - 120°C).

6.3.6 – *Other Pyrenees thrusts of the southern fold-thrust belt*

Clay gouge from a previous clay gouge dating study included the Boixols thrust 80 km west along strike from the Ter-Freser section, which was dated at 71.2 +/- 6.4 Ma (Rahl et al., 2011). Δ_{47} temperatures from syn-faulting calcite veins at the same outcrop have since been reported as 88 +/- 4°C (Nardini et al., 2018).

From our collective observations, we conclude that the most likely temperature interval for authigenic 1M_a illite in Pyrenees gouges is 50 - 160°C, although the Abocador thrust gouge could have formed at higher temperatures, if the poorly constrained Δ_{47} temperature is to

be relied upon. This temperature range is similar to previous temperature ranges of 80 – 180°C (Haines and van der Pluijm, 2012), and between the closure temperatures of ZFT and AFT systems (Zwingmann and Mackentelow, 2004). We note that continued fault slip at temperatures below the interval at which illite grows in fault gouge is possible, and may explain why stratigraphic and geochronological estimations of fault activity do not always agree. For at least some faults in the Ter-Freser section, this scenario appears possible. The footwall of the Vallfogona thrust contains growth strata as young as Bartonian to earliest Oligocene (44.3 – 31.6 Ma, Carrigan et al., 2016), somewhat younger than the 38.5 +/- 5.5 Ma gouge age. Fault gouge ages can thus be thought of as recording time since a fault zone was last active at thermal conditions sufficient for the growth of 1M_d illite (50 – 180°C).

6.3.7 – Comparison with central Pyrenees thrusting

Faulting along a transect in the south-central Pyrenees along the ECORS deep seismic profile was dated by Rahl et al., (2011), which documented both early thrusting on the Boixols thrust, inverting early Cretaceous normal faults, and later thrusting in the central region of the range, as the Axial Zone antiformal stack grew in a piggy-back manner during the Eocene, as well as local out-of-sequence thrusting. (Figure 15). The Axial Zone antiformal stack in the interior portion of the central Pyrenees consists of 4 thrusts, successively the Noguères, Gavarnie, Orri and Rialp thrusts (Munoz, 1992; Teixell et al., 2018). The Noguères (56.4 +/- 1.3 Ma) and the Gavarnie (36.5 +/- 1.4 Ma) thrusts were active in-sequence, although the closeness in age of the Gavarnie gouge age to Priabonian (37.7 – 33.9 Ma) growth strata associated with the Orri thrust indicates the Gavarnie and Orri thrust may have been active essentially simultaneously (Burrell et al., 2021). Several

sets of thermochronometer data similarly suggest that a significant pulse of tectonically-driven exhumation occurred in the central Axial Zone region around 35 - 25 Ma, linked to growth of the antiformal stack and local out-of-sequence thrusting in the interior portion of the range as the orogenic wedge thickened (Fitzgerald et al., 1999; Sinclair et al., 2005; Gibson et al., 2007; Jolivet et al., 2007; Metcalf et al., 2009; Labaume et al., 2016; Bosch et al., 2016, Waldner et al., 2021). A clay gouge age from the interior Llavorsi-Senet thrust (24.0 +/- 1.3 Ma; Rahl et al., 2011) directly identified an out-of-sequence thrust in Axial Zone rocks that had only been speculated at from thermochronometer data (e.g. Jolivet et al., 2007; Labaume et al., 2016a), or growth strata in the outboard portion of the range (Meigs and Burbank, 1997). Those results demonstrated the advantages of dating clay gouges directly to identify active faults in deeply eroded regions where other direct constraints, such as growth strata on key faults are absent.

Our fault gouge ages from the eastern portion of the range suggest a quite different pattern of thrust evolution in the evaporate-detached cover compared to the central portion of the range, with thrusting mostly in-sequence in the eastern detached cover, while in the central Pyrenees, the detached cover records significant out-of-sequence thrusting (Meigs & Burbank, 1997). Exhumation patterns deduced from thermochronometer data in both the eastern portion and central regions of the Pyrenees indicate a significant acceleration in the mid-Eocene to Oligocene, and are similar to those in the central portion of the range (Rushlow et al., 2013; Ternois et al., 2019). The overall similarity of thermochronometer age distributions between eastern and central regions of the range suggest a similar evolution of the orogenic core in both areas of the range, but the different thrusting ages

between the eastern and central Pyrenees suggest a different propagation response of foreland thrusting, perhaps controlled by differing foreland basin stratigraphy changing orogenic wedge taper. The Ebro Foreland Basin stratigraphic architecture is different between the eastern and central Pyrenees. In both the central and eastern Pyrenees, the Ebro Basin contains latest Cretaceous/Paleogene rocks overlying basement and are overlain by Eocene and Oligocene basin fill sediments (Vergés, 1992, 2000; Oldum et al., 2019; Figures 4 and 12). In the Central Pyrenees, the basin also contains a thick Mesozoic section, a relic of pre-Pyrenean rifting (e.g. Muñoz, 2019), which is detached along the late Triassic Keuper evaporites. The Mesozoic section, including the Keuper, is absent from the eastern Pyrenees. Three evaporite horizons are known in the Tertiary of Ebro Basin, the middle Eocene Beuda gypsum (~46 Ma), the late Eocene Cardona salt (~37 Ma), and the latest Eocene/Oligocene Barbastro salt (~36 - 34 Ma, Vergés, 1992, 2002; Oldum et al., 2019, Figure 12). The evaporites young from east to west as the basin depocenter migrated westwards and southwards during the Eocene (Vergés, 2002). The Beuda is confined to the eastern Ebro Basin, while the Cardona and Barbastro are found in the central and western portions of the basin respectively, and are more areally extensive (Vergés, 1993). Well penetrations indicate the South-Central Pyrenees under the Serres Marginales and Montsec thrust sheets are detached on autochthonous Cardona salt, and locally Oligocene marls near the Barbastro anticline (Vergés, 1993; Muñoz et al., 2018), and that the Cardona extends into the foreland basin for 10's of km to the south. By contrast, the eastern Ebro Basin lacks the Cardona salt, and the sole thrust instead follows the top of the Beuda, which has a much smaller areal extent and does not extend out into the basin. We suggest that the narrower fold-thrust belt in the southeastern Pyrenees is a function of the lack of a low-

friction decollement in this portion of the basin, at either the Tertiary or deeper Mesozoic level.

7.0 - Summary and Conclusions

We report new fault rock ages from a suite of clay gouges from 5 thrust faults in the southeastern Pyrenees of Spain along the Ter and Freser Rivers, dated by illite age analysis. The new ages determine the absolute timing of thrust motion along a well-exposed section and constrain thrust belt shortening velocities and strain rates. Our results show ages with a broadly in-sequence propagating of thrusts in the outer portion of the fold-thrust belt into the foreland over about 19 my (9.3 my to 25.9 my, incorporating uncertainties). Our ages for the most outboard thrusts, Vallfogona (38.6 $\pm$ 5.8 Ma), Abocador (36.1 $\pm$ 4.8 Ma) and L'Escala (31.9 $\pm$ 3.9 Ma) are within error of the ages of the Gavarnie, Serres Marginals, and Montsec thrusts (Meigs et al., 1996; Rahl et al., 2011) in the south-central portion of the range, and thrusts in the northern reaches of the range (Grool et al., 2018) demonstrating coeval thrust activity at a variety of positions in the orogenic wedge during the middle Eocene.

1. Slip on the oldest thrust of the inboard Freser antiformal stack occurred at 49.9 $\pm$ 4.4 Ma, an age coinciding with the observed Early Eocene acceleration of subsidence at the northern edge of the Ebro Basin (Vergés et al., 1998). Subsequent shortening in the lower Eocene marls of the Ripoll syncline occurred at 40.9 $\pm$ 7.2 Ma, perhaps contemporaneously with shortening on the younger thrusts of the Freser stack. The Vallfogona thrust has an age of 38.6 $\pm$ 5.8 Ma, while the Abocador thrust is immediately outboard of the Vallfogona thrust and records an

- age of 36.1 +/- 4.8 Ma. The L'Escala thrust is the most outboard thrust and appears to record the final period of thrusting in the southeastern Pyrenees at 31.9 +/- 3.9 Ma. Shortening rates for the Ter-Freser section range from 1.2 to 2.7 km/my. Bulk strain rates for the Ter-Freser section range from $7.0 \times 10^{-16} \text{ s}^{-1}$ to $1.6 \times 10^{-15} \text{ s}^{-1}$.
2. Our thrust ages reveal a marked contrast in thrust propagation style between the southeastern and south-central portions of the range, with forward-breaking in-sequence thrusting dominating the southeastern detached Ter-Freser section, while in the south-central transect, outboard evaporite-detached and inboard deeply-rooted sets of thrusts are evolving simultaneously (e.g. Munoz, 1992; Meigs and Burbank, 1997; Rahl et al., 2011; Muñoz, 2019), owing to inversion of a Mesozoic pre-orogenic rift basin in the central portion of the range, and different stratigraphic position of evaporites in the foreland basin fill. Thus, kinematics in a detached foreland fold-thrust belt can vary significantly even on the scale of tens of km along strike in an orogen, in response to the interaction between deformation, deposition and uplift.
 3. The ages of the detrital (cataclastically-derived) component of fault gouge range from 325 +/- 12 Ma to 235 +/- 10 Ma, consistent with the interpretation that the age of the cataclastically-derived component is the pooled age of wall rock micas. Our ages indicate the primary source region for Paleogene rocks of the southeastern Pyrenees was Hercynian in age (310 – 280 Ma), showing that the southern Pyrenean foreland basin received detrital clay input primarily from exhumed and eroding Hercynian rocks in the central portion of the range at that time.

4. Temperature of clay gouge formation is constrained by pre-existing thermochronometer ages from wall rocks and Δ_{47} temperatures of syn-faulting calcite veins. These data bracket clay gouge temperatures as 50 - 210°C, with the most likely range of temperatures of 50 - 160°C, in accordance with the stability field of the low-temperature illite 1M_d polymorph.

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Figure captions

Figure 1: Sketch of balanced cross-section through a hypothetical thin-skinned fold-and-thrust belt illustrating possible thrust propagation scenarios that can be tested by brittle fault dating. Section simplified from Powers et al., (1998), timing altered for clarity.

Figure 2: Sketch illustrating the illite dating method to directly date clay-rich fault gouge containing illite as the neoformed clay.

Figure 3: Sketch geological map of the Pyrenees in Spain and France, after Verges, (1993) Location map of faults sampled in this study are shown with red circles. Letters refer to other faults mentioned in text. SET = Sierras Exteriores Thrust; GvT = Gavarnie Thrust; NPF = North Pyrenean Fault; L-S T = Llavorsi-Senet thrust, NT = Noguères zone, BT = Boixols thrust, MT = Montsec thrust, SM = Serres Marginals; P = Pedraforca nappe, PPV T = Pic de Port Vieux Thrust; VT = Vallfogona Thrust; CdC = Cap de Creus. Box shows area of Figure 3. Trace of balanced cross-section J-1 of Vergés (1993) shown in red, section appears on Figure 3.

Figure 4: Geologic map, stratigraphic section, and cross-section of the study area. Upper: Geologic map of a portion of the south-east Pyrenees, with sample locations, and stratigraphic column for the Ter-Freser river section shown. Map is redrawn after the Mapa Geològic de Catalunya (2002) and the section is redrawn after Vergés (1993) and modified slightly by Travé et al., (2007). The section extends along the line shown and extends about 10 km to the south of the map area, but with no apparent shortening south of the region shown.

Figure 5: Outcrop photographs of several thrusts sampled for this study. A) L'Escala thrust on Route C-17, ~25 km north of Vic. Arrow shows rock hammer for scale at sample site. B.) Vallfogona thrust on route C-26, ~5 km W of Vilada. Sample taken 5 m below pine tree. C) Freser Stack thrust at Pont de les Coves on west side of river on side road. D.) Abocador thrust outcrop on route C-17, ~26 km north of Vic.

Figure 6: XRD spectra of clay-fraction ($<2\ \mu\text{m}$) separates from all fault gouges dated in this paper. Samples are prepared air-dried oriented mounts to accentuate (00l) peaks for clay identification. Samples were analyzed air-dried, and then again after ethylene glycol solvation for 24 hours to 7 days. Note 6e shows a representative separation of each $<2\ \mu\text{m}$ size fraction into three or four distinct size fractions by repeated centrifugation of the $<2\ \mu\text{m}$ fraction.

Figure 7: Representative polytype quantification of clay gouge illite. Patterns show gouge from the Abocador Thrust (black), together with modelled XRD pattern using WILDFIRE-generated XRD patterns to quantify the relative abundance of the $2M_1$ and $1M_d$ polytypes of illite in the coarse ($2 - 0.4\ \mu\text{m}$), medium ($0.4 - 0.05\ \mu\text{m}$), and fine ($<0.05\ \mu\text{m}$) size fractions. Note the decreasing amount of the $2M_1$ (detrital) component in progressively finer size fractions, and that the finest fraction consists almost entirely of the $1M_d$ polytype. B = Berthierine.

Figure 8: Ar-Ar spectra for each size fraction of gouge dated in this study. Note spectra do not contain well-defined plateaus, as each spectrum is a pooled ages of grains of two age populations, whose relative abundances are determined by the XRD modelling. Note also the significant fraction of ^{39}Ar (18 – 45%) released due to recoil. See text for discussion.

Figure 9: Illite Age Analyses plot for each of the five gouges sampled. Bold numbers are interpreted age of authigenic illite in fault gouge, italicized ages are interpreted pooled age of cataclastically-derived wall rock mica and illite

Figure 10: Illite Age Analysis results of all faults sampled viewed together. A) IAA plot showing gouge and pooled hanging wall ages for all samples used in this study. Note all gouge ages are from the latter half of the Pyrenean orogeny, and the pooled wallrock ages are all approximately Hercynian in age. Orogenic ages are from Denele et al., (2014) and Vergés, 2002). Box shows the area of Fig. 10B. Note that age increases up the Y axis in both plots, so periods and ages on the right-hand Y axis appear upside-down relative to a conventional geologic time scale. B) Detail of graph on left. Note the systematic younging-to-south progression of ages, towards the foreland. Legend is same in both plots, and is arranged north-to-south.

Figure 11: Ter-Freser section gouge ages and possible interpretations of shortening. A) Map view of same area as Figure 3 with simplified geology and gouge ages. Grey is Paleozoic Axial Zone rocks. Cenozoic lithologies are whited out for clarity, except for Beuda evaporite (pink), Armancies marls (hashed pattern), and Bellmunt sandstones (dotted pattern). Note consistent southward younging progression of ages. Stratigraphic ages of emplacement of Upper and Lower Pedraforca Nappes from Verges et al., (2002) are shown with *superscript, and (U-Pb) ages of syn-tectonic calcite veins from Cruset et al., (2020) are shown in italics. B) Plot showing ages with error bars, structural position, and possible durations of thrusting. Corresponding geologic periods and ages are shown on the right-hand side. Ages in Ma of age boundaries are shown in small numbers. Note that age increases up the Y axis, so periods and ages on the right-hand Y axis appear upside down relative to a conventional geologic time scale. Note in-sequence north-to-south progression and that 4 samples have overlapping error bars between 35.8 and 33.7 Ma (L'Escala, Abocador, Vallfogona and Colonia Pernau). Note also that Ter-Freser section fault ages are mostly younger than Pedraforca Nappe emplacement ages to the west. C) Authigenic gouge ages on section J-1 of Vergés (1993).

Figure 12: Pooled ages of wallrock-derived 2M_1 mica/illite component as determined from IAA. Note lack of clear spatial trend, and that all ages are Hercynian in age of slightly younger, reflecting a possible minor contribution of Cretaceous or Pyrenean micas to the predominantly Hercynian source.

Figure 13: Field relations at exposure of Gavarnie thrust at Plan de Larri, Huesca, Spain, dated by Rahl et al., (2011). A) Annotated field photograph showing thrust geometry and proximity of hanging wall Cretaceous carbonates to gouge exposure. Box shows area of Figure 13B. Note position of outcrop 400 m below Cretaceous unconformity, B) Field

photograph of Gavarnie thrust exposure, showing fault core and surrounding wall rocks. Dark grey clayey shales entrained in fault zone were dated by Rahl et al., (2011 C) Hand specimen of calc-silicate fault rock. D) Thin section of material from c), cross-polarized light.), Note spaced planar foliation, evidence of dissolution and re-precipitation of carbonate, re-precipitation of carbonate in strain shadows, dynamic recrystallization of carbonate, and brittle fracture of quartz. These features collectively suggest deformation at 150 – 250°C (Passchier & Trouw, 2005), temperatures much higher than the field stratigraphic constraints would suggest, and instead suggest hot fluids migrating up the fault plane and partially re-setting the Ar/Ar systematics of wall rock derived 2M₁ micas in the gouge.

Figure 14: Constraints on temperature of formation of authigenic illite in fault gouge. A) Freser Antiformal Stack with modelled thermal history for sample ET1 of Rushlow et al., (2013) in hanging wall of Freser antiformal stack thrust. B) Vallfogona thrust with thermal history of hanging wall sample CET1 of Rushlow et al., (2013), and carbonate clumped isotope data of Cruset et al., (2018). C) Abocador Thrust with carbonate clumped isotope data of Cruset et al., (2018). Grey line is best fit thermal history, darker grey field is good, and lighter grey is acceptable thermal history from Rushlow et al., (2013).

Figure 15: Published balanced cross-sections of the Eastern and Central Pyrenean foreland fold-thrust belts together with age constraints of thrusting and evaporite distribution. Both sections redrawn to same scale and V:H = 1:1. Thrust name abbreviations: **A)** Fr: Freser Antiformal stack; CP: Colonia Pernaut; Vf: Vallfogona; Ab: Abocador; LE: L'Escala. **B)** L-S: Llavorsi-Senet; Gv: Gavarnie; Ng: Noguères; Bx: Boixols; Mt: Montsec.); SM: Serres Marginals. IAA ages from Rahl et al., (2011). Thrusting ages in italics are magnetostratigraphy-derived ages from Meigs and Burbank, (1997).

Fault sampled	North	East
	(decimal degrees)	(decimal degrees)
L'Escala	42.145697°	2.205370°
Abocador	42.151268°	2.200726°
Vallfogona	42.130112°	1.900347°
Ripoll syncline thrust	42.238889°	2.164444°
Freser antiformal stack	42.269650°	2.159133°

Table 1: Locations of faults sampled in this study. Datum is WGS 1984.

Fault	Sample name	Size fraction (μm Stoke's Law equivalent)	Mineralogy from XRD									Illite polytypism		Ar-Ar ages				
			Smectite	Chlorite	Illite	Kaolinite	Quartz	Calcite	Dolomite	Halite	Bertherine	%2M1	%1Md	Total gas age (Ma)	Total gas age error (+/-Ma)	f39 in recoil (%)	Retention age (Ma)	Retention age error (+/-Ma)
L'Escala	Lesc-1 (C)	2.0 - 0.4		X	X		X	X	Tr			45	55	125.3	0.3	19.9	155.0	0.4
	Lesc-1 (M)	0.4 - 0.05		X	X			X	Tr			22	78	80.1	0.2	24.5	105.1	0.3
	Lesc-1 (F)	<0.05			X			X		Tr		0	100	31	0.1	42.1	52.8	0.2
Abocador	Aboc-1 (C)	2.0 - 0.4		X	X		X	X			X	40	60	138.4	0.5	17.7	166.6	0.6
	Aboc-1 (M)	0.4 - 0.05		X	X			Tr			X	21	79	87.9	0.2	30.6	124.8	0.3
	Aboc-1 (F)	<0.05			X			X				2	98	37.2	0.1	41.5	62.9	0.2
Vallfogona	Vallfogona E-1 (VC)	2.0 - 1.0	X	X	X	X	X	Tr	Tr			49	51	157.4	0.4	12.8	179.2	0.4
	Vallfogona E-1 (C)	1.0 - 0.5	X	X	X	X	X	Tr	Tr			41	59	135.8	0.3	17.8	163.8	0.3
	Vallfogona E-1 (M)	0.5 - 0.05	X	X	X							27	73	105.6	0.3	23.1	136.0	0.3
	Vallfogona E-1 (F)	<0.05	Tr		X							11	89	63	0.3	35.8	96.8	0.4
Ripoll Syncline	Arman-1 (C)	2.0 - 0.4		X	X		X	X				54	46	196.4	0.6	18.7	238.3	0.7
	Arman-1 (M)	0.4 - 0.05		X	X		X	X				31	69	139.8	0.4	32.3	201.9	0.6
	Arman-1 (F)	<0.05			X			Tr				10	90	68.5	0.3	46.4	124.9	0.4
Cavallera	Cavall-1 (C)	2.0 - 0.4		X	X		X	X	Tr			28	72	107.6	0.3	17.7	129.6	0.3
	Cavall-1 (M)	0.4 - 0.05		X	X		X	Tr				10	90	77.7	0.2	26.9	105.2	0.3
	Cavall-1 (F)	<0.05		X	X		Tr	X				4	96	54.6	0.2	30.2	77.6	0.2

Haines & van der Pluijm for Tectonics, Table 2

Column1	Column2	Column3	Column4	Column5	Column6	Column7	Column8	Column9	Column10	Column11	Column12	Column13	Column14	Column15
Data were collected on a VG-1200S equipped with a Daly detector operated in analog mode. The de														
MC0813	mass=	0.001	J=	0.0060237	+/-	8.86576E-06	tot.gas.age=	157.394	+/-	0.345	Reten.Age=	179.195	+-	0.397
MC08-13 Viiaf VC Illite	F39	LasPowmW	Peak36	Err36	Peak37	Err37	Peak38	Err38	Peak39	Err39	Peak40	Err40	Age(Ma)	AgeErr
	0.12816	0	2.2522E-02	1.7197E-03	4.4173E+00	1.6210E-02	9.0739E-02	2.5303E-03	1.0242E+01	1.9760E-02	8.2222E+00	1.8777E-02	1.66	0.54
	0.12814	50	8.0743E-04	1.1103E-03	-3.9806E-03	4.3692E-03	1.1540E-03	1.3538E-03	-2.0372E-03	1.6384E-03	-3.7952E-02	1.1993E-02	1078.09	1163.89
	0.12812	100	-2.3934E-03	1.2340E-03	-7.1730E-03	5.0387E-03	3.6361E-04	1.4664E-03	-1.7889E-03	1.7011E-03	-4.1618E-02	1.0940E-02	-85276.20	3574.83
	0.13215	150	-4.3306E-04	1.2741E-03	1.6168E-01	6.0614E-03	6.4374E-03	1.4274E-03	3.2200E-01	2.3090E-03	3.4399E-01	1.1455E-02	15.86	12.60
	0.13856	200	4.1714E-04	1.2592E-03	2.1012E-01	7.1355E-03	5.9654E-03	1.6185E-03	5.1254E-01	3.4134E-03	1.4754E+00	1.7458E-02	28.44	7.78
	0.14719	250	2.4153E-03	1.3859E-03	2.5718E-01	6.1019E-03	7.3970E-03	1.4401E-03	6.8983E-01	4.7952E-03	3.3727E+00	1.5305E-02	41.41	6.32
	0.16117	300	5.6466E-03	1.2949E-03	4.5308E-01	8.0447E-03	1.1169E-02	1.0291E-03	1.1167E+00	6.4479E-03	7.2054E+00	1.3137E-02	53.09	3.63
	0.19502	400	1.5356E-02	1.1619E-03	1.1674E+00	1.0967E-02	3.0995E-02	1.3078E-03	2.7052E+00	3.3176E-03	2.0624E+01	2.7933E-02	63.49	1.34
	0.24276	500	1.8562E-02	1.1694E-03	2.1009E+00	1.6176E-02	3.7579E-02	1.5851E-03	3.8146E+00	1.0825E-02	3.6188E+01	3.6390E-02	85.41	0.97
	0.29364	600	2.1387E-02	1.2221E-03	2.6938E+00	1.8506E-02	3.7694E-02	1.4709E-03	4.0665E+00	9.9710E-03	4.9806E+01	2.6955E-02	112.62	0.95
	0.36546	800	2.5143E-02	1.1301E-03	4.5490E+00	1.2092E-02	4.0848E-02	2.5085E-03	5.7388E+00	1.0660E-02	8.9071E+01	4.4231E-02	148.33	0.65
	0.43646	1000	1.9009E-02	1.2367E-03	4.6271E+00	5.9428E-03	3.2557E-02	1.6092E-03	5.6736E+00	7.5669E-03	1.0033E+02	5.1302E-02	172.86	0.68
	0.46475	1200	9.7632E-03	1.3824E-03	1.8247E+00	1.3220E-02	1.4879E-02	9.4591E-04	2.2611E+00	7.2611E-03	3.8266E+01	3.0395E-02	162.50	1.87
	0.55431	1600	2.6757E-02	1.0017E-03	6.0671E+00	2.0898E-02	4.6927E-02	1.6039E-03	7.1565E+00	1.1487E-02	1.3756E+02	6.9050E-02	186.86	0.51
	0.63989	2000	2.7894E-02	1.4932E-03	5.6137E+00	2.8780E-02	4.0874E-02	1.3856E-03	6.8384E+00	1.3424E-02	1.3632E+02	5.2548E-02	192.85	0.73
	0.74562	2600	3.2159E-02	9.5677E-04	7.1639E+00	2.1638E-02	4.9055E-02	2.4421E-03	8.4492E+00	9.5627E-03	1.7660E+02	5.8706E-02	203.05	0.40
	0.82370	3200	2.6927E-02	1.2534E-03	5.6164E+00	2.1218E-02	3.9048E-02	2.1388E-03	6.2394E+00	8.6049E-03	1.4188E+02	5.5852E-02	219.36	0.64
	0.93565	4000	2.3160E-01	2.3897E-03	6.5263E+00	3.9714E-02	9.1720E-02	2.3562E-03	8.9463E+00	1.4630E-02	2.8203E+02	1.3156E-01	242.41	0.85
	0.99234	4001	4.1220E-02	1.4999E-03	1.9143E+00	1.0658E-02	3.7094E-02	1.1749E-03	4.5298E+00	1.1510E-02	1.2370E+02	8.0810E-02	249.46	1.11
	0.99873	4002	1.7093E-01	2.7754E-03	4.0400E-01	6.4573E-03	3.6192E-02	1.2379E-03	5.1048E-01	3.4898E-03	6.1205E+01	3.3221E-02	214.40	15.58
	1.00000	4010	1.1422E-01	1.8650E-03	5.9974E-02	5.1234E-03	2.2829E-02	8.3302E-04	1.0167E-01	2.0025E-03	3.4579E+01	3.4042E-02	86.18	56.29
MC0814	mass=	0.0008	J=	0.00601593	+/-	1.03459E-05	tot.gas.age=	135.84	+/-	0.283	Reten.Age=	163.777	+-	0.34
MC08-14 Vaiiaf-1 C Illite	F39	LasPowmW	Peak36	Err36	Peak37	Err37	Peak38	Err38	Peak39	Err39	Peak40	Err40	Age(Ma)	AgeErr
	0.17848	0	4.3356E-02	1.4394E-03	3.4149E+00	2.0053E-02	1.0501E-01	2.2853E-03	2.4196E+01	3.0088E-02	1.5834E+01	2.1968E-02	1.36	0.19
	0.18844	50	-5.1767E-04	1.0532E-03	2.1396E-01	7.1538E-03	1.4823E-02	1.7079E-03	1.3507E+00	5.0793E-03	2.3502E+00	1.0713E-02	20.00	2.48
	0.23471	100	3.3159E-02	1.1953E-03	8.7054E-01	5.4597E-03	3.6182E-02	1.5814E-03	6.2721E+00	1.2739E-02	3.9487E+01	4.0709E-02	50.66	0.61
	0.30898	150	7.0021E-02	1.3426E-03	1.4171E+00	1.2557E-02	6.6475E-02	2.8543E-03	1.0068E+01	1.8447E-02	8.5330E+01	5.7905E-02	68.37	0.43
	0.40409	200	7.2631E-02	1.4868E-03	1.8763E+00	8.1785E-03	9.3009E-02	2.3580E-03	1.2894E+01	1.8936E-02	1.1637E+02	5.0126E-02	78.17	0.37
	0.51204	250	7.4521E-02	1.9210E-03	2.2092E+00	9.2933E-03	9.1056E-02	2.1786E-03	1.4634E+01	1.9437E-02	1.6482E+02	3.5225E-02	102.91	0.42
	0.61160	300	6.4473E-02	1.7952E-03	2.1343E+00	6.4808E-03	6.4031E-02	2.2804E-03	1.3496E+01	2.3006E-02	2.0005E+02	1.0451E-01	139.98	0.46
	0.71582	400	5.5104E-02	1.6632E-03	2.4581E+00	1.8432E-02	5.7640E-02	3.2651E-03	1.4129E+01	2.0071E-02	2.8564E+02	7.6045E-02	195.88	0.43
	0.81076	500	4.0923E-02	1.1587E-03	2.5297E+00	1.1118E-02	3.8283E-02	2.9385E-03	1.2872E+01	9.4557E-03	3.1520E+02	1.5004E-01	239.01	0.32
	0.86872	600	1.7887E-02	1.5104E-03	1.7420E+00	1.0811E-02	2.4072E-02	2.0413E-03	7.8563E+00	1.7613E-02	2.1628E+02	6.4065E-02	270.19	0.78
	0.92484	800	1.7954E-02	1.1545E-03	1.3122E+00	1.1430E-02	2.1479E-02	2.5841E-03	7.6082E+00	7.3557E-03	2.1762E+02	9.4562E-02	279.98	0.50
	0.95878	1000	7.2268E-03	1.3579E-03	4.5884E-01	7.2507E-03	1.4792E-02	1.5908E-03	4.6018E+00	9.3726E-03	1.2793E+02	7.4445E-02	274.67	0.98
	0.97301	1200	5.9643E-03	1.0355E-03	2.1368E-01	7.0256E-03	6.6971E-03	1.5244E-03	1.9290E+00	6.9642E-03	5.3415E+01	5.8279E-02	269.45	1.76
	0.98203	1600	2.4447E-02	1.5366E-03	1.5366E-01	5.6413E-03	1.1614E-02	1.7620E-03	1.2221E+00	6.1742E-03	3.6426E+01	3.9138E-02	242.30	3.99
	0.98779	2000	3.2221E-02	1.1694E-03	1.1255E-01	5.3567E-03	1.0367E-02	1.3255E-03	7.8071E-01	5.0383E-03	2.6152E+01	3.3580E-02	217.54	4.48
	0.99142	2600	5.1297E-02	1.9074E-03	9.5320E-02	6.8317E-03	1.2935E-02	1.6986E-03	4.9331E-01	4.0306E-03	2.4253E+01	3.4997E-02	189.75	11.28
	0.99334	3200	4.6154E-02	9.3525E-04	5.8847E-02	3.7718E-03	1.2698E-02	9.6719E-04	2.5936E-01	2.2381E-03	1.7495E+01	2.2330E-02	154.57	10.73
	0.99531	4000	7.4538E-02	1.7680E-03	7.9575E-02	4.3482E-03	1.7368E-02	1.5125E-03	2.6766E-01	2.4970E-03	2.6248E+01	1.8919E-02	163.55	19.42
	0.99918	4010	1.7770E-02	1.1384E-03	1.6616E-01	5.7086E-03	1.3131E-02	1.0752E-03	5.2424E-01	2.8841E-03	1.2652E+01	2.1623E-02	147.06	6.48
	1.00000	4011	1.8835E-01	3.7162E-03	4.7349E-02	4.3968E-03	3.8049E-02	1.1369E-03	1.1128E-01	1.8260E-03	5.5758E+01	4.1150E-02	9.70	106.60
MC0819	mass=	0.0009	J=	0.00602681	+/-	1.25816E-05	tot.gas.age=	105.648	+/-	0.254	Reten.Age=	135.987	+-	0.32
MC08-19 Viiaf M Illite	F39	LasPowmW	Peak36	Err36	Peak37	Err37	Peak38	Err38	Peak39	Err39	Peak40	Err40	Age(Ma)	AgeErr
	0.23127	0	8.1507E-02	2.2753E-03	4.4604E+00	2.7068E-02	2.9446E-01	4.8514E-03	4.3670E+01	3.3978E-02	2.7988E+01	1.3719E-02	0.97	0.17
	0.23244	50	1.4555E-03	1.3412E-03	2.1651E-02	3.0810E-03	7.8769E-03	2.1992E-03	2.2092E-01	2.9134E-03	2.3722E-01	1.2816E-02	-9.52	19.62
	0.24672	100	1.2833E-02	1.3742E-03	2.9636E-01	7.3776E-03	3.1083E-02	2.5811E-03	2.6965E+00	1.0507E-02	5.3726E+00	1.9080E-02	6.36	1.63
	0.27655	150	4.9160E-02	2.4088E-03	5.6937E-01	1.4073E-02	3.5569E-02	2.9256E-03	5.6323E+00	9.5947E-03	2.9125E+01	4.1715E-02	27.96	1.36
	0.31908	200	1.2262E-01	2.2124E-03	8.1570E-01	8.2051E-03	5.6078E-02	2.5000E-03	8.0303E+00	1.7942E-02	7.7726E+01	3.6623E-02	55.32	0.87
	0.37289	250	1.7298E-01	2.2435E-03	1.0355E+00	1.0026E-02	7.9516E-02	3.1628E-03	1.0161E+01	1.3155E-02	1.1726E+02	7.4188E-02	69.43	0.69
	0.43497	300	1.5801E-01	1.9311E-03	1.2090E+00	8.6261E-03	7.7287E-02	3.2000E-03	1.1722E+01	2.4066E-02	1.2883E+02	6.4058E-02	74.62	0.53
	0.53388	400	1.9991E-01	2.3664E-03	1.9329E+00	1.4159E-02	1.1272E-01	2.7957E-03	1.8677E+01	2.2265E-02	2.0870E+02	1.1448E-01	85.07	0.41
	0.67433	500	2.1481E-01	1.6017E-03	2.7651E+00	2.0035E-02	1.4737E-01	2.9286E-03	2.6520E+01	2.6672E-02	3.4737E+02	8.0473E-02	112.79	0.22
	0.81815	600	1.8264E-01	1.1725E-03	2.8993E+00	1.2962E-02	1.1733E-01	3.5385E-03	2.7156E+01	1.5634E-02	4.7978E+02	1.5652E-01	162.90	0.17
	0.94724	800	1.1783E-01	2.3485E-03	3.0418E+00	1.6923E-02	8.7379E-02	4.1286E-03	2.4374E+01	8.5563E-03	6.1486E+02	5.1325E-01	241.79	0.35
	0.98402	1000	1.9311E-02	1.7235E-03	1.8700E+00	1.6286E-02	3.2311E-02	2.0822E-03	6.9454E+00	1.3256E-02	1.9554E+02	6.6604E-02	275.10	0.85
	0.99237	1200	4.4913E-03	1.4813E-03	5.4618E-01	1.1982E-02	1.6574E-02	1.8710E-03	1.5761E+00	5.2641E-03	3.7020E+01	4.1482E-02	230.82	2.77
	0.99621	1600	9.0559E-03	1.5689E-03	1.0376E-01	5.7830E-03	1.2088E-02	1.3054E-03	7.2658E-01	4.7446E-03	1.3620E+01	2.9209E-02	156.75	6.45

	0.99709	2000	2.0967E-02	1.3134E-03	3.2702E-02	5.2968E-03	8.2914E-03	1.4045E-03	1.6617E-01	3.3581E-03	8.5225E+00	2.0514E-02	146.16	23.62
	0.99767	2600	3.7958E-02	1.7400E-03	1.5130E-02	6.0815E-03	9.1247E-03	1.5011E-03	1.0915E-01	2.4699E-03	1.2479E+01	2.4190E-02	121.58	48.01
	0.99814	3200	4.8557E-02	1.5504E-03	1.9460E-02	2.9165E-03	1.1213E-02	1.5183E-03	8.7990E-02	1.4765E-03	1.4314E+01	1.6296E-02	-4.31	56.78
	0.99860	4000	8.1150E-02	1.8264E-03	2.4520E-02	3.4029E-03	1.9374E-02	1.1086E-03	8.7775E-02	1.7241E-03	2.3892E+01	2.9687E-02	-10.86	67.36
	1.00000	4001	2.3299E-01	1.6943E-03	7.0883E-02	4.9310E-03	5.2432E-02	2.0063E-03	2.6378E-01	3.1224E-03	6.9392E+01	3.1915E-02	22.22	20.43
MC0820	mass=	0.0009	J=	0.00595462	+/-	1.65421E-05	tot.gas.age=	62.962	+/-	0.285	Reten.Age=	96.773	+-	0.43
MC08-20 Viiaf F Illite	F39	LasPowmW	Peak36	Err36	Peak37	Err37	Peak38	Err38	Peak39	Err39	Peak40	Err40	Age(Ma)	AgeErr
	0.35825	0	1.9672E-01	1.8276E-03	3.3314E+00	8.7193E-03	9.4143E-01	2.9241E-03	4.3262E+01	3.2639E-02	6.1206E+01	3.0616E-02	0.76	0.13
	0.36104	50	2.1644E-03	1.1231E-03	1.4979E-02	5.3997E-03	1.6782E-02	2.0197E-03	3.3647E-01	3.7989E-03	7.8616E-01	1.6800E-02	4.67	10.58
	0.37908	100	1.9828E-02	1.1073E-03	1.6517E-01	8.9385E-03	3.7112E-02	1.1857E-03	2.1786E+00	9.7576E-03	7.5781E+00	2.0845E-02	8.46	1.61
	0.41067	150	5.6151E-02	1.1305E-03	2.7375E-01	7.6107E-03	5.2876E-02	1.5659E-03	3.8150E+00	7.0009E-03	2.5834E+01	2.6807E-02	25.84	0.93
	0.45631	200	1.3421E-01	2.1748E-03	4.0711E-01	5.7389E-03	7.1176E-02	2.5308E-03	5.5111E+00	9.8288E-03	6.4895E+01	4.3731E-02	48.53	1.23
	0.51241	250	2.1707E-01	2.4548E-03	5.0215E-01	7.4960E-03	9.3201E-02	1.9562E-03	6.7749E+00	1.7659E-02	1.0479E+02	4.0922E-02	63.33	1.12
	0.57006	300	2.2465E-01	2.6932E-03	5.1679E-01	9.6967E-03	9.0217E-02	2.1406E-03	6.9608E+00	1.5805E-02	1.1368E+02	6.9413E-02	71.55	1.20
	0.68187	400	3.5652E-01	2.7766E-03	1.0385E+00	1.0788E-02	1.4671E-01	3.5132E-03	1.3502E+01	1.8729E-02	2.1287E+02	5.1843E-02	83.58	0.64
	0.79965	500	3.0718E-01	1.6781E-03	1.1551E+00	1.0708E-02	1.2347E-01	2.2466E-03	1.4224E+01	1.5384E-02	2.3064E+02	7.4601E-02	102.66	0.37
	0.90331	600	2.1968E-01	2.8435E-03	1.2459E+00	1.1595E-02	9.8968E-02	3.2199E-03	1.2518E+01	2.2185E-02	2.2081E+02	1.4612E-01	129.06	0.71
	0.97943	800	1.3073E-01	2.6657E-03	2.3419E+00	1.7807E-02	8.4731E-02	2.3386E-03	9.1922E+00	1.0995E-02	1.8947E+02	5.7448E-02	168.19	0.86
	0.99315	1000	2.9600E-02	1.5156E-03	3.9566E+00	2.3504E-02	2.7364E-02	7.3903E-04	1.6565E+00	5.3043E-03	3.9799E+01	3.9432E-02	190.91	2.69
	0.99738	1200	1.8427E-02	1.3967E-03	7.7751E+00	2.5664E-02	2.4569E-02	1.3183E-03	5.1051E-01	2.8439E-03	1.0317E+01	3.7032E-02	99.72	8.27
	0.99898	1600	1.6899E-02	1.9226E-03	4.6186E+00	1.9684E-02	8.9991E-03	8.7857E-04	1.9312E-01	1.5286E-03	7.2960E+00	1.9902E-02	123.74	29.54
	0.99908	2000	3.0542E-02	1.2989E-03	8.9319E-01	1.2119E-02	7.2527E-03	8.1652E-04	1.2658E-02	1.4154E-03	8.6865E+00	2.5251E-02	-313.18	390.22
	0.99925	2600	4.6697E-02	1.9958E-03	6.7287E-01	8.4363E-03	8.5360E-03	1.2785E-03	2.0298E-02	1.0413E-03	1.4235E+01	1.3119E-02	217.10	277.01
	0.99946	3200	4.0636E-02	1.9217E-03	6.2367E-01	7.1212E-03	8.1849E-03	9.6618E-04	2.5614E-02	2.0718E-03	1.2703E+01	1.8989E-02	270.05	206.18
	1.00000	4000	2.6409E-01	3.2598E-03	5.8782E-01	8.0179E-03	5.1795E-02	1.6093E-03	6.4796E-02	2.1560E-03	7.7780E+01	5.5528E-02	-43.20	163.85
MC13-6	mass=	0.001	J=	0.00365817	+/-	7.25513E-06	tot.gas.age=	107.55	+/-	0.28	Reten.Age=	129.646	+-	0.34
MC13-6 Cav-1 C Illite	F39	LasPowmW	Peak36	Err36	Peak37	Err37	Peak38	Err38	Peak39	Err39	Peak40	Err40	Age(Ma)	AgeErr
	0.17656	0	7.0806E-02	1.2377E-03	2.5804E+00	1.1771E-02	1.2850E-01	2.5842E-03	1.0365E+01	1.1868E-02	2.2127E+01	1.6021E-02	0.77	0.23
	0.17757	50	-3.0932E-04	1.2454E-03	1.9113E-02	4.0095E-03	5.5169E-03	1.1548E-03	5.9562E-02	2.5218E-03	2.4154E-02	1.0815E-02	12.76	40.51
	0.18436	100	1.3292E-04	1.4177E-03	1.8242E-01	3.2946E-03	2.5711E-02	2.3000E-03	3.9859E-01	2.5484E-03	1.5499E-01	1.0589E-02	1.92	6.93
	0.19472	150	-8.5143E-05	1.0197E-03	1.9177E-01	4.5981E-03	7.5088E-03	1.6085E-03	6.0823E-01	6.0699E-03	9.9894E-01	1.3556E-02	11.08	3.26
	0.20762	200	6.9452E-04	9.7462E-04	1.6931E-01	3.8188E-03	4.8088E-03	1.5314E-03	7.5722E-01	3.6936E-03	3.8960E+00	1.0801E-02	31.88	2.47
	0.22490	250	2.4400E-03	1.1791E-03	2.2609E-01	4.4621E-03	4.8245E-03	1.0444E-03	1.0145E+00	5.0697E-03	9.4369E+00	2.0089E-02	55.83	2.22
	0.24492	300	3.4493E-03	8.9866E-04	2.5878E-01	4.3315E-03	3.4010E-03	1.4551E-03	1.1751E+00	7.5169E-03	1.3703E+01	2.0949E-02	69.86	1.51
	0.28031	400	9.0339E-03	1.2797E-03	4.7319E-01	5.9975E-03	5.9562E-03	9.8057E-04	2.0775E+00	6.8682E-03	2.6027E+01	2.6099E-02	72.71	1.18
	0.32755	500	1.3043E-02	1.1983E-03	6.4350E-01	3.2596E-03	1.1573E-02	1.5616E-03	2.7733E+00	6.4960E-03	3.6278E+01	3.6590E-02	75.56	0.83
	0.38405	600	1.5561E-02	8.5949E-04	8.3664E-01	7.4249E-03	1.3043E-02	2.2286E-03	3.3169E+00	5.4264E-03	4.6721E+01	2.1808E-02	81.92	0.50
	0.47130	800	2.4292E-02	1.3946E-03	1.4467E+00	6.3435E-03	1.7960E-02	1.8200E-03	5.1217E+00	1.0726E-02	8.3095E+01	4.3013E-02	95.26	0.54
	0.57426	1000	2.9417E-02	1.2046E-03	1.8314E+00	1.2750E-02	2.1764E-02	1.6529E-03	6.0445E+00	1.3571E-02	1.1403E+02	7.0593E-02	111.49	0.45
	0.67404	1200	2.9783E-02	1.3909E-03	1.8453E+00	8.9343E-03	1.8724E-02	2.2584E-03	5.8576E+00	9.6833E-03	1.2682E+02	7.3337E-02	128.30	0.48
	0.79706	1600	3.9029E-02	1.2558E-03	2.4145E+00	1.2908E-02	2.2733E-02	2.1597E-03	7.2215E+00	8.7017E-03	1.9051E+02	9.3408E-02	156.57	0.37
	0.89971	2000	3.3040E-02	1.4133E-03	2.1314E+00	1.0432E-02	2.3692E-02	1.6033E-03	6.0260E+00	8.7562E-03	1.8799E+02	6.7175E-02	185.34	0.49
	0.96240	2600	2.1085E-02	9.8917E-04	1.0893E+00	1.0988E-02	1.8801E-02	2.2699E-03	3.6800E+00	1.1851E-02	1.3546E+02	9.0885E-02	218.03	0.82
	0.98689	3200	8.3774E-03	1.1920E-03	4.1137E-01	5.2790E-03	8.2935E-03	7.4405E-04	1.4377E+00	7.6464E-03	5.7248E+01	3.7020E-02	235.38	1.85
	1.00000	4000	2.1827E-01	2.7167E-03	4.0013E-01	6.6370E-03	4.8643E-02	1.1830E-03	7.6970E-01	3.4323E-03	8.4326E+01	5.0485E-02	162.47	6.34
MC1312	mass=	0.0014	J=	0.00359505	+/-	7.58075E-06	tot.gas.age=	77.687	+/-	0.188	Reten.Age=	105.176	+-	0.25
MC13-12 Cav-1 M Illite	F39	LasPowmW	Peak36	Err36	Peak37	Err37	Peak38	Err38	Peak39	Err39	Peak40	Err40	Age(Ma)	AgeErr
	0.26877	0	5.8955E-02	1.6632E-03	4.0232E+00	1.0265E-02	2.1924E-01	5.1764E-03	3.5038E+01	2.3302E-02	2.1243E+01	4.4655E-02	0.71	0.09
	0.26900	50	1.5873E-03	9.4725E-04	-3.1000E-03	3.9747E-03	1.9857E-03	1.2597E-03	2.9174E-02	1.3871E-03	2.9787E-01	1.6129E-02	-38.47	63.70
	0.27471	100	8.9936E-04	6.4964E-04	1.1073E-01	5.7410E-03	5.7462E-02	1.4912E-03	7.4556E-01	4.4995E-03	4.8900E-01	1.4253E-02	1.94	1.67
	0.28506	150	1.7041E-03	1.0847E-03	1.7518E-01	4.5938E-03	3.6886E-02	1.3018E-03	1.3482E+00	5.4379E-03	1.8154E+00	1.5226E-02	6.30	1.54
	0.29703	200	4.8541E-03	9.7175E-04	1.7668E-01	5.3990E-03	1.0568E-02	1.0835E-03	1.5611E+00	4.3778E-03	7.4330E+00	2.0664E-02	24.75	1.18
	0.31410	250	9.8780E-03	9.6549E-04	2.3932E-01	3.7934E-03	1.1145E-02	1.1943E-03	2.2246E+00	8.3684E-03	2.1125E+01	3.9962E-02	52.31	0.84
	0.33597	300	1.5809E-02	1.4442E-03	3.2900E-01	4.8310E-03	6.7303E-03	1.8608E-03	2.8511E+00	6.7009E-03	3.8648E+01	4.8042E-02	75.68	0.95
	0.37691	400	3.2723E-02	2.1954E-03	5.8278E-01	3.0919E-03	2.5204E-02	1.5621E-03	5.3372E+00	1.4651E-02	8.1090E+01	5.1203E-02	84.77	0.79
	0.43027	500	4.4444E-02	1.6476E-03	7.6458E-01	1.0164E-02	2.4204E-02	2.1909E-03	6.9560E+00	5.7978E-03	1.0100E+02	3.3524E-02	80.12	0.44
	0.49704	600	5.0025E-02	1.4876E-03	9.6807E-01	8.1907E-03	2.7216E-02	1.4344E-03	8.7045E+00	1.1774E-02	1.2448E+02	6.1276E-02	79.94	0.33
	0.61597	800	8.3524E-02	1.6145E-03	1.7753E+00	1.1625E-02	5.0757E-02	2.7227E-03	1.5504E+01	2.5172E-02	2.3278E+02	4.9343E-02	85.02	0.23
	0.76727	1000	9.2834E-02	2.0285E-03	2.3163E+00	1.1936E-02	6.3918E-02	1.9512E-03	1.9725E+01	9.5409E-03	3.2269E+02	9.4403E-02	94.56	0.20
	0.91239	1200	9.1918E-02	2.4425E-03	2.1709E+00	1.1013E-02	6.1203E-02	2.2365E-03	1.8917E+01	2.3578E-02	4.1246E+02	9.1055E-02	127.49	0.28
	0.97866	1600	5.1423E-02	1.6173E-03	9.1119E-01	1.1131E-02	3.9120E-02	1.4982E-03	8.6398E+00	1.1225E-02	2.9017E+02	9.0398E-02	195.44	0.41
	0.99357	2000	1.4785E-02	1.9799E-03	2.1595E-01	3.6492E-03	1.1152E-02	1.8255E-03	1.9439E+00	9.1579E-03	7.9068E+01	3.7677E-02	233.45	2.01
	0.99828	2600	1.0372E-02	1.7085E-03	7.8712E-02	4.1568E-03	8.2497E-03	1.2474E-03	6.1330E-01	2.8597E-03	2.4687E+01	3.8093E-02	215.29	4.85

	0.99913	3200	1.3011E-02	1.1436E-03	2.7065E-02	3.7099E-03	2.9884E-03	9.9524E-04	1.1164E-01	1.9069E-03	6.6554E+00	1.7979E-02	156.31	18.21
	1.00000	4000	3.9344E-02	1.4107E-03	3.3706E-02	4.7106E-03	8.1058E-03	1.1335E-03	1.1283E-01	1.5520E-03	1.2130E+01	3.4988E-02	28.75	23.67
MC1313	mass=	0.0013	J=	0.00351658	+/-	9.13451E-06	tot.gas.age=	54.578	+/-	0.171	Reten.Age=	77.596	+-	0.24
MC13-13 Cav-1 F Illite	F39	LasPowmW	Peak36	Err36	Peak37	Err37	Peak38	Err38	Peak39	Err39	Peak40	Err40	Age(Ma)	AgeErr
	0.30202	0	6.1082E-02	1.0463E-03	3.7824E+00	2.6304E-02	5.8015E-01	4.1014E-03	3.6598E+01	3.6773E-02	1.9379E+01	3.0610E-02	0.23	0.05
	0.30368	50	3.8614E-04	1.3694E-03	1.8037E-02	4.1689E-03	1.3484E-02	1.0768E-03	2.0166E-01	3.4594E-03	2.7783E-01	7.2578E-03	5.14	12.70
	0.31621	100	3.6985E-03	1.2022E-03	1.5755E-01	3.9536E-03	6.5537E-02	1.7986E-03	1.5182E+00	8.0827E-03	1.6734E+00	2.0922E-02	2.42	1.49
	0.33648	150	6.4997E-03	1.2115E-03	2.4868E-01	5.3285E-03	3.1972E-02	1.4446E-03	2.4558E+00	4.4262E-03	5.7920E+00	1.5854E-02	9.97	0.92
	0.36213	200	1.4395E-02	1.8127E-03	3.1450E-01	5.1921E-03	2.4724E-02	1.3927E-03	3.1084E+00	7.9656E-03	1.8764E+01	3.6137E-02	29.37	1.08
	0.39357	250	2.6269E-02	1.0591E-03	3.7964E-01	4.3215E-03	3.2166E-02	1.5498E-03	3.8089E+00	8.1197E-03	4.3967E+01	3.7859E-02	59.32	0.52
	0.42798	300	3.8141E-02	1.9809E-03	4.2832E-01	5.4415E-03	3.4795E-02	1.9897E-03	4.1698E+00	8.4309E-03	6.3431E+01	6.8423E-02	77.66	0.87
	0.48647	400	6.1075E-02	2.0364E-03	7.2029E-01	6.9351E-03	4.8446E-02	1.9339E-03	7.0875E+00	1.6619E-02	1.1118E+02	4.5333E-02	81.49	0.55
	0.56073	500	7.4286E-02	1.0239E-03	9.2476E-01	8.7197E-03	4.9523E-02	3.2984E-03	8.9996E+00	1.3237E-02	1.3432E+02	5.0379E-02	77.52	0.24
	0.65162	600	8.4206E-02	1.9853E-03	1.1296E+00	1.3730E-02	5.1438E-02	2.3899E-03	1.1014E+01	2.4592E-02	1.6341E+02	8.2045E-02	78.08	0.37
	0.79203	800	1.1613E-01	1.8070E-03	1.8862E+00	1.2767E-02	7.2664E-02	3.3785E-03	1.7014E+01	2.8457E-02	2.5158E+02	6.1385E-02	79.24	0.23
	0.94532	1000	1.1510E-01	1.2108E-03	2.2528E+00	8.6536E-03	8.0732E-02	2.9374E-03	1.8576E+01	2.8496E-02	2.8839E+02	6.7220E-02	84.85	0.17
	0.99513	1200	6.6402E-02	1.8487E-03	1.8603E+00	9.1317E-03	4.6299E-02	2.0947E-03	6.0353E+00	1.2203E-02	1.3738E+02	1.2009E-01	119.72	0.60
	0.99922	1600	2.1782E-02	1.1405E-03	1.2585E+00	9.8478E-03	9.9192E-03	9.3266E-04	4.9605E-01	2.0448E-03	1.7667E+01	3.5024E-02	138.19	4.05
	0.99966	2000	4.5871E-03	1.4796E-03	1.8888E-02	3.9648E-03	6.7433E-04	1.0956E-03	5.2913E-02	1.8753E-03	3.2840E+00	2.1804E-02	217.56	47.09
	0.99985	2600	6.1443E-03	1.1539E-03	6.6138E-03	3.9252E-03	4.9864E-04	1.1433E-03	2.3054E-02	1.6938E-03	2.5157E+00	1.8203E-02	183.03	85.86
	0.99995	3200	3.8332E-03	8.8859E-04	-5.0281E-03	4.8485E-03	1.2109E-03	1.2214E-03	1.2031E-02	1.6169E-03	1.9738E+00	1.2353E-02	396.55	121.12
	1.00000	4000	1.2603E-02	1.0415E-03	-3.6091E-03	3.4110E-03	6.0823E-03	1.5048E-03	5.9592E-03	1.5868E-03	5.1774E+00	1.1489E-02	1117.24	283.48
MC1801	mass=	0.0007	J=	0.0090368	+/-	3.07264E-05	tot.gas.age=	138.436	+/-	0.48	Reten.Age=	166.58	+-	0.57
MC18-1 ABOC-1C Illite	F39	LasPowmW	Peak36	Err36	Peak37	Err37	Peak38	Err38	Peak39	Err39	Peak40	Err40	Age(Ma)	AgeErr
	0.17660	0	9.5718E-02	1.8740E-03	6.7090E+00	1.9406E-02	8.9049E-02	4.0908E-03	3.2041E+01	2.9345E-02	3.0416E+01	3.1643E-02	1.08	0.28
	0.17910	1200	4.0340E-03	2.0445E-03	1.0987E-01	2.4572E-03	3.8334E-03	1.1457E-03	4.5402E-01	3.0553E-03	1.4288E+00	1.0189E-02	8.48	21.60
	0.18554	1600	8.8468E-03	1.4182E-03	2.5863E-01	5.2536E-03	6.6951E-03	1.2274E-03	1.1673E+00	2.8722E-03	5.4172E+00	1.4313E-02	38.73	5.73
	0.19611	2000	1.0314E-02	1.1874E-03	4.6414E-01	9.1512E-03	7.4044E-03	1.5873E-03	1.9192E+00	6.9281E-03	1.0172E+01	2.7043E-02	59.52	2.90
	0.21223	2600	1.5950E-02	1.2321E-03	7.7911E-01	7.4720E-03	1.3056E-02	1.4805E-03	2.9247E+00	6.6285E-03	1.7503E+01	1.7398E-02	69.92	1.96
	0.23866	3200	2.1291E-02	1.1776E-03	1.4457E+00	1.6316E-02	1.9743E-02	1.5948E-03	4.7945E+00	9.2700E-03	3.3110E+01	2.2810E-02	88.96	1.14
	0.28095	4000	2.8661E-02	1.7188E-03	2.4074E+00	1.1854E-02	2.7933E-02	2.3081E-03	7.6722E+00	7.8280E-03	6.0970E+01	3.8434E-02	108.25	1.03
	0.30694	4001	1.1377E-02	1.1006E-03	1.5620E+00	1.1304E-02	2.1103E-02	1.7384E-03	4.7159E+00	1.0711E-02	2.8849E+01	2.1088E-02	86.03	1.09
	0.31059	1000	2.0644E-03	6.7580E-04	1.2536E-01	6.2493E-03	2.0786E-03	1.1119E-03	6.6262E-01	2.4580E-03	3.1095E+00	7.9158E-03	60.47	4.76
	0.31979	2000	6.1863E-03	9.5474E-04	4.1969E-01	7.1928E-03	6.4414E-03	1.0359E-03	1.6687E+00	6.0774E-03	7.5546E+00	1.2685E-02	55.10	2.68
	0.33336	3000	7.2094E-03	9.8063E-04	8.7798E-01	9.8375E-03	9.6796E-03	1.1245E-03	2.4632E+00	7.7477E-03	1.5980E+01	2.4790E-02	89.41	1.85
	0.70168	4000	1.8840E-01	1.9343E-03	2.3521E+01	2.4203E-02	2.3253E-01	4.5865E-03	6.6825E+01	4.6768E-02	7.3584E+02	1.3334E-01	158.75	0.17
	0.78586	4001	5.5996E-02	2.4944E-03	4.9490E+00	2.2715E-02	5.9681E-02	2.0700E-03	1.5274E+01	2.2506E-02	2.2563E+02	1.1013E-01	210.41	0.77
	0.94320	4002	9.7159E-02	1.7235E-03	1.1459E+01	2.7058E-02	1.0019E-01	3.8529E-03	2.8546E+01	3.3556E-02	4.0601E+02	1.1669E-01	203.55	0.35
	0.98464	4003	3.2140E-02	1.0412E-03	3.3990E+00	1.9216E-02	2.1965E-02	1.5806E-03	7.5200E+00	1.5858E-02	1.4201E+02	5.4624E-02	266.58	0.79
	1.00000	4004	1.7378E-02	9.8424E-04	7.0267E-01	9.2073E-03	1.4728E-02	1.5092E-03	2.7861E+00	8.8787E-03	5.5393E+01	2.8716E-02	272.44	1.68
MC1802	mass=	0.001	J=	0.00892563	+/-	2.21941E-05	tot.gas.age=	125.311	+/-	0.323	Reten.Age=	154.953	+-	0.40
MC18-2 LESC-1C Illite	F39	LasPowmW	Peak36	Err36	Peak37	Err37	Peak38	Err38	Peak39	Err39	Peak40	Err40	Age(Ma)	AgeErr
	0.19952	0	9.9417E-02	2.0118E-03	1.1796E+01	3.6288E-02	1.1982E-01	3.9937E-03	4.9226E+01	4.6615E-02	3.3138E+01	3.2730E-02	1.23	0.20
	0.19982	50	-6.9843E-04	7.9835E-04	1.7352E-02	3.6276E-03	-1.8663E-03	1.4484E-03	7.3905E-02	2.2336E-03	1.2392E-01	7.8430E-03	70.57	49.50
	0.20171	100	-8.0700E-04	2.1918E-03	1.3758E-01	5.3435E-03	4.1690E-03	1.3511E-03	4.6756E-01	4.5198E-03	1.7784E-01	5.9540E-03	14.28	22.13
	0.20569	150	-2.0951E-03	1.1222E-03	2.6714E-01	6.5668E-03	6.3987E-03	1.0128E-03	9.8030E-01	3.8224E-03	6.7975E-01	6.7094E-03	21.21	5.39
	0.21238	200	1.2351E-03	1.2030E-03	3.9500E-01	5.5128E-03	3.3164E-03	1.0528E-03	1.6511E+00	8.1324E-03	2.6930E+00	1.4707E-02	22.56	3.43
	0.22282	250	4.4526E-03	1.0471E-03	5.7181E-01	6.8892E-03	2.7005E-03	1.5745E-03	2.5752E+00	8.3880E-03	7.0318E+00	8.9677E-03	35.39	1.90
	0.23923	300	1.1780E-02	1.1974E-03	9.2372E-01	7.8990E-03	4.5272E-03	2.5099E-03	4.0484E+00	6.5508E-03	1.5138E+01	1.5250E-02	45.78	1.38
	0.27518	400	2.5334E-02	1.5043E-03	2.0118E+00	1.7390E-02	1.5165E-02	1.7638E-03	8.8715E+00	1.8879E-02	3.8898E+01	3.1530E-02	56.13	0.79
	0.32640	500	3.0416E-02	1.1912E-03	3.0535E+00	1.4368E-02	2.8511E-02	3.3879E-03	1.2635E+01	1.2040E-02	5.7645E+01	3.7984E-02	60.97	0.44
	0.38913	600	3.8113E-02	8.3627E-04	4.0752E+00	1.1934E-02	3.6515E-02	3.1438E-03	1.5477E+01	1.5350E-02	7.9489E+01	4.2486E-02	69.62	0.26
	0.49574	800	5.6172E-02	1.6889E-03	7.9068E+00	2.7303E-02	4.7656E-02	4.2830E-03	2.6304E+01	2.5673E-02	1.7454E+02	7.2138E-02	94.19	0.31
	0.62003	1000	5.6816E-02	1.4279E-03	1.1320E+01	2.2984E-02	5.3939E-02	3.1205E-03	3.0664E+01	2.5950E-02	2.7413E+02	9.2459E-02	130.31	0.24
	0.72696	1200	4.1420E-02	1.5466E-03	1.3173E+01	4.5467E-02	4.4326E-02	4.7184E-03	2.6384E+01	1.5961E-02	3.1115E+02	1.0192E-01	173.79	0.28
	0.85198	1600	3.9543E-02	1.3827E-03	1.6380E+01	4.4878E-02	4.8085E-02	3.0620E-03	3.0844E+01	2.0311E-02	4.7469E+02	9.8500E-02	226.84	0.24
	0.93210	2000	2.0404E-02	2.1462E-03	7.7589E+00	2.2249E-02	2.8428E-02	3.1409E-03	1.9766E+01	1.7131E-02	3.5595E+02	9.6672E-02	264.67	0.50
	0.97429	2600	1.1206E-02	1.2055E-03	2.1732E+00	1.1164E-02	2.1046E-02	2.6041E-03	1.0411E+01	2.4455E-02	1.9353E+02	7.2091E-02	272.54	0.77
	0.99169	3200	7.5856E-03	8.0843E-04	1.0858E+00	1.4559E-02	1.3983E-02	2.0636E-03	4.2931E+00	1.1214E-02	7.2698E+01	3.7741E-02	246.62	1.00
	1.00000	4000	1.0093E-01	1.4927E-03	7.2339E-01	6.6735E-03	3.0413E-02	1.2922E-03	2.0498E+00	6.1690E-03	5.6499E+01	4.6365E-02	198.24	3.17
MC1803	mass=	0.0016	J=	0.00882569	+/-	2.10512E-05	tot.gas.age=	30.985	+/-	0.125	Reten.Age=	52.752	+-	0.21
MC18-3 LESC-1F Illite	F39	LasPowmW	Peak36	Err36	Peak37	Err37	Peak38	Err38	Peak39	Err39	Peak40	Err40	Age(Ma)	AgeErr

	0.42144	0	4.2623E-01	2.6063E-03	2.1923E+01	5.2613E-02	1.4038E+01	1.5814E-02	1.7853E+02	8.0810E-02	1.3344E+02	7.9802E-02	0.67	0.07
	0.42178	50	-1.3511E-03	1.0927E-03	2.2366E-02	5.5460E-03	1.8441E-02	1.5422E-03	1.4473E-01	2.8759E-03	2.0293E-01	1.7701E-02	65.06	34.34
	0.42188	100	-2.0902E-03	1.3463E-03	1.2137E-02	4.2638E-03	1.7519E-02	1.5771E-03	4.3845E-02	2.3762E-03	1.3549E-02	1.6110E-02	215.79	128.76
	0.42203	150	-1.4128E-03	1.3438E-03	1.9900E-02	5.4217E-03	3.3849E-02	2.2958E-03	6.3274E-02	2.1315E-03	4.6186E-02	1.3215E-02	113.06	93.98
	0.42275	200	-8.2630E-04	1.1335E-03	5.2350E-02	5.2803E-03	9.8043E-02	2.5192E-03	3.0402E-01	3.6996E-03	1.7290E-01	1.5432E-02	21.71	17.35
	0.42516	250	1.5203E-04	9.5235E-04	1.3553E-01	7.3585E-03	3.4117E-01	2.8459E-03	1.0193E+00	5.6711E-03	6.6489E-01	1.6283E-02	9.66	4.38
	0.42894	300	3.9792E-03	1.3674E-03	1.9313E-01	7.6739E-03	3.7441E-01	3.6050E-03	1.6021E+00	4.7236E-03	1.4111E+00	1.8117E-02	2.34	4.01
	0.43889	400	1.4826E-02	1.4281E-03	5.4051E-01	8.2067E-03	3.9904E-01	2.4251E-03	4.2162E+00	3.4777E-03	6.6790E+00	2.1923E-02	8.66	1.59
	0.45764	500	4.8390E-02	1.5547E-03	1.0583E+00	6.7079E-03	3.1988E-01	2.5260E-03	7.9428E+00	1.1942E-02	2.4030E+01	2.4163E-02	19.40	0.91
	0.48696	600	1.0331E-01	2.2642E-03	1.5882E+00	1.7122E-02	4.2205E-01	4.2734E-03	1.2421E+01	1.4946E-02	5.7223E+01	4.9143E-02	33.90	0.85
	0.55051	800	2.7331E-01	2.2705E-03	3.3123E+00	1.4615E-02	7.9233E-01	5.5866E-03	2.6919E+01	2.2508E-02	1.5572E+02	6.5523E-02	43.80	0.39
	0.63042	1000	3.2481E-01	3.0771E-03	4.1000E+00	2.9354E-02	7.6406E-01	4.7899E-03	3.3854E+01	3.3533E-02	2.0189E+02	7.7801E-02	49.14	0.42
	0.72474	1200	3.6925E-01	2.8459E-03	4.9127E+00	2.1233E-02	6.4845E-01	4.7525E-03	3.9952E+01	1.6986E-02	2.4277E+02	8.6954E-02	52.49	0.33
	0.83587	1600	4.0033E-01	2.6725E-03	6.7537E+00	3.4897E-02	5.9306E-01	4.8318E-03	4.7076E+01	2.8451E-02	2.9697E+02	9.7787E-02	59.44	0.26
	0.90739	2000	2.7017E-01	2.6771E-03	7.2195E+00	2.6014E-02	3.7265E-01	4.5993E-03	3.0300E+01	3.5598E-02	1.9822E+02	7.1902E-02	61.16	0.41
	0.95840	2600	2.0587E-01	3.8316E-03	1.0807E+01	3.4511E-02	2.5346E-01	3.5856E-03	2.1609E+01	2.2184E-02	1.4767E+02	7.3524E-02	62.88	0.81
	0.98628	3200	1.2030E-01	1.8624E-03	1.3406E+01	5.5723E-02	1.3726E-01	3.5783E-03	1.1809E+01	1.2682E-02	8.8964E+01	5.5962E-02	70.62	0.72
	1.00000	4000	1.9305E-01	2.2080E-03	3.1948E+01	7.3842E-02	1.6178E-01	2.2298E-03	5.8122E+00	1.1617E-02	8.7514E+01	9.4750E-02	81.59	1.73
MC1804	mass=	0.0008	J=	0.00873104	+/-	0.000026438	tot.gas.age=	196.41	+/-	0.619	Reten.Age=	238.254	+-	0.74
MC18-4 ARMAN-1C Illite	F39	LasPowmW	Peak36	Err36	Peak37	Err37	Peak38	Err38	Peak39	Err39	Peak40	Err40	Age(Ma)	AgeErr
	0.18677	0	4.1523E-01	2.9022E-03	1.7713E+01	3.9478E-02	4.1156E-01	2.6556E-03	2.6041E+01	2.7031E-02	1.2597E+02	6.4282E-02	1.98	0.52
	0.18682	50	-1.2961E-03	1.2079E-03	1.8972E-03	6.1844E-03	4.4815E-04	9.2150E-04	7.3608E-03	1.6786E-03	2.1429E-01	2.3397E-02	966.27	479.44
	0.18690	100	-9.4534E-04	1.2382E-03	9.9326E-03	6.8130E-03	1.6386E-03	1.2119E-03	1.0624E-02	1.4865E-03	-3.3773E-02	1.4116E-02	331.64	453.68
	0.18737	150	1.4359E-05	1.1502E-03	6.8720E-02	6.2445E-03	3.9059E-03	1.2573E-03	6.6230E-02	1.8939E-03	-4.6239E-02	1.7608E-02	-12.05	81.48
	0.18870	200	-1.8975E-04	1.5243E-03	1.8493E-01	8.9273E-03	1.0596E-02	1.0682E-03	1.8548E-01	2.4141E-03	4.8626E-02	1.5360E-02	8.87	38.09
	0.19032	250	-9.6566E-04	1.2669E-03	1.9470E-01	9.4171E-03	7.1813E-03	1.6987E-03	2.2579E-01	2.3009E-03	1.8079E-01	1.9141E-02	32.23	25.69
	0.19053	300	1.0503E-03	1.3403E-03	2.6895E-02	6.9243E-03	5.4045E-04	1.6797E-03	2.8402E-02	1.4933E-03	7.4988E-02	2.4895E-02	-135.51	237.37
	0.20109	400	7.8741E-03	1.5385E-03	1.1670E+00	1.4837E-02	1.5664E-02	1.6900E-03	1.4725E+00	8.3391E-03	5.2843E+00	1.9324E-02	31.36	4.79
	0.21493	500	1.3208E-02	1.4255E-03	1.4964E+00	8.8352E-03	1.4379E-02	1.9920E-03	1.9297E+00	7.4003E-03	1.3176E+01	2.6150E-02	74.15	3.32
	0.23422	600	2.0281E-02	7.3450E-04	2.3668E+00	2.1030E-02	1.7204E-02	7.3878E-03	2.6898E+00	1.4526E-02	2.3988E+01	4.9296E-02	102.41	1.35
	0.27531	800	3.6847E-02	1.6279E-03	6.5427E+00	1.9682E-02	4.0614E-02	2.4953E-03	5.7290E+00	1.0856E-02	5.9802E+01	4.7509E-02	129.71	1.26
	0.32689	1000	4.4864E-02	2.0315E-03	8.7710E+00	3.8376E-02	4.9224E-02	2.6392E-03	7.1926E+00	8.1993E-03	8.6364E+01	3.7742E-02	153.39	1.22
	0.38508	1200	3.8340E-02	2.0961E-03	9.9150E+00	4.6553E-02	5.0450E-02	2.5664E-03	8.1131E+00	1.1274E-02	1.1083E+02	7.2276E-02	183.52	1.12
	0.49230	1600	5.4472E-02	2.6196E-03	1.7153E+01	5.9195E-02	7.9160E-02	2.6726E-03	1.4950E+01	2.7712E-02	2.4344E+02	1.1912E-01	224.91	0.83
	0.60615	2000	4.6630E-02	1.7974E-03	1.8231E+01	4.0011E-02	7.1734E-02	1.8805E-03	1.5873E+01	1.7150E-02	2.9520E+02	9.3674E-02	259.65	0.53
	0.73502	2600	4.3174E-02	1.9079E-03	1.9881E+01	6.9724E-02	6.8771E-02	2.4536E-03	1.7968E+01	2.4844E-02	3.6167E+02	1.1996E-01	282.54	0.56
	0.83297	3200	2.8722E-02	1.3292E-03	1.2654E+01	3.9099E-02	4.5122E-02	2.4427E-03	1.3658E+01	1.4938E-02	2.8354E+02	9.7307E-02	292.22	0.50
	0.92897	4000	3.2202E-02	1.6256E-03	1.1318E+01	3.0753E-02	4.7418E-02	2.4499E-03	1.3386E+01	1.6866E-02	2.7950E+02	1.1089E-01	292.63	0.60
	0.99049	4001	5.8169E-02	1.7179E-03	6.4701E+00	3.0514E-02	5.5306E-02	1.8381E-03	8.5768E+00	1.9136E-02	1.7382E+02	5.9555E-02	266.90	0.98
	1.00000	4002	1.0534E-01	2.9209E-03	1.5027E+00	1.4724E-02	2.9777E-02	1.3652E-03	1.3263E+00	4.5266E-03	5.2417E+01	3.5489E-02	236.62	9.03
MC1805	mass=	0.0011	J=	0.00891621	+/-	1.48747E-05	tot.gas.age=	68.55	+/-	0.257	Reten.Age=	124.902	+-	0.41
MC18-5 ARMAN-1F Illite														

	0.24525	50	2.7451E-03	1.1707E-03	4.5347E-03	5.1077E-03	-1.0117E-03	9.5569E-04	1.8876E-02	1.9673E-03	5.2350E-03	1.7494E-02	-855.99	484.70
	0.24526	100	1.0522E-03	1.0486E-03	4.3346E-04	4.1015E-03	-6.0630E-04	1.2500E-03	3.6955E-03	1.7401E-03	-1.6122E-03	1.6952E-02	-2387.46	5902.01
	0.24530	150	4.3138E-04	8.3028E-04	5.5318E-03	2.6367E-03	-3.2981E-04	1.2854E-03	1.1702E-02	1.4960E-03	1.8304E-02	1.7032E-02	-155.49	366.41
	0.24888	200	3.6699E-03	1.0703E-03	1.3155E-01	4.7367E-03	3.4536E-02	1.3212E-03	1.3252E+00	7.1535E-03	6.3462E-01	1.8721E-02	-5.43	3.83
	0.25733	250	5.9971E-03	1.0871E-03	2.9867E-01	6.6983E-03	3.2119E-02	1.8529E-03	3.1180E+00	7.4452E-03	2.4295E+00	1.6688E-02	3.36	1.64
	0.26964	300	1.1772E-02	1.2457E-03	3.9839E-01	6.9307E-03	1.4099E-02	1.8188E-03	4.5459E+00	8.0480E-03	8.7097E+00	2.1035E-02	18.28	1.28
	0.29493	400	3.2449E-02	1.4477E-03	7.9111E-01	1.1122E-02	2.0351E-02	3.6628E-03	9.3407E+00	1.7266E-02	3.2611E+01	3.1947E-02	38.94	0.72
	0.33216	500	7.3422E-02	1.5453E-03	1.1610E+00	1.0072E-02	3.7575E-02	2.6668E-03	1.3749E+01	9.7061E-03	6.6602E+01	5.7377E-02	51.42	0.52
	0.37769	600	8.6040E-02	2.1756E-03	1.3872E+00	1.8107E-02	3.9648E-02	2.3401E-03	1.6816E+01	2.3682E-02	8.6028E+01	6.1501E-02	56.65	0.60
	0.45676	800	1.3771E-01	2.3104E-03	2.4988E+00	1.6345E-02	7.2881E-02	3.5371E-03	2.9201E+01	2.9131E-02	1.4704E+02	7.5359E-02	57.24	0.37
	0.57511	1000	1.8369E-01	2.5723E-03	3.7868E+00	1.0282E-02	9.0196E-02	3.4057E-03	4.3710E+01	1.8500E-02	2.4166E+02	8.6605E-02	67.19	0.27
	0.71127	1200	1.8833E-01	1.7935E-03	4.4932E+00	2.0012E-02	9.6254E-02	3.3092E-03	5.0285E+01	3.4837E-02	3.4775E+02	9.3948E-02	90.46	0.17
	0.87746	1600	2.0139E-01	2.2533E-03	6.6395E+00	3.3546E-02	1.1271E-01	4.3119E-03	6.1376E+01	2.5622E-02	6.2197E+02	1.0931E-01	140.71	0.17
	0.96401	2000	8.5359E-02	2.5543E-03	5.8751E+00	2.2760E-02	6.0591E-02	2.9976E-03	3.1961E+01	2.5310E-02	4.6115E+02	1.0005E-01	205.63	0.37
	0.99077	2600	3.2052E-02	1.5204E-03	1.6135E+00	1.0249E-02	3.1935E-02	1.7682E-03	9.8826E+00	1.5607E-02	1.5183E+02	4.9867E-02	216.50	0.72
	0.99756	3200	1.6365E-02	1.6405E-03	2.7489E-01	7.6640E-03	1.4629E-02	1.1590E-03	2.5098E+00	1.0555E-02	3.0366E+01	3.4328E-02	155.54	2.91
	1.00000	4000	6.3303E-02	1.4141E-03	1.1432E-01	5.4126E-03	2.8521E-02	1.5396E-03	9.0018E-01	3.7928E-03	2.2869E+01	4.1001E-02	72.37	7.16
MC1807	mass=	0.0015	J=	0.00873785	+/-	2.34092E-05	tot.gas.age=	87.884	+/-	0.246	Reten.Age=	124.834	+-	0.34
MC18-7 ABOC-1M Illite	F39	LasPowmW	Peak36	Err36	Peak37	Err37	Peak38	Err38	Peak39	Err39	Peak40	Err40	Age(Ma)	AgeErr
	0.30639	0	3.6471E-01	3.4069E-03	7.8761E+00	1.4978E-02	3.0122E-01	4.7853E-03	1.3138E+02	7.1835E-02	1.1885E+02	7.0293E-02	1.33	0.12
	0.30654	50	5.4294E-06	1.0253E-03	-4.4674E-03	6.7842E-03	2.3343E-03	1.5863E-03	6.5319E-02	1.5660E-03	1.6784E-01	1.4689E-02	39.68	71.62
	0.30727	100	2.0654E-03	8.8571E-04	1.3232E-02	7.1345E-03	5.8721E-03	2.0918E-03	3.1171E-01	4.1806E-03	4.0344E-01	1.4227E-02	-10.49	13.33
	0.31002	150	4.3674E-03	1.3530E-03	7.4525E-02	8.4322E-03	1.3324E-02	2.1541E-03	1.1794E+00	5.9049E-03	1.2602E+00	1.1907E-02	-0.41	5.35
	0.31584	200	4.9425E-03	1.1636E-03	1.4126E-01	1.0279E-02	1.1201E-02	2.6184E-03	2.4982E+00	1.0500E-02	3.9790E+00	2.0450E-02	15.82	2.16
	0.32485	250	1.0645E-02	8.5748E-04	2.2789E-01	6.8563E-03	9.1887E-03	1.8718E-03	3.8611E+00	1.2312E-02	1.0868E+01	2.3992E-02	31.26	1.03
	0.33757	300	1.9458E-02	1.1090E-03	3.4109E-01	7.2586E-03	1.2094E-02	2.8173E-03	5.4558E+00	6.6491E-03	2.3194E+01	1.8883E-02	49.71	0.93
	0.36779	400	6.7021E-02	1.0868E-03	7.7331E-01	1.1130E-02	3.6617E-02	1.4781E-03	1.2956E+01	2.2562E-02	7.5163E+01	4.3737E-02	66.13	0.40
	0.41055	500	1.0792E-01	9.8102E-04	1.0810E+00	1.1089E-02	5.3187E-02	2.4961E-03	1.8335E+01	2.1071E-02	1.1938E+02	3.3927E-02	73.70	0.26
	0.45934	600	1.1169E-01	1.5053E-03	1.2659E+00	1.2336E-02	6.7933E-02	1.3915E-03	2.0921E+01	2.3982E-02	1.3514E+02	3.0633E-02	75.36	0.33
	0.54549	800	1.7522E-01	1.5557E-03	2.2734E+00	1.8186E-02	1.1371E-01	4.8503E-03	3.6941E+01	3.1671E-02	2.4582E+02	5.8004E-02	80.96	0.20
	0.65685	1000	1.8374E-01	1.4564E-03	3.0240E+00	1.6041E-02	1.4335E-01	3.6969E-03	4.7752E+01	4.0958E-02	3.5988E+02	1.0744E-01	98.16	0.16
	0.77707	1200	1.7404E-01	3.1264E-03	3.3916E+00	2.3470E-02	1.2832E-01	3.8222E-03	5.1546E+01	3.3416E-02	4.9221E+02	9.1348E-02	130.00	0.28
	0.88283	1600	1.3601E-01	2.7584E-03	3.1978E+00	1.0436E-02	9.4971E-02	3.0830E-03	4.5349E+01	1.6767E-02	5.6170E+02	1.8274E-01	172.74	0.27
	0.89392	2000	1.4576E-02	1.7476E-03	3.8275E-01	9.4035E-03	1.2509E-02	1.5075E-03	4.7567E+00	1.2511E-02	6.5908E+01	3.3923E-02	193.40	1.62
	0.91052	2600	1.9734E-02	1.2807E-03	5.2338E-01	8.3375E-03	1.8530E-02	1.7458E-03	7.1164E+00	1.3356E-02	9.9950E+01	3.8369E-02	197.29	0.83
	0.93269	3200	2.3359E-02	2.4208E-03	6.2716E-01	1.0079E-02	2.1388E-02	1.7876E-03	9.5063E+00	1.1654E-02	1.3359E+02	7.4808E-02	198.72	1.09
	0.96101	4000	3.1733E-02	1.9298E-03	8.5282E-01	9.6997E-03	2.9217E-02	2.2926E-03	1.2145E+01	1.8546E-02	1.7886E+02	5.0562E-02	207.58	0.73
	1.00000	4001	1.0265E-01	2.4190E-03	1.2955E+00	1.3613E-02	6.6698E-02	2.7156E-03	1.6719E+01	2.4878E-02	2.8257E+02	9.1224E-02	223.40	0.68
MC1808	mass=	0.0015	J=	0.00859887	+/-	2.73461E-05	tot.gas.age=	139.776	+/-	0.447	Reten.Age=	201.931	+-	0.63
MC18-8 ARMAN-1M Illite	F39	LasPowmW	Peak36	Err36	Peak37	Err37	Peak38	Err38	Peak39	Err39	Peak40	Err40	Age(Ma)	AgeErr
	0.32267	0	9.2728E-01	6.2442E-03	1.8470E+01	4.9148E-02	6.2685E-01	5.9590E-03	1.1029E+02	5.2487E-02	2.8748E+02	2.6810E-01	1.89	0.26
	0.32265	50	-8.9889E-04	1.3953E-03	-6.5537E-04	5.3159E-03	2							

	0.42306	100	5.9152E-03	1.4298E-03	1.4141E-01	7.3304E-03	3.7693E-02	1.2614E-03	2.6369E+00	9.7978E-03	3.5733E+00	2.3864E-02	10.99	2.54
	0.43895	150	2.4732E-02	1.3942E-03	3.6634E-01	1.1770E-02	5.1890E-02	2.2229E-03	6.1791E+00	1.3971E-02	1.4093E+01	2.7441E-02	17.40	1.06
	0.46452	200	5.1650E-02	1.5568E-03	5.4962E-01	5.6383E-03	7.2127E-02	2.2477E-03	9.9395E+00	1.7072E-02	3.5532E+01	4.0035E-02	32.19	0.73
	0.49704	250	8.0437E-02	2.2171E-03	6.7869E-01	8.9500E-03	8.9767E-02	1.9898E-03	1.2640E+01	1.4002E-02	6.2991E+01	4.0915E-02	48.75	0.81
	0.53575	300	1.1473E-01	1.1051E-03	8.0147E-01	1.4069E-02	1.0204E-01	3.0633E-03	1.5047E+01	1.1031E-02	8.7716E+01	4.1934E-02	56.07	0.34
	0.60375	400	2.2971E-01	2.0751E-03	1.4394E+00	1.9393E-02	1.6002E-01	2.7085E-03	2.6433E+01	1.9914E-02	1.6911E+02	5.2826E-02	59.98	0.36
	0.68138	500	2.8450E-01	3.2661E-03	1.6955E+00	1.6914E-02	1.7489E-01	3.5600E-03	3.0177E+01	2.5747E-02	2.0512E+02	6.0041E-02	62.78	0.50
	0.76030	600	2.9550E-01	2.4191E-03	1.8655E+00	1.3759E-02	1.5499E-01	3.5376E-03	3.0675E+01	3.0811E-02	2.1550E+02	8.5297E-02	65.34	0.37
	0.86169	800	3.8407E-01	2.9058E-03	2.9945E+00	2.3142E-02	1.8868E-01	2.8853E-03	3.9414E+01	2.8662E-02	2.8730E+02	7.2155E-02	68.89	0.34
	0.93497	1000	2.9869E-01	2.9524E-03	3.4427E+00	1.1061E-02	1.3981E-01	2.7493E-03	2.8484E+01	2.0660E-02	2.1992E+02	1.1844E-01	72.15	0.48
	0.97465	1200	1.8240E-01	1.6037E-03	4.3259E+00	1.9558E-02	9.0538E-02	1.8228E-03	1.5426E+01	1.5510E-02	1.3028E+02	6.7168E-02	77.17	0.48
	0.99525	1600	1.5557E-01	2.0535E-03	8.5979E+00	4.5677E-02	9.1022E-02	3.0121E-03	8.0047E+00	1.1680E-02	9.4695E+01	7.4041E-02	94.41	1.16
	0.99860	2000	8.3445E-02	2.9508E-03	6.2040E+00	1.5952E-02	5.2804E-02	1.1032E-03	1.3021E+00	6.3470E-03	3.4319E+01	5.3285E-02	114.44	10.04
	0.99924	2600	8.0719E-02	2.1336E-03	4.1902E+00	2.6530E-02	3.9939E-02	1.1074E-03	2.5198E-01	4.0407E-03	2.4732E+01	6.1661E-02	54.72	38.85
	0.99966	3200	7.8844E-02	1.7942E-03	2.1270E+00	1.4779E-02	2.8814E-02	1.5807E-03	1.6217E-01	3.5165E-03	2.4310E+01	3.2704E-02	96.68	49.48
	1.00000	4000	1.3145E-01	2.4284E-03	1.6434E+00	7.6794E-03	3.2765E-02	1.6060E-03	1.3151E-01	1.7993E-03	3.8630E+01	5.1142E-02	-25.95	88.38

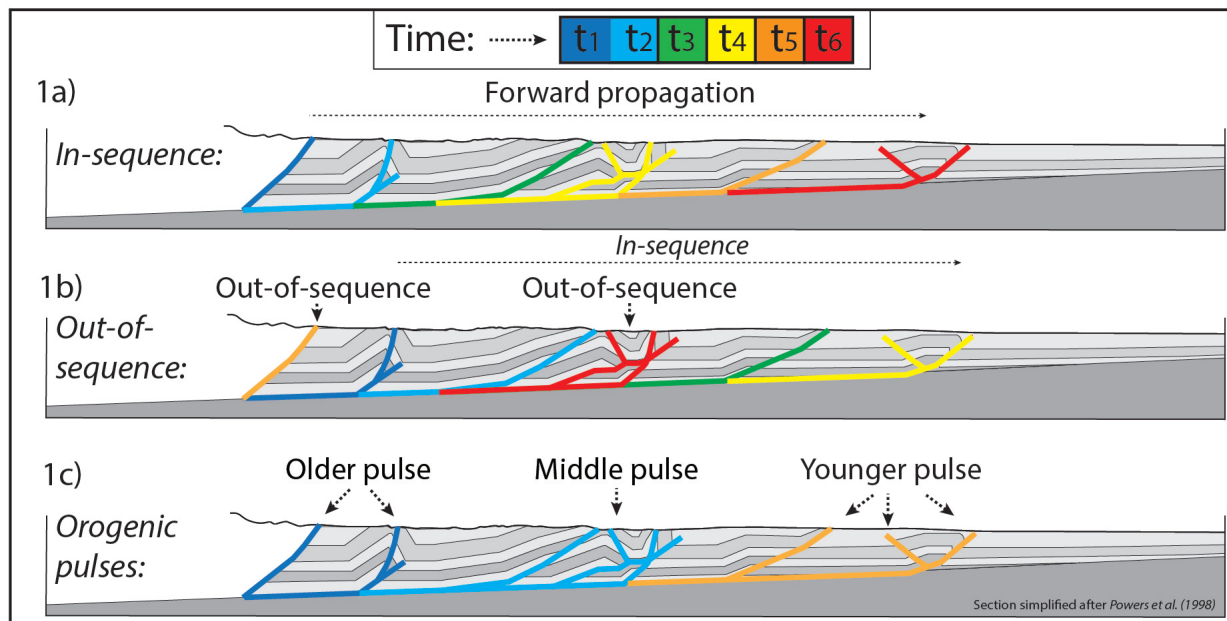


Fig 1 - Haines & van der Pluijm. for Tectonics

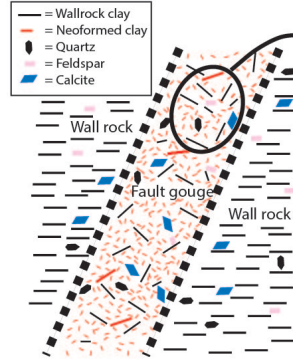
Illite Age Analysis to date fault gouge

A) Clay gouge at outcrop

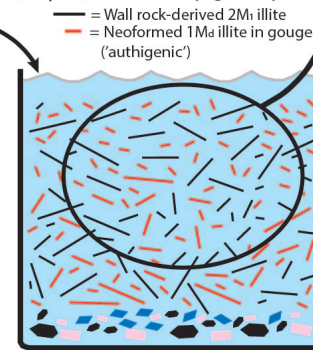


B) Schematic gouge

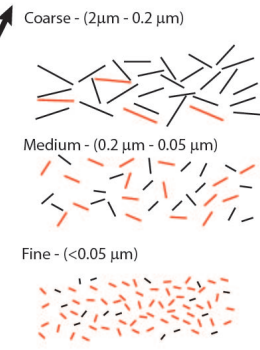
Wall rock-derived clay and authigenic clay



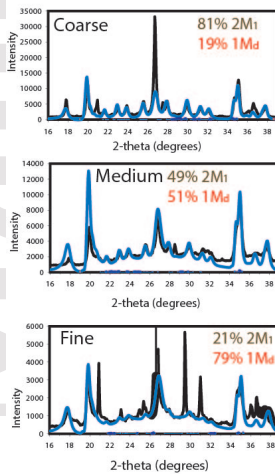
C) Separate out clay size (<2µm) fraction by gravity



D) Centrifugation clay fraction into size fractions

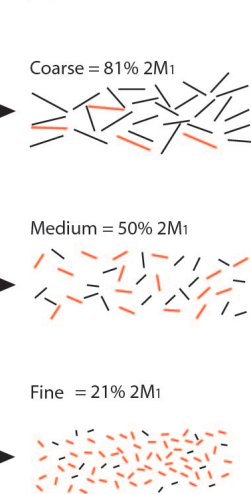


E) Polytype quantification using XRD (WILDFIRE®)

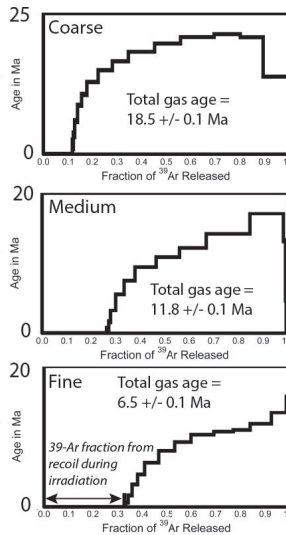


Black = Size fraction XRD pattern
Blue = Mixture of calculated WILDFIRE 2M1 and 1Ma patterns

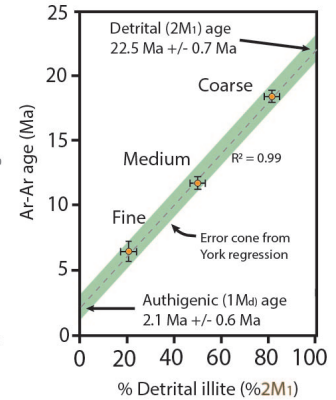
F) Quantified size fractions



G) Ar-Ar date size fractions



H) Illite Age Analysis plot:



Haines and van der Pluijm for Tectonics Figure 2

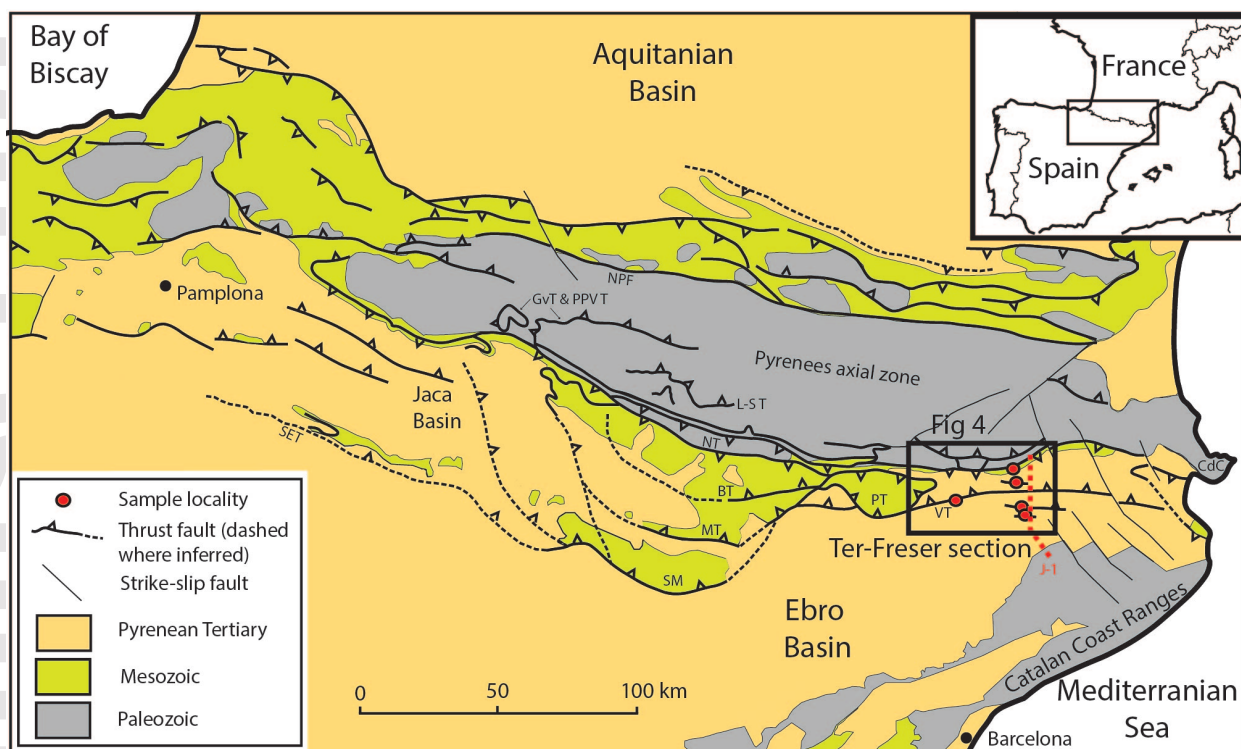


Fig 3 - Haines & van der Pluijm for Tectonics

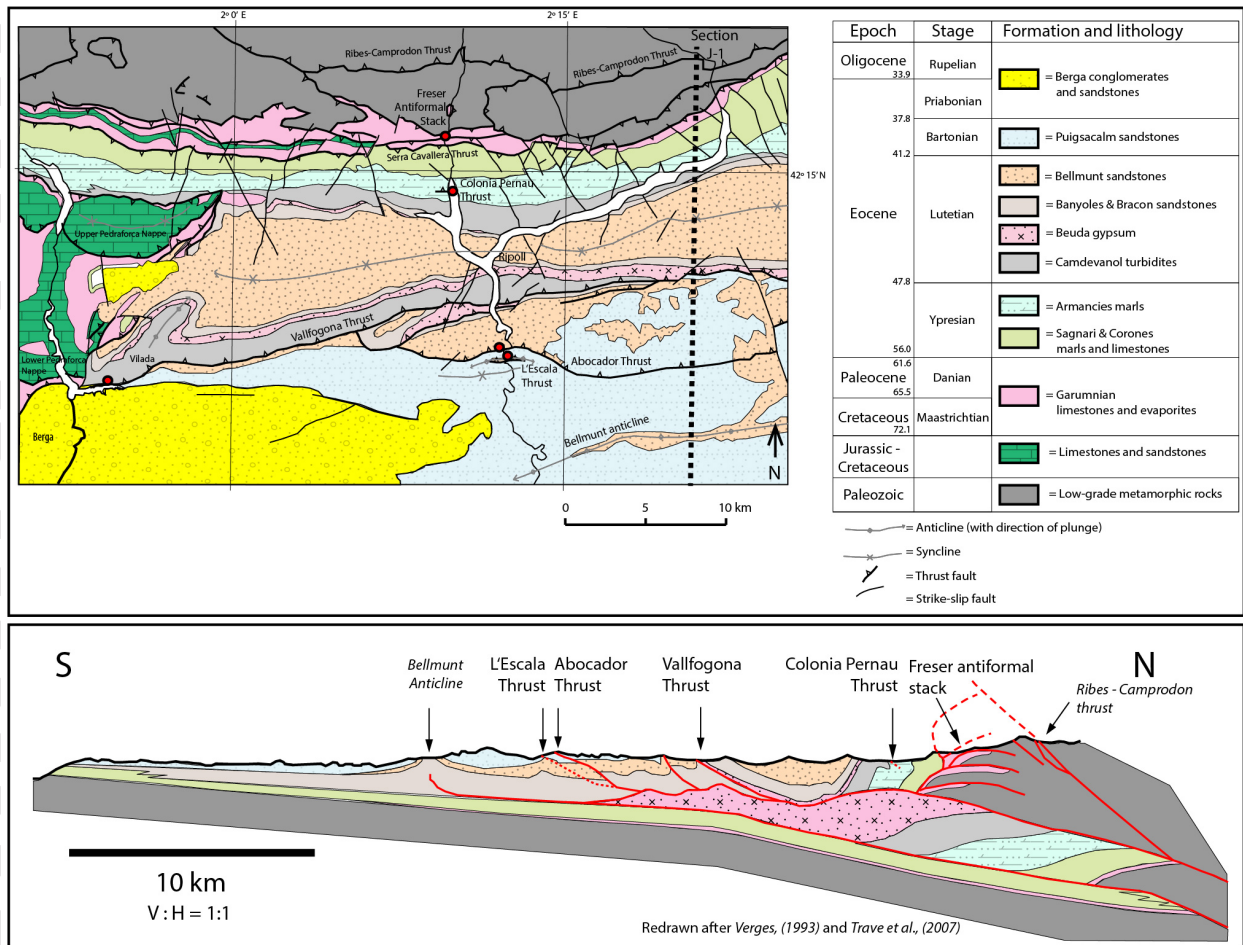


Fig 4 - Haines & van der Pluijm for Tectonics



Fig 5 - Haines & van der Pluijm for Tectonics

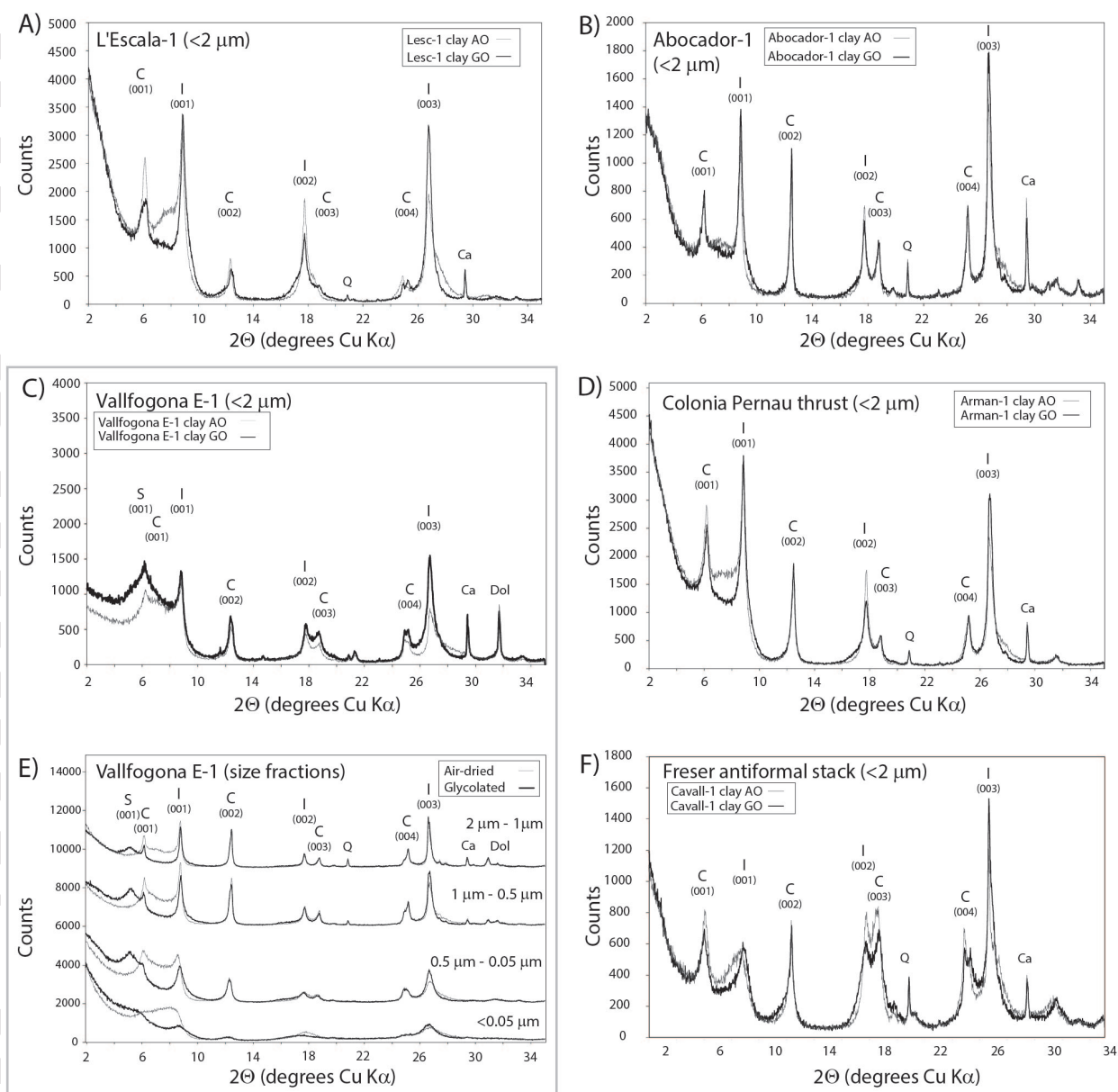


Fig 6 - Haines & van der Pluijm for Tectonics

Abocador Thrust

Polytypism quantifications

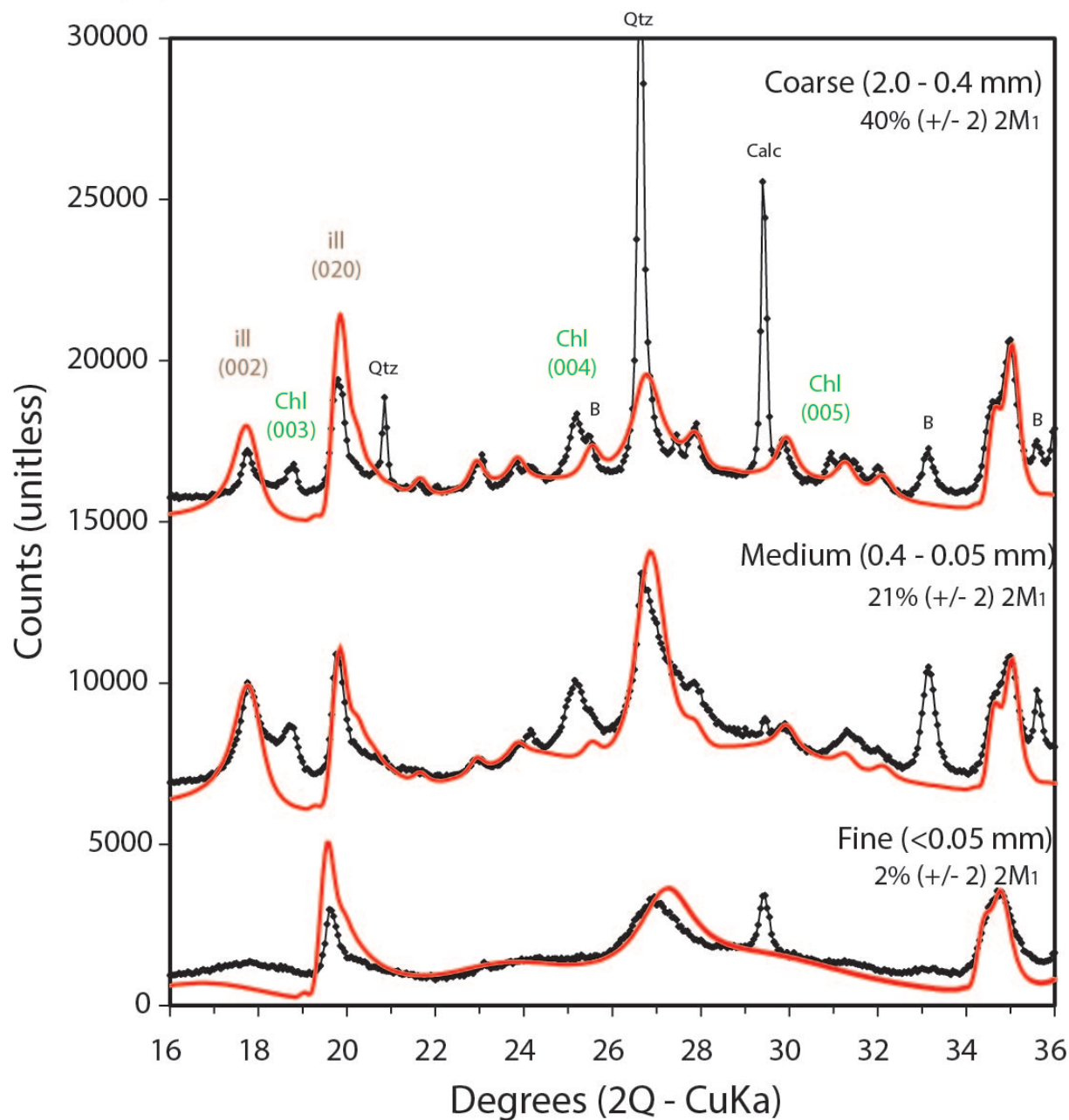


Fig 7 - Haines & van der Pluijm for Tectonics

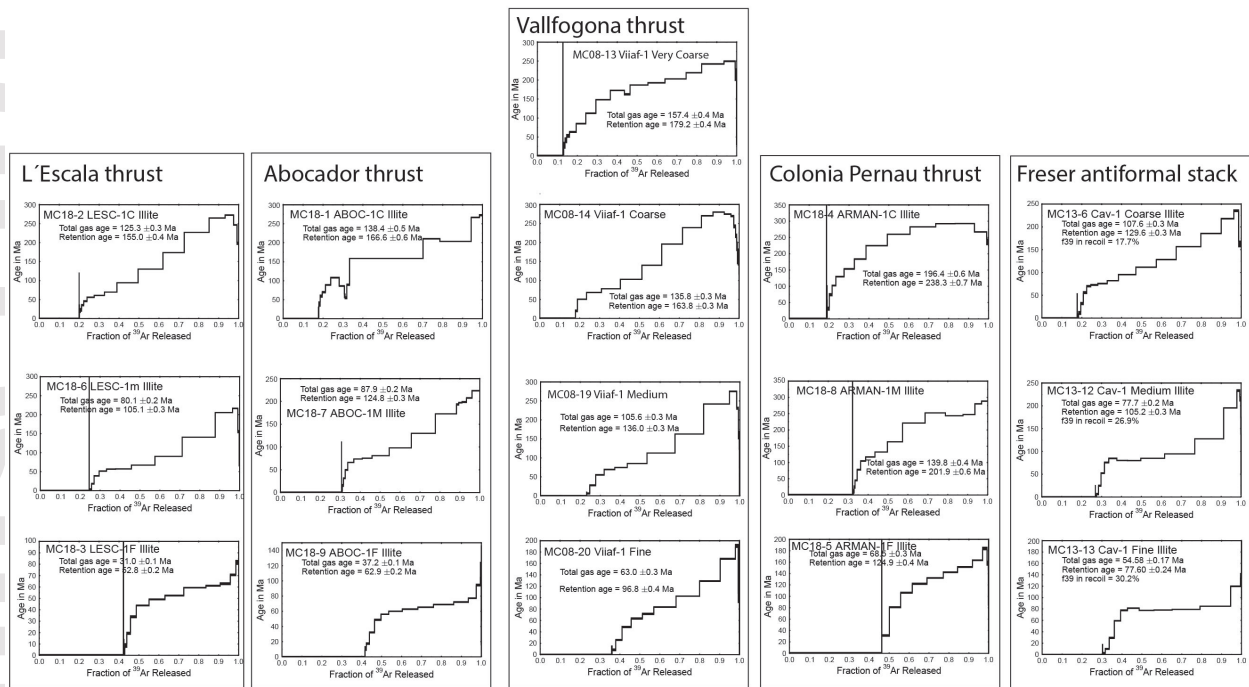


Fig 8, Haines & van der Pluijm, for Tectonics

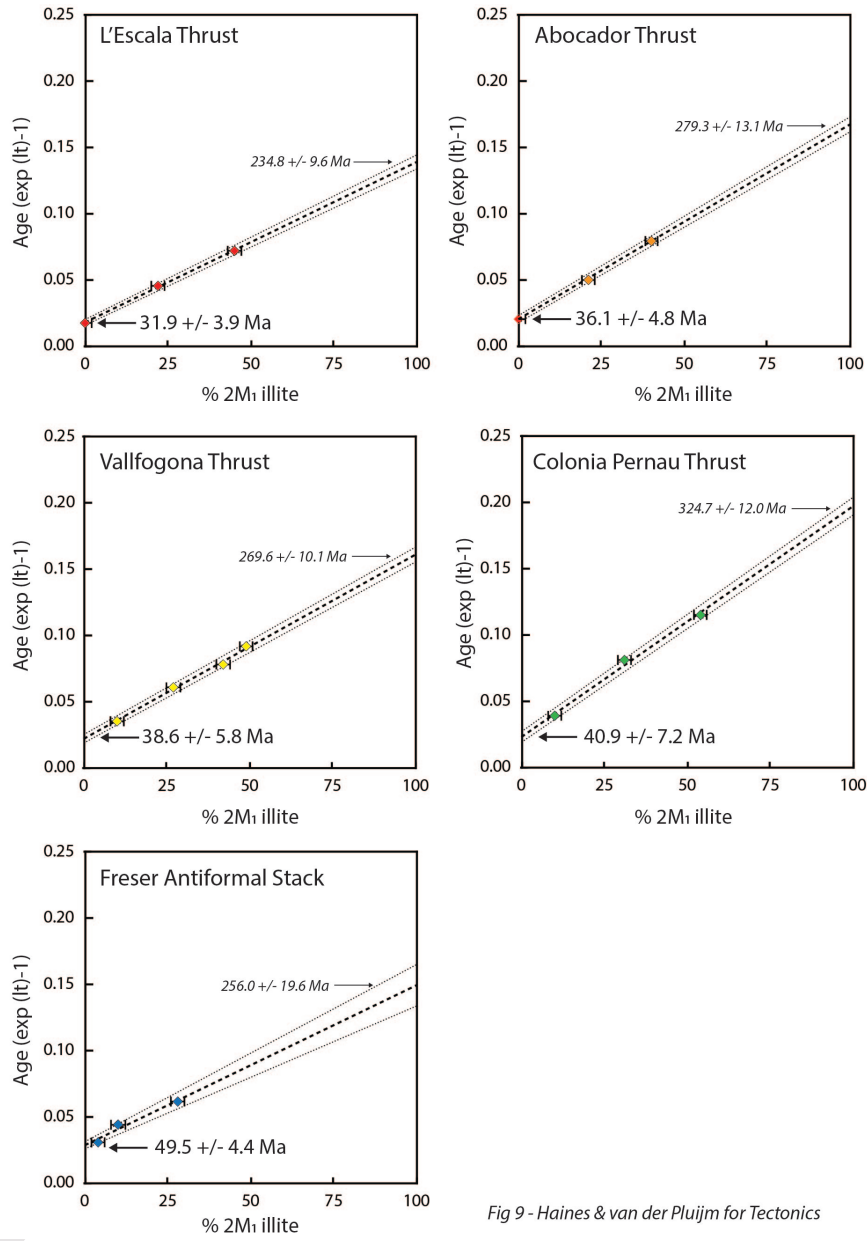


Fig 9 - Haines & van der Pluijm for Tectonics

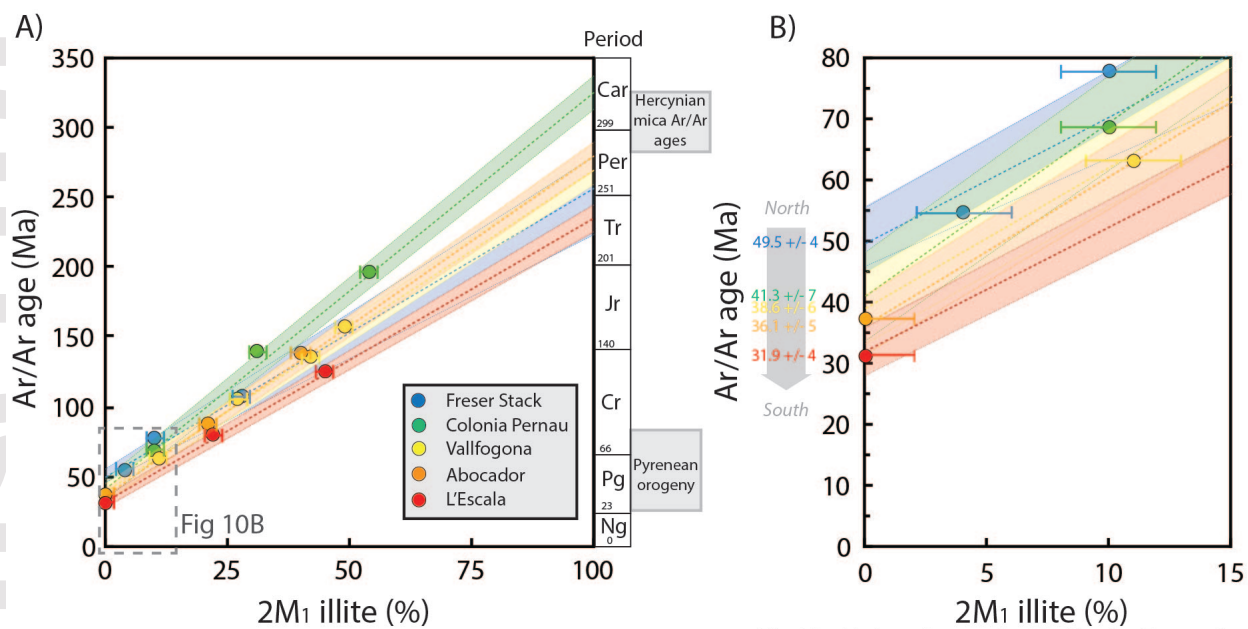


Fig 10 - Haines & van der Pluijm for Tectonics

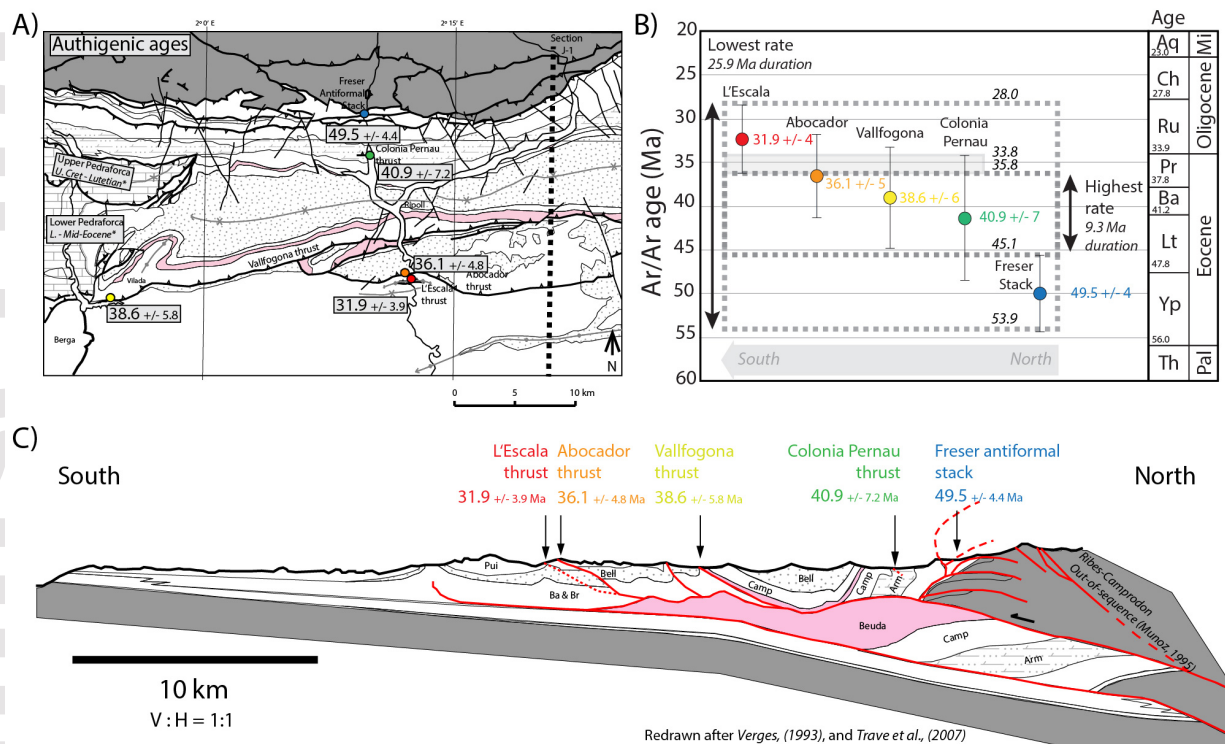


Fig 11 - Haines & van der Pluijm for Tectonics

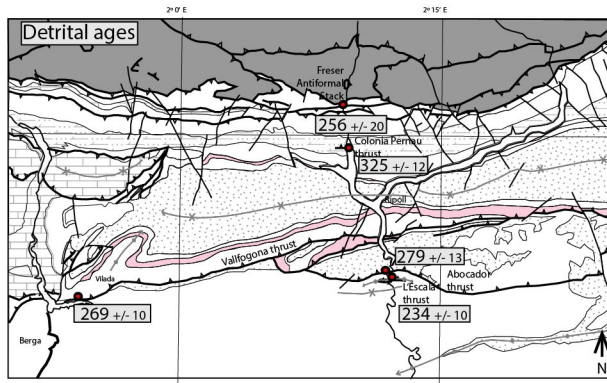
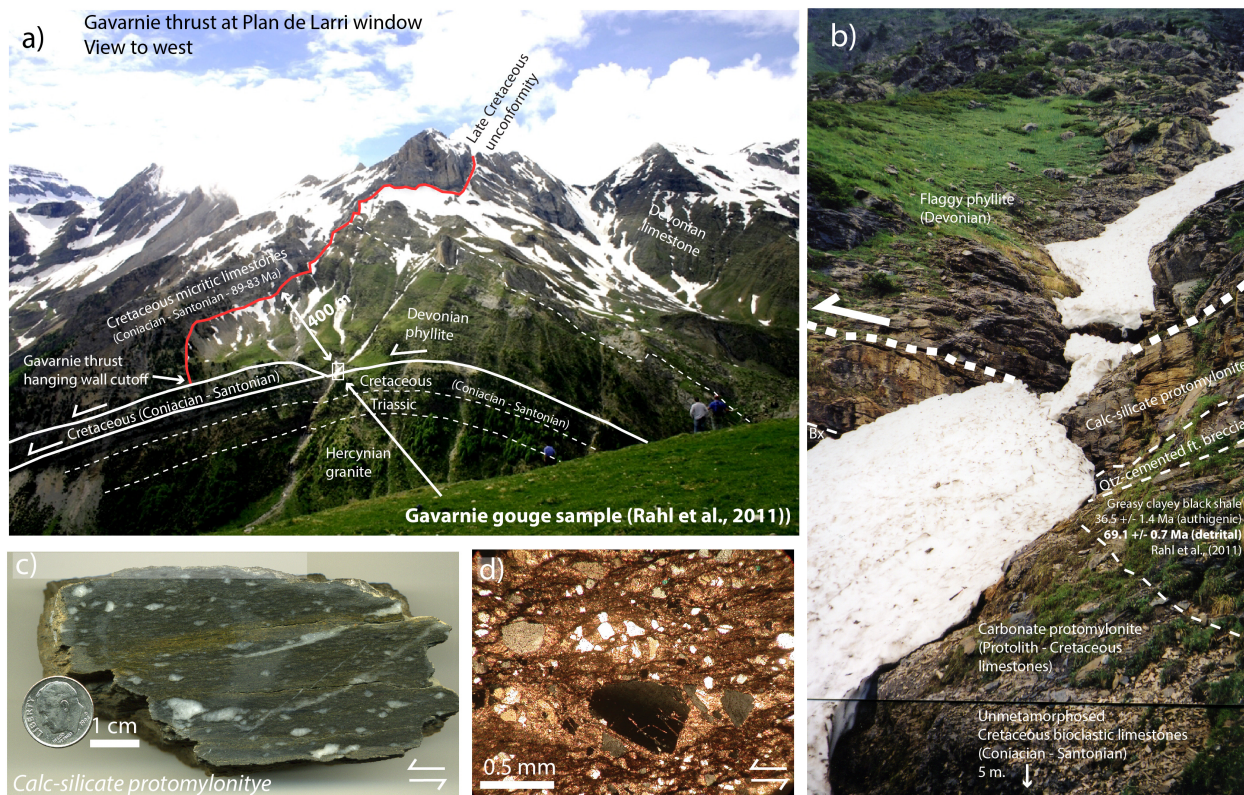


Fig 12 - Haines & van der Pluijm for Tectonics



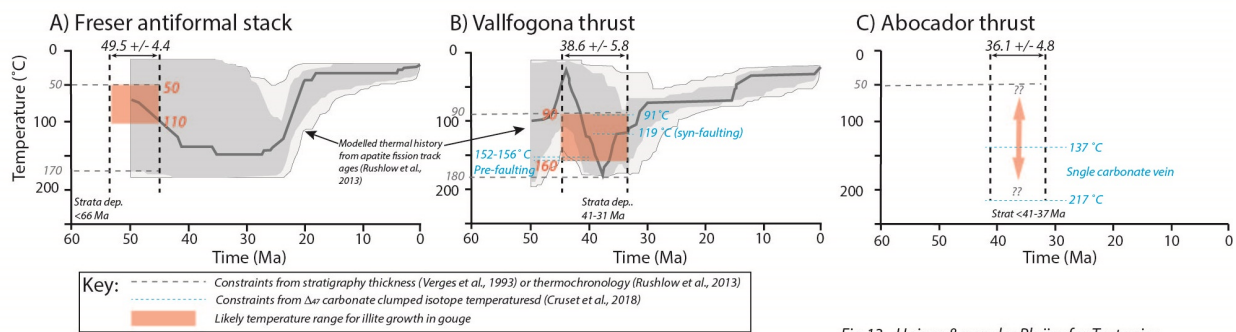
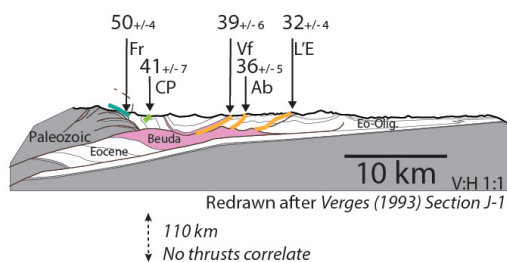


Fig 13 - Haines & van der Pluijm for Tectonics

A) South-East Pyrenees - Ter-Freser



B) South-Central Pyrenees - ECORS profile

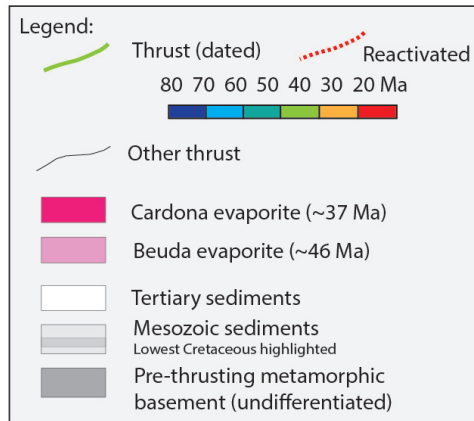
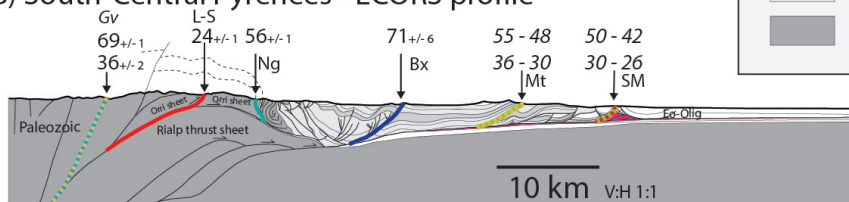


Fig 14- Haines & van der Pluijm for Tectonics