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Displacement localization and palaeo-seismicity of the Rencurel Thrust Zone, French Sub-Alpine Chains

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Abstract—The palaeo-seismicity and history of strain accumulation within the Rencurel Thrust Zone, French Sub-Alpine Chains, has been investigated by examining fracture-filling cements. Two generations of fracture-filling cement with distinct petrographic characteristics, cation geochemistries and ^{13}C and ^{18}O stable isotopic compositions have been distinguished within the Rencurel Thrust Zone. The hanging-wall rocks contain fracture-filling calcite cements, whereas ferroan calcite fills fractures within the Central Gouge Zone. Calcite-cemented faults include frontal, oblique and lateral ramps, as well as faults dipping in the movement direction, whereas, ferroan calcite-cemented faults include only frontal ramps and faults dipping in the movement direction. Fragments of calcite cement occur as clasts within the Central Gouge Zone, indicating that the calcite cements formed prior to precipitation of ferroan calcite in the Central Gouge Zone. Lineation data indicate that precipitation of both generations of cement occurred during a single phase of thrusting.

The lack of ferroan calcite cements in the hanging-wall rocks suggests that the hanging-wall of the Rencurel Thrust was not fractured during displacements within the Central Gouge Zone. This contrasts with seismogenic faults where rocks surrounding major faults are fractured during fault slip, and it is inferred that the exposed portion of the Rencurel Thrust may have experienced aseismic fault displacements. The aseismic fault slip may have been the consequence of the shallow burial depths (<3 km) experienced by the exposed portion of the Rencurel Thrust during faulting.

INTRODUCTION

EVIDENCE from seismological studies suggests that the style of faulting changes with depth due to variations in confining pressure along natural fault zones in the upper continental crust. At low confining pressures with burial depths <3 km, deformation along faults with well-developed gouge zones does not involve large stress drops and is effectively aseismic. At greater burial depths (>3 km) where higher confining pressures exist, faulting is usually associated with large stress drops and earthquakes (Scholz *et al.* 1969, Sibson 1986, Marone & Scholz 1988). It is also interesting to note that in addition to the change in seismicity along faults with increasing burial depth and/or confining pressure, Donath (1970), in his classic rock deformation experiments, showed that the style of faulting and/or fracturing in a rock specimen changes with increasing confining pressure. At low confining pressures, the result of deformation is a localized fault surface without widespread fracturing of the specimen, whereas at higher confining pressures, intense fracturing occurs in the volume of rock containing the fault resulting in a fault zone with a braided appearance.

Depth variations in seismicity *within* the seismogenic upper crust are well-documented, widely-accepted and may be compatible with the changes in faulting style observed in rock deformation experiments spanning a range of confining pressures. However, the relationship that exists between confining pressure and/or burial depth and faulting style has largely been ignored by structural geologists examining the evolution of fault zones in the upper continental crust. To date, few studies have demonstrated variations between natural fault zones formed at different confining pressures such as those formed above and below the upper cut-off in seismicity in the upper continental crust (~3 km). This is a significant omission when it is considered that fault zone evolution is a theme that is central to studies covering a wide range of subjects such as fluid migration, mineralization and earthquake hazard assessment.

This paper suggests that it should be possible to distinguish, from outcrop-based studies, faults that have operated above and below the upper cut-off in seismicity discussed by Scholz *et al.* (1969), Sibson (1986) and Marone & Scholz (1988). The methodology is simple, and involves examining the strain accumulation history experienced by the rocks surrounding major fault surfaces. In particular, the method involves an attempt to correlate fracture-filling syn-kinematic cements between a fault zone and the rocks containing the fault zone in order to establish the volume of rock which experiences fracturing during fault slip. The reasoning behind this methodology is set out below.

Let us examine the style of deformation which is documented from seismogenic faults. It is well known that during earthquake episodes, the rocks surrounding major seismogenic faults accumulate strain by fracturing during fault slip. For example, studies of fault populations around major faults suggest that the level of strain accommodated by minor faults surrounding major fault surfaces changes during displacement on the major fault surfaces (Wojtal 1986, Wojtal & Mitra 1986, Woodward *et al.* 1988, Childs *et al.* 1990). The results of fault population studies agree with the Gutenberg–Richter relationship which indicates that a large number of small faults are active around major active faults during deformation (Aki 1981, King 1983). These fault populations resemble the structures produced during rock deformation experiments conducted at high confining pressures (e.g. Donath 1970).

Strain accumulation occurs in the rocks surrounding established seismogenic faults during two main stages of the seismic cycle:

—first, during the pre-seismic stage, dilatant deformation in the rocks surrounding the fault surface results in the opening of fractures. A wealth of evidence for this type of deformation comes from studies of fault-related fluid flow where fracture dilatancy accompanies fluid-pressure variations and fluid migration during the pre-seismic stage of the seismic cycle (Stermitz 1964, Swensen 1964, Sibson *et al.* 1975, Sibson 1981, 1990). Dilatancy in the wall-rocks to faults is induced by the frictional resistance to slip on the fault surface;

—second, immediately after co-seismic fault slip, aftershocks occur within the rocks surrounding major fault surfaces indicating that strain is accumulating as a result of faulting and fracturing (King *et al.* 1985, Stein *et al.* 1988, Eberhart-Phillips 1989, Sibson 1989). Aftershocks occur to alleviate stress concentrations within the wall-rocks caused by irregular mainshock ruptures (Sibson 1989).

A great deal of information exists concerning deformation in the volume of rock containing seismogenic faults. However, aseismic faults operating in the top 3 km of continental crust have been overlooked and very little information is available concerning their evolution. Presumably, initial loading prior to fault zone localization leads to the formation of a network of fractures, and this type of deformation has been observed in a large number of rock deformation experiments (e.g. Meredith *et al.* 1990, Aves *et al.* 1993). However, after the fault has localized, it is unlikely that wall-rock dilatancy and fracturing will occur during fault slip. This is because Byerlee's law states that faults are relatively weak at low confining pressures, so that a fault surface will be unable to support the large stresses necessary to induce dilatant deformation and fracturing in the volume surrounding the fault. It is therefore possible that, in contrast to the deeper seismogenic portions of faults, the upper aseismic portions of faults will not experience wall-rock fracturing *during* fault displacements.

The preceding discussion provides the basis of a method which may allow seismogenic faults (>3 km burial) to be distinguished from aseismic faults (<3 km burial). The wall-rocks surrounding seismogenic faults become fractured during fault slip. It is possible that pore waters would leak from the main fault surface into fractures in the wall-rocks, so that fracture-filling cements along the main fault surface would have the same composition as the fracture-filling cements within the wall-rocks. In contrast, during aseismic faulting (e.g. faults in the top ~3 km of continental crust), fault slip would not be accompanied by fracturing in the rocks surrounding the fault because the fault would be too weak to support stresses large enough to induce deformation in the wall-rocks. In this scenario, fluids along the main fault surface would not be able to leak into fractures in the wall-rocks as no open fractures would exist. Thus, in contrast to seismogenic faults, along aseismic faults developed at low confining pressures, the fracture-filling cements that characterize the fault zone would not be found in the wall-rocks to the fault zone. Fracture-filling cements around aseismic faults would be precipitated prior to fault localization. The distribution of fracture-filling cements around faults can be mapped at outcrop and this type of study can therefore provide a basis for distinguishing aseismic faults from seismogenic faults.

This paper presents the results of a study of fracture-filling cements from the Rencurel Thrust Zone, French Sub-Alpine Chains, which uses the methodology discussed above to assess the palaeo-seismicity of the fault zone. The exposed portion of the Rencurel Thrust Zone underwent deformation at <3 km burial with relatively low confining pressures so that it is likely that the deformation would have been effectively aseismic (cf. Scholz *et al.* 1969, Sibson 1986, Marone & Scholz 1988). A cross-section is presented, showing the spatial distributions and cross-cutting relationships between two syn-kinematic cement generations distinguished within the fault zone. This cement-generation map is used, in conjunction with lineation and fault plane orientation data, to interpret the strain accumulation history and palaeo-seismicity of the Rencurel Thrust. The fracture-filling cements that characterize the centre of fault zone are not found in the wall-rocks, suggesting that the exposed portion of the Rencurel Thrust was indeed the site of aseismic fault slip.

GEOLOGICAL BACKGROUND TO THE RENCUREL THRUST

The Rencurel Thrust Sheet is located within the Vercors Massif which forms part of the French Sub-Alpine Chains Thrust Belt (see Fig. 1). The thrust belt contains the outer foreland structures of the Western Alpine Mountain Belt (Goguel 1948, Ramsay 1963, Gidon 1981, Menard & Thouvenot 1987, Butler 1989, Vialon *et al.* 1989, Vialon 1990). Formed in late Miocene times, the structures within the Sub-Alpine Chains accommodate the last 20–30 km of WNW-directed thrusting within the Western Alps (Butler 1989). Drill-hole, gravity and seismic refraction data yield a depth to basement map for the region (Menard 1979). This depth to basement map, together with a deep seismic reflection line (Bayer *et al.* 1987), indicates that the basement is not involved in the fold–thrust structures directly beneath the Vercors, but that the structures are detached along the basement–cover contact due to the presence of Triassic sabkha evaporites. Deep gorge sections and local relief of up to 1 km provide excellent opportunities to examine the geometry of structures.

The Mesozoic saw the deposition of extensive carbonate sequences (Graciansky *et al.* 1979, Lemoine *et al.* 1986, Arnaud-Vanneau & Arnaud 1990). The Mesozoic

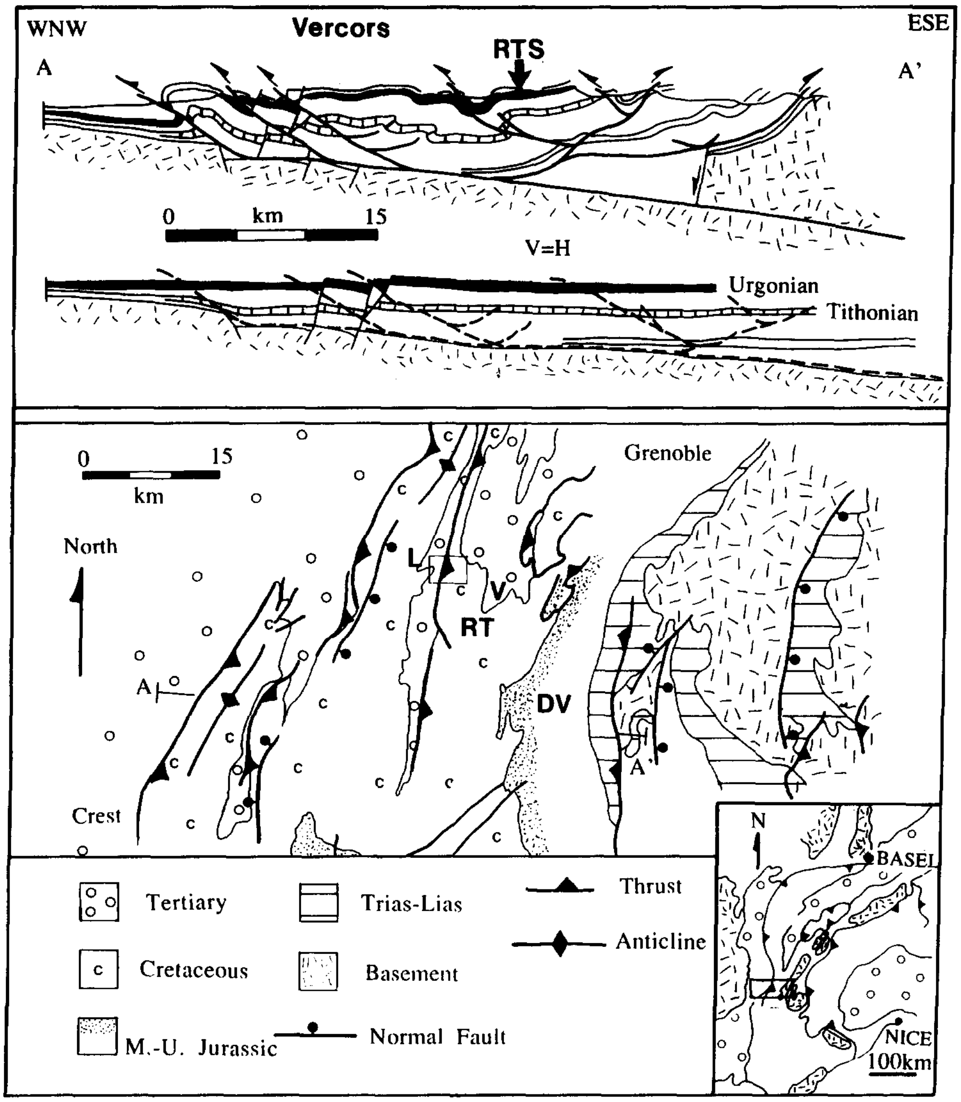

Fig. 1. Location map and balanced cross-section across the Vercors (adapted from Butler 1989). RTS—Rencurel Thrust Sheet; L—La Balme de Rencurel; V—Villard de Lans; RT—Rencurel Thrust; DV—Drac Valley. Box between L and V locates Fig. 2.

sequence is overlain by Tertiary foredeep clastic sediments. The stratigraphy of the Vercors is shown in detail on published geological maps such as B.R.G.M. Charpey (1968), B.R.G.M. Romans sur Isere (1975), B.R.G.M. Grenoble (1978), B.R.G.M. Vif (1983) and in geological reviews of the area (Debrand-Passard *et al.* 1984, Arnaud-Vanneau & Arnaud 1990). Thermal maturities of the rocks exposed at the surface in the Vercors are low with vitrinite reflectance values of 0.3–0.45% R.E. and spore colouration of yellow–yellow/orange for Hauterivian limestones and lime-mudstones (Roberts 1991a, Moss 1992). The rocks have experienced burial temperatures of 40–80°C. Assuming a palaeo-geothermal gradient of 25–35°C km^{-1}, the rocks have been buried to 2–3 km (Roberts 1991a, Moss 1992). The region has experienced several kilometres of uplift and erosion during post-thrusting isostatic rebound. Bitumen seeps (Zweidtler 1985), together with higher thermal maturities values further north along the strike of the thrust belt (Moss 1992, Schegg 1992) indicate the maturation of source rocks and migration of hydrocarbons within the more northern parts of the Sub-Alpine Chains where greater peak burial depths were experienced (~3–10 km).

Regional cross-sections across the Vercors (Gidon 1981, Arpin *et al.* 1988, Butler 1989) suggest that individual structures consist of foreland-directed fold–thrust complexes that accommodate only a few kilometres of displacement. Figure 1 shows one of these cross-sections across the Vercors taken from Butler (1989). The cross-section suggests that burial of the rocks now exposed at the surface in the Vercors to ~2–3 km was not due to the area being over-ridden by higher-level thrust sheets that have since been eroded off. Instead, the burial probably occurred beneath Miocene foredeep sediments deposited above the area that was to become the Vercors, ahead of the growing western Alpine mountain belt that lay to the east at this time. These foredeep sediments have been removed by erosion during regional isostatic uplift. Thrust activity within the rocks presently exposed within the Vercors, initiated when the rocks were at their peak burial depth (<3 km) (Roberts 1991a, Moss 1992).

The Rencurel Thrust Sheet can be examined in exposures within the eastern portions of the Gorges de la Bourne, between the towns of La Balme de Rencurel and Villard de Lans (see Fig. 1). The thrust sheet has been the focus of studies concentrating on structural styles and structural controls on syn-kinematic fluid migration (Roberts 1990, 1991a,b). The Rencurel Thrust Sheet was mapped at 1:10,000 scale with the results presented in detail by Roberts (1991a). Figure 2 shows a simplified geological map and cross-section across the Rencurel Thrust Sheet. The Chalimont, Valchevriere and Ferriere Thrusts, which deform internally the Rencurel Thrust Sheet, are also marked on Fig. 2.

In the exposures within the Gorges de la Bourne, the Rencurel Thrust emplaces Barremian to Aptian carbonates, termed locally the Urgonian limestones, onto Miocene molasse clastic sediments. The Rencurel Thrust is the most important structure on a regional scale, and can be traced to the north to merge with the Voreppe Thrust (B.R.G.M. Grenoble 1978), and to the south into an area where thrust displacements die out and large-scale gentle folds are developed (B.R.G.M. La Chapelle en Vercors 1967).

INTERNAL STRUCTURE OF THE RENCUREL THRUST ZONE

The Rencurel Thrust Zone is well exposed in road cuttings along the D103 road between Pont de Goule Noire and St. Julien en Vercors. Faults and fractures were identified, and their position marked onto a photo-montage of the road cutting that was used as a base map. Fractures produced by faulting were distinguished from fractures produced during uplift and weathering or excavation and blasting of the road section using the following methodology. Fault gouge was found along all of the fractures and faults mapped onto the photo-montage. Where fault gouges could not be found along fractures, it was concluded that they may not have been produced by faulting. Fractures that were not lined with fault gouge were rejected from the study and not marked on the photo-montage. This technique produces a minimum estimate of fault and/or fracture densities within the fault zone. Fault gouge may have been eroded from some fractures so that they cannot be identified positively as due to faulting, and some faults may have been missed. A minimum estimate of fault–fracture densities is however still useful information to input into fault zone models.

The existence of carbonate gouge indicates that all of

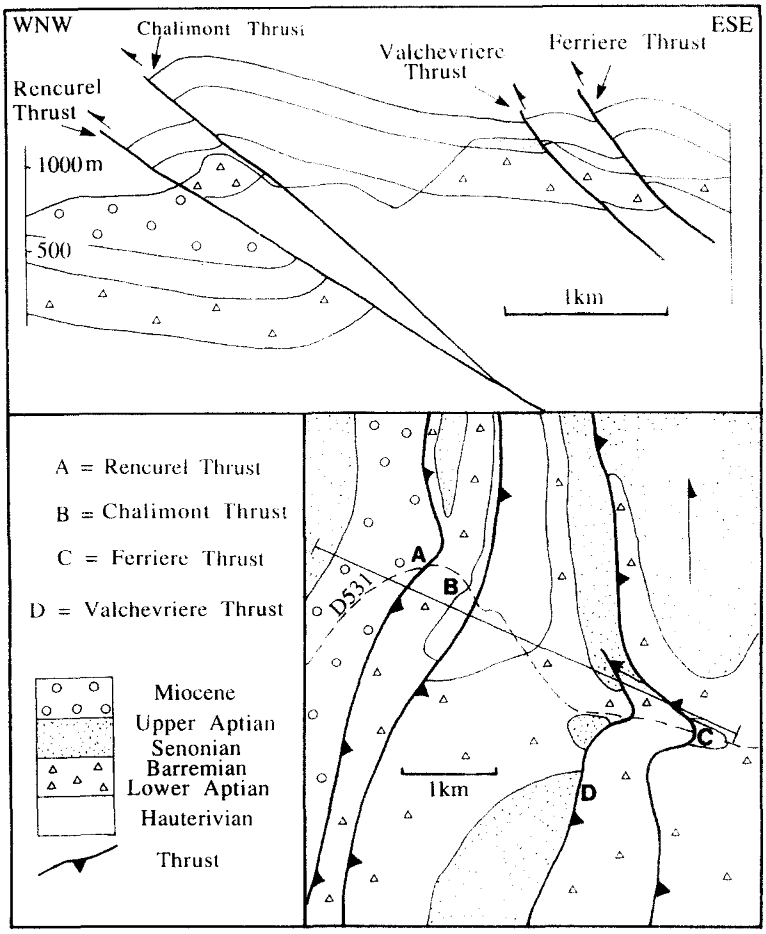

Fig. 2. Map and cross-section across the Rencurel Thrust Sheet French Sub-Alpine Chains (adapted from Roberts 1991a). The Barremian and Aptian rocks are called locally the Urgonian limestones.

these fractures have undergone fracture-parallel shear, so that they are termed faults in this paper. Veins filled with cement where no evidence of vein-parallel shear could be found were restricted to within gouge zones developed along the faults. Veins filled with cement were uncommon in the rocks between the faults. Thus, all of the features marked on the photo-montage are referred to as faults lined with carbonate fault gouge.

One hundred and fifty samples were taken from the Rencurel Thrust Zone and the sample sites were recorded accurately on the photo-montage. One hundred and eight thin-sections were prepared, and these, together with the sawn faces of hand specimens, were examined in order to ascertain the composition and distribution of syn-kinematic cements within the Rencurel Thrust Zone. The fault rocks were studied using petrographic, geochemical and ^{13}C and ^{18}O stable isotope techniques described by Roberts (1991a). The results of these studies are summarized below (See Fig. 3).

Observations concerning the distribution of syn-kinematic cements allow an interpretation where the Rencurel Thrust Zone is divided into two parts, namely the Central Gouge Zone and the Hanging-wall Fault Array (see Fig. 3). The Central Gouge Zone and the Hanging-wall Fault Array can be distinguished on the grounds of thickness of gouge zones, displacement and stratigraphic separation across the faults, but more significantly, due to their different fracture-filling syn-kinematic cements and kinematics (see Figs. 3–8). Details of the differences between the Central Gouge Zone and the Hanging-wall Fault Array are described below. The division of the fault zone into two parts is an interpretation made by the author. This interpretation has been made prior to a detailed description of the data because it is felt that this will assist the reader.

Central Gouge Zone

A zone of fault gouge at least 2.3 m thick is found at the western end of the road section; it is termed the Central Gouge Zone. The fault gouge lines the contact between the Urgonian limestones in the hanging-wall and the Miocene sandstones in the footwall to the thrust zone (see Fig. 4). The Central Gouge Zone contains at least 30 cm of lithified carbonate gouge derived from the comminution and grain-size reduction of the overlying Urgonian limestones, and at least 2 m of gouge derived from both the Urgonian hanging-wall rocks and the molasse footwall rocks. Field geometries shown in the cross-section in Fig. 2 indicate that the majority of the 1 km displacement across the Rencurel Thrust Zone has been accommodated by deformation within the Central Gouge Zone. A small and poorly exposed outcrop of faulted and vertically bedded Senonian limestone exists two metres to the west of the view of the Central Gouge Zone shown in Fig. 4. An area of no exposure exists between the outcrop of faulted Senonian limestones and outcrops of unfaulted Miocene sandstones that lie 300 m further to the south-west along the road. Thus, the Central Gouge Zone is the lowest structural level that is well-exposed within the Rencurel Thrust Zone.

The gouges within the Central Gouge Zone contain fracture-filling ferroan calcite. The ferroan calcite, although only weakly luminescent, can be seen to be zoned when viewed under cathodoluminescence. The ferroan calcite was sampled using a dentists' drill from the sawn faces of hand specimens and thin sections, but, individual cement zones could not be separated. Isotopic results could only be obtained from a bulk sample of the ferroan calcite. This means that the stable isotopic values obtained from the ferroan calcite represent averages of any isotopic variation which may exist between

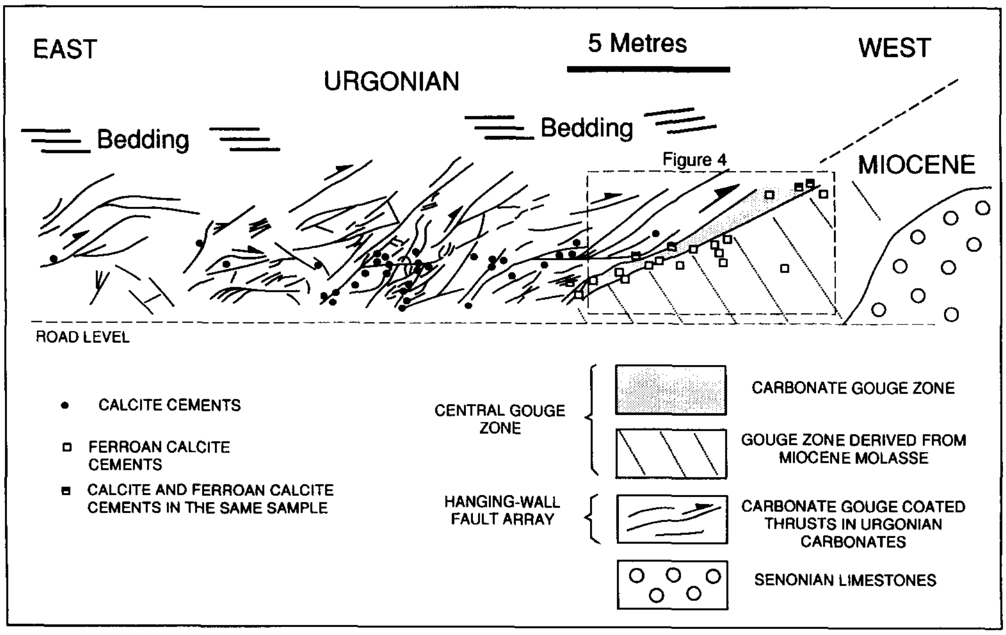

Fig. 3. Cross-section showing syn-kinematic cement generations within the Rencurel Thrust Zone located close to A on Fig. 2. The symbols for cement types indicate the positions from which samples were taken from the exposure. Note the array of minor faults in the Urgonian limestones. The western end of the section is shown in Fig. 4.

cement zones. Values of -1 to 1 per mil $\delta^{13}C$ and -6 to -8 $\delta^{18}O$ were obtained for the ferroan calcite (see Fig. 6). The iron-rich gouges also contain fractures filled with bitumen, interpreted by Roberts (1991a,b) as the residue of hydrocarbons which migrated through the thrust zone during deformation. No fracture-filling non-ferroan calcite has been found in the Central Gouge Zone.

Hanging-wall Fault Array

In the hanging-wall of the Central Gouge Zone, minor thrusts exist within the Urgonian limestones (see Fig. 3). This portion of the Rencurel Thrust Zone is termed the Hanging-wall Fault Array. The array of faults persists for around 100 m to the east along the road section before exposure is lost. Outcrops within the Urgonian limestones 50 m further along the road contain few faults indicating that the density of faults decreases into the hanging-wall of the Rencurel Thrust Zone and that these outcrops lie outside the Hanging-wall Fault Array.

Individual thrusts within the array are characterized by small displacements (<50 cm), and are coated in <10 cm of fault gouge composed of finely-comminuted Urgonian limestones and dolomites. The fault rocks contain un-zoned vein-filling calcite exhibiting a dull luminescence. The vein-filling calcite is relatively depleted in ^{13}C and ^{18}O (values around -4.0 per mil $\delta^{13}C$ and -8.5 per mil $\delta^{18}O$ (see Fig. 6). In the areas between the faults, the original foraminiferal grainstone fabric of the Urgonian limestones is still clearly visible, indicating that the rocks are not intensely fractured or recrystallized.

As reported by Roberts (1991a,b), a cross-cutting relationship exists between parts of the fault zone containing these two cement generations. Microtextures such as calcite vein material derived from the Hanging-wall Fault Array can be found as clasts within the Central Gouge Zone characterized by ferroan calcite vein material, and no intact calcite veins have been found in the Central Gouge Zone. This relationship is evident at outcrop (see Fig. 4) and has been confirmed in several thin-sections (see Fig. 5).

Interpretation of the distribution of syn-kinematic cements within the Rencurel Thrust Zone

The sample sites for thin-sections containing syn-kinematic cements are shown in Fig. 3. Clearly, the ferroan calcite cements showing $\delta^{13}C$ values between -1 and 1, and $\delta^{18}O$ values between -6 and -8 are restricted to the Central Gouge Zone containing the thrust contact between the Urgonian limestones and the Miocene sandstones. Calcite cements with isotopic values around -4.0 per mil $\delta^{13}C$ and -8.5 per mil $\delta^{18}O$ are only found along minor faults in the hanging-wall of the thrust contact between the Urgonian and Miocene rocks. It is this spatial variation in syn-kinematic cements which allows the two portions of Rencurel Thrust Zone to be distinguished, namely the Central Gouge Zone and the Hanging-wall Fault Array. Clasts of calcite occur within the Central Gouge Zone, indicating that the Hanging-wall Fault Array was formed prior to the Central Gouge Zone. If the hanging-wall to the Central Gouge Zone had been fractured during displacement in the Central Gouge Zone, then it is possible that fluids could have leaked from the Central Gouge Zone into the hanging-wall fractures and precipitated ferroan calcite cements. However, no ferroan calcite cements with isotopic compositions of -1 to 1 $\delta^{13}C$ and -6 to -8 $\delta^{18}O$ have been found within the area occupied by the Hanging-wall Fault Array. It is concluded that the hanging-wall was not fractured as it was carried above the Central Gouge Zone.

In summary, the Hanging-wall Fault Array formed prior to the deformation that formed the Central Gouge Zone. Later deformation that resulted in the production of the Central Gouge Zone did not redeform the Hanging-wall Fault Array. The 'frozen-in remnants' of the early deformation were carried passively during displacements within the Central Gouge Zone and preserved as the Hanging-wall Fault Array (see Fig. 9).

A detailed account of the evolution of the exposed portion of the Rencurel Thrust Zone is given below.

(1) Deformation prior to the formation of the Central Gouge Zone produced an array of faults. Individual faults accumulated only small displacements (<50 cm). The rocks between the faults were not intensely deformed by fracturing or recrystallization and retain their pre-deformation fabrics. Within the fault zones, displacements were accompanied by cataclastic grain-size reduction resulting in the accumulation of the carbonate fault gouge along the faults. Fracture porosity opened within the gouge zones during fault displacements to become filled with fluids from which unzoned, dull-luminescent calcite precipitated with stable isotopic composition around -4.0 per mil $\delta^{13}C$ and -8.5 per mil $\delta^{18}O$. The record of this deformation is preserved in the hanging-wall to the Rencurel Thrust.

(2) Deformation post-dating the formation of the Hanging-wall Fault Array was restricted to within a gouge zone; a <5 m-thick portion of which is preserved today as the Central Gouge Zone. Fault slip within the Central Gouge Zone produced the majority of displacement within the Rencurel Thrust Zone. Displacements were accompanied by cataclastic grain-size reduction resulting in the accumulation of the fault gouge derived in part from the overlying Urgonian limestones. The Urgonian limestones already contained minor thrusts, some of which are preserved today within the Hanging-wall Fault Array. However, cataclastic grain-size reduction destroyed the pre-deformation fabric of the Urgonian Limestones, as well as the fabrics of the fault gouges contained within the Urgonian limestones that were to become incorporated into the Central Gouge Zone. The fracture-filling calcite cements of the Hanging-wall Fault Array underwent grain-size reduction within the Central Gouge Zone, and the fine-grained remains of the cement were dispersed within the accumulating carbonate gouge. No intact calcite-filled

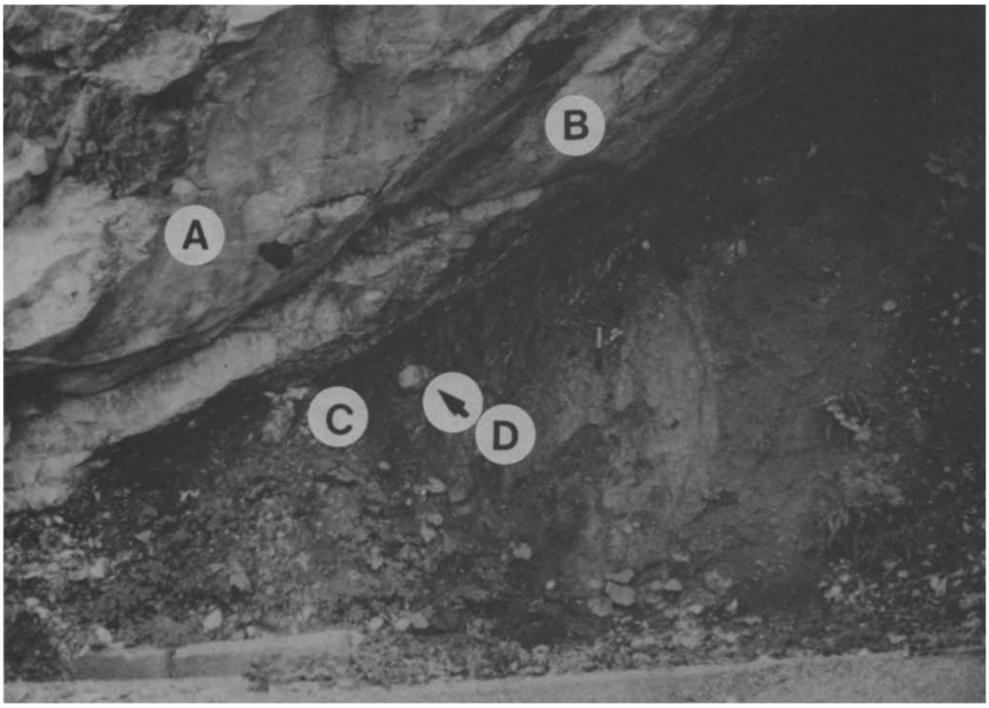

Fig. 4. View looking south onto the thrust contact between the Urgonian limestones and the Miocene sandstones within the Rencurel Thrust Zone. A—Urgonian limestones; B—carbonate gouge derived from comminution of the overlying Urgonian limestones; C—gouge derived from Miocene sandstones; D—clast containing fracture-filling calcite cements and calcite fault gouge derived from the earlier-formed Hanging-wall Fault Array within the Urgonian limestones. Hammer is 40 cm long. See Fig. 3 for location.

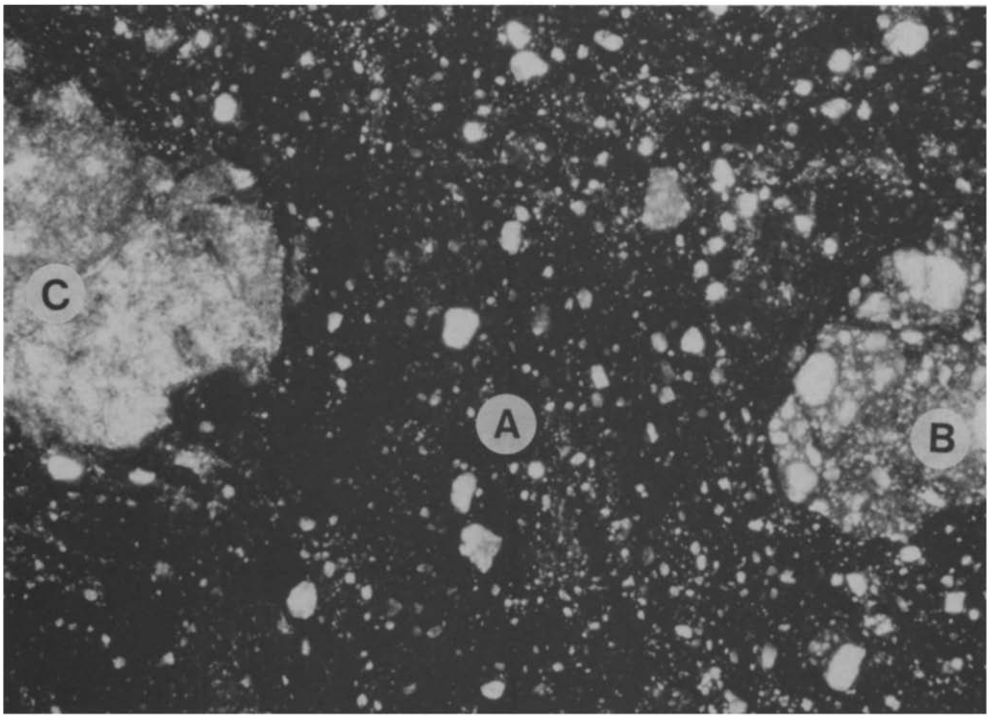

Fig. 5. Microtexture of the fault gouge along the thrust contact between the Urgonian limestones and the Miocene shales within the Rencurel Thrust Zone. A—iron-rich gouge composed of calcite and dolomite which contains ferroan calcite veins not shown in this photograph; B—clast of indurated iron-rich gouge composed of calcite and dolomite which has been re-fractured and incorporated into a later gouge texture. Induration occurred during cementation and chemical compaction which post-dated initial grain-size reduction of the precursor carbonate, but pre-dated the final increments of displacement and grain-size reduction within the gouge; C—clast of calcite derived from the Hanging-wall Fault Array developed within the Urgonian limestones. Field of view is 4 mm.

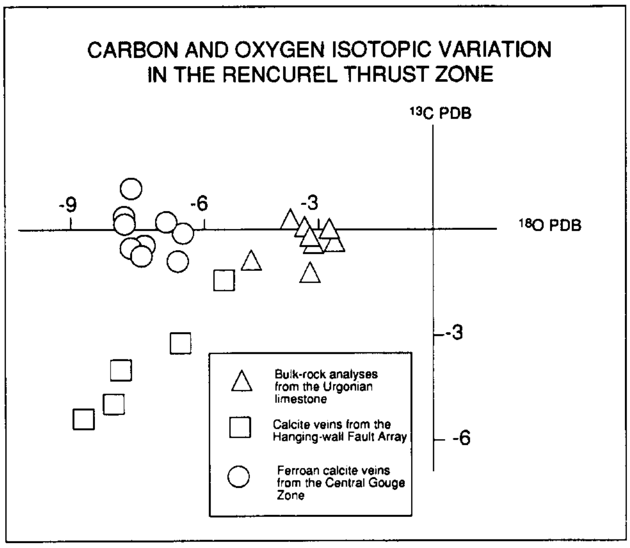

Fig. 6. Cross-plot showing ^{13}C and ^{18}O stable isotopic variation of syn-tectonic calcite cements within the Rencurel Thrust Zone.

veins have been found within the Central Gouge Zone. Fault gouge also accumulated as a result of the deformation of Miocene sandstones.

Fracture porosity opened during fault displacements in the Central Gouge Zone, to become filled with fluids from which precipitated zoned, fracture-filling ferroan calcite with isotopic compositions of -1 to 1 δ^{13}C and -6 to -8 δ^{18}O. The fluids also contained traces of hydrocarbons, preserved today as bitumen.

In addition to cataclastic grain-size reduction, displacement within the Central Gouge Zone may also have been accommodated by frictional grain-boundary sliding within unconsolidated gouges (Roberts 1991a, b). Frictional grain-boundary sliding may have operated due to the low burial depths (<3 km) and low confining pressures. Frictional grain-boundary sliding would dominate immediately after grain-size reduction events as the gouge would be unconsolidated. Grain-size reduction is a dilatant deformation mechanism (Knipe 1989), so that fluids would have been drawn into the fault zone to fill inter-granular fracture porosity within the gouge. Thus, after grain-size reduction events, the gouge was certainly unconsolidated, and probably fluid-saturated, promoting frictional grain-boundary sliding. The microstructural record of frictional grain-boundary sliding may be difficult to resolve (Knipe 1989) because frictional grain-boundary sliding results simply in the repacking of grains without permanent shape changes to the grains involved.

LINEATION AND FAULT PLANE ORIENTATION DATA FOR THE RENCUREL THRUST ZONE

Lineation and fault plane orientation data were collected along the road section represented in Fig. 3. Data for the Hanging-wall Fault Array and the Central Gouge Zone are described and interpreted separately below.

Hanging-wall Fault Array

Seventy-one lineations were measured from ninety one fault planes along the road section shown in Fig. 3. Lineations found on fault planes were striations and scratches on gouge-coated surfaces. No mineral fibre or stretching fibre lineations were found. All of the structural data were collected from faults within the portion of the Rencurel Thrust Zone containing non-ferroan calcite syn-kinematic cements (see Figs. 7 and 8). Kinematic indicators such as the offset of foliations within fault gouge, cement-filled pull-aparts and steps on fault planes were found on ten faults. Kinematic indicators show a top-to-the-west movement sense, regardless of the dip-direction of the fault plane. Displacements were observed and measured from five faults, the maximum being around 50 cm. The cluster of lineation orientations (see Fig. 7), the kinematic indicators and the vergence of the Rencurel Thrust as a whole indicates that the dominant thrusting direction was towards the west-north-west. The poles to fault planes do not show a tightly-

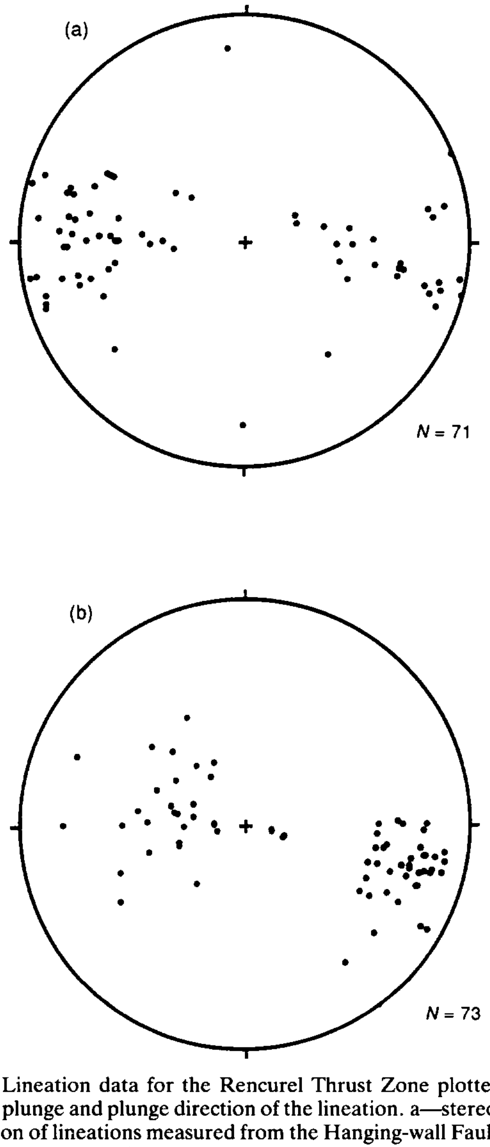

Fig. 7. Lineation data for the Rencurel Thrust Zone plotted in the form of plunge and plunge direction of the lineation. a—stereographic projection of lineations measured from the Hanging-wall Fault Array; b—stereographic projection of lineations measured from the Central Gouge Zone.

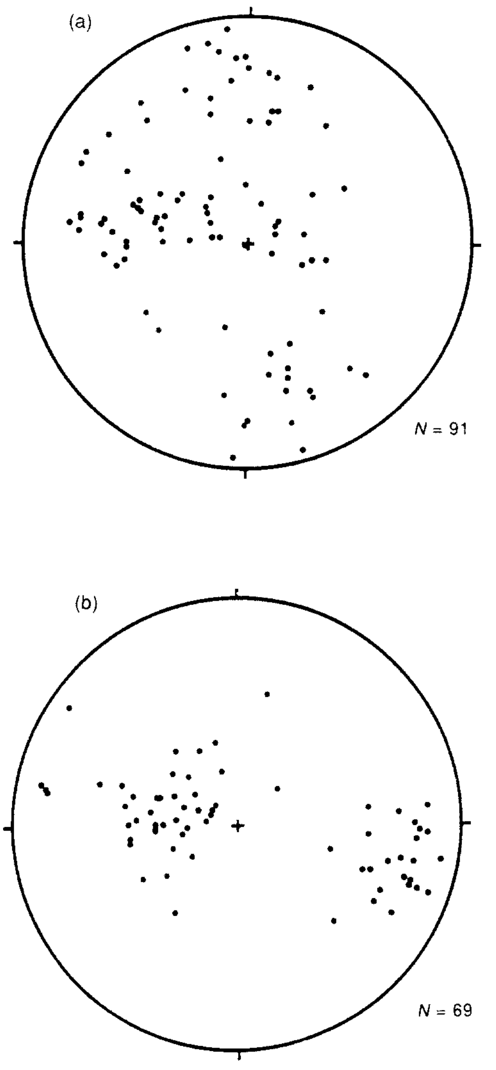

Fig. 8. Fault plane orientation data for the Rencurel Thrust Zone plotted in the form of poles to fault planes. a—stereographic projection of poles to fault planes measured from the Hanging-wall Fault Array; b—stereographic projection of poles to fault planes measured from the Central Gouge Zone.

clustered pattern (see Fig. 8) indicating a wide variety of fault plane orientations.

Central Gouge Zone

Seventy-three lineations were measured from 69 fault surfaces within the 2.3 m thick Central Gouge Zone exposed along the thrust contact between the Urgonian and the Miocene rocks (see Figs. 7 and 8). Lineations on fault planes consist of striations or scratches on gouge-coated surfaces. No mineral-fibre or stretching fibre lineations were found. All of the structural data were collected from faults within the zone containing ferroan syn-kinematic cements (see Fig. 3). Two distinct groupings of faults exist. One grouping contains faults that dip towards the east-south-east with lineations plunging in the same direction. The other grouping contains faults that dip towards the west-north-west with lineations also plunging towards the west-north-west. Kinematic indicators such as the offset of foliations within fault gouge, cement-filled pull-aparts and steps on fault planes indicate top to the west movements on both these sets of faults. The first grouping contains faults that dip towards the east-south-east in the same direction as the Rencurel Thrust Zone as a whole. The faults dipping towards the west-north-west dip in the direction of movement. Displacements along the faults dipping towards the west-north-west were measured from five examples, all of which had top to the west kinematic indicators and had a maximum displacement of 30 cm. The cluster of lineation orientations, the kinematic indicators and the vergence of the Rencurel Thrust as a whole indicates that the dominant thrusting direction was towards the west-north-west.

Interpretation

Fault planes within the Hanging-wall Fault Array show a greater variety of orientations than fault planes within the Central Gouge Zone (see Fig. 8). As mentioned above, cross-cutting relationships indicate that the Hanging-wall Fault Array formed before the Central Gouge Zone. Lineation data suggest that thrusting was towards the west-north-west throughout the history of the Rencurel Thrust Zone (see Fig. 7). Thus, during the early history of the Rencurel Thrust, strain was accommodated by displacements on minor fault surfaces (displacements <50 cm) having the geometry of frontal, oblique and lateral ramps as well as faults dipping in the direction of movement. During the later history of the Rencurel Thrust when displacements were localized within the portion of the fault zone preserved today in the Central Gouge Zone, strain was accommodated by displacements on fault surfaces having the geometry of frontal ramps, and faults dipping in the direction of movement. Fault surfaces having the geometry of oblique and lateral ramps did not develop during these displacements and are not found within the Central Gouge Zone.

Lineation data from both the Central Gouge Zone and from the Hanging-wall Fault Array indicate that the dominant thrusting direction was towards the west-north-west. Thus, the Central Gouge Zone and the Hanging-wall Fault Array formed during existence of the same bulk stress field with the maximum shortening direction (σ_1) orientated along a WNW–ESE axis. A change in the bulk stress field did not trigger the modification in the mechanisms of strain accumulation that have been shown to have occurred during the displacement history of the Rencurel Thrust Zone. The spread of lineation data within the Rencurel Thrust Zone is interpreted to reflect the natural range of movement directions occurring within a fault zone during the incremental addition of displacements.

DISCUSSION OF THE RENCUREL THRUST ZONE AND IMPLICATIONS FOR THE PALAEOSEISMICITY OF FAULTS

The variation in width of the deformation zone, fault plane orientations and syn-kinematic cement compositions together with cross-cutting relationships, indicate that the Central Gouge Zone and the Hanging-wall Fault Array were formed at different times during the evolution of the Rencurel Thrust Zone. The Hanging-wall Fault Array is the 'frozen-in remnant' of the embryonic Rencurel Thrust and contains a record of the early deformation history prior to fault zone localization, whereas the Central Gouge Zone records the later history of the thrust zone (see Fig. 9).

The most important point to emerge from this study is that a change occurred in the mechanisms of strain accommodation during the displacement history of the Rencurel Thrust Zone. Deformation became localized within a single zone of fault gouge as the fault matured. The embryonic form of the thrust where strain was accommodated across an array of minor faults, was abandoned when displacements became localized onto a single thrust surface. During displacement on the single thrust surface, strain within the rocks surrounding the thrust surface remained unchanged.

The history of strain accumulation described above for the Rencurel Thrust contrasts with the history of strain accumulation that is characteristic of the seismogenic faults described in the introduction. Evidence from seismological studies (King *et al.* 1985, Stein *et al.* 1988, Sibson 1989, Scholz 1990), quantification of observed fault populations (Aki 1981, King 1983, Wojtal 1986, Wojtal & Mitra 1986, Woodward *et al.* 1988, Childs *et al.* 1990) and observations of fluid flow associated with earthquakes (Stermitz 1964, Swensen 1964, Sibson *et al.* 1975, Sibson 1981, 1990), suggests that the rocks surrounding a major seismogenic fault surface undergo deformation during displacements on the fault surface.

So the question arises as to why the Rencurel Thrust has experienced a faulting style that is anomalous when compared to seismogenic fault zones described in the literature? One answer may be that there exists a depth variation in faulting style that can be correlated with the seismologically defined upper boundary between the seismogenic and aseismic upper crust. As described above, at depths shallower than 3 km, deformation along faults with well-developed gouge zones does not involve the large stress drops associated with earthquakes (Scholz *et al.* 1969, Sibson 1986, Marone & Scholz 1988). A cut-off in seismicity occurs at a depth of around 3 km that is attributed to the downwards transition from inherently-stable velocity strengthening

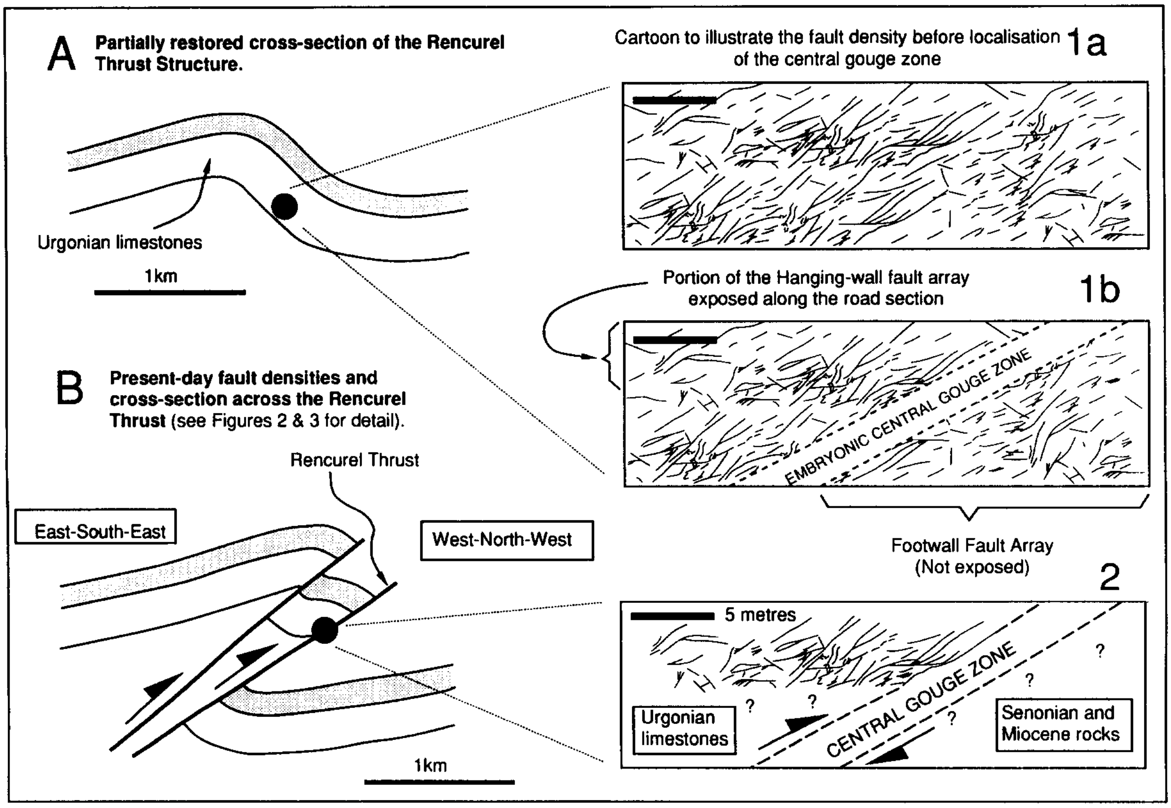

Fig. 9. Structural evolution of the exposed portion of the Rencurel Thrust Zone. A—The early history of the fault zone involved formation of an array of faults within the Urgonian limestones. Fracture porosity became filled with fluids from which precipitated dull-luminescent calcite cement. 1a—illustration of the possible fault densities during stage A. Only within the top left quarter of the inset are fault densities that can be seen at outcrop (compare with inset 2). Fault densities within the rest of the inset 1a have been drawn schematically. 1b—illustration of the position where the Central Gouge Zone became localized. B—Later in the history of the Rencurel Thrust, displacement became localized into the Central Gouge Zone. Fracture porosity opened within the Central Gouge Zone and became filled with fluids from which precipitated zoned, luminescent, ferroan calcite. No fracture filling ferroan calcite has been found within the hanging-wall rocks. Thus, within the hanging-wall Urgonian limestones, fracture porosity was not formed and strain accumulated during the early history of the thrust was not altered during displacement within the Central Gouge Zone. 2—illustration of the present-day configuration which is exposed within the Rencurel Thrust Zone (see Fig. 3 for more detail). Question marks indicate the areas that are not exposed.

within unconsolidated gouge to velocity weakening within well-consolidated gouge (Marone & Scholz 1988).

The exposed portion of the Rencurel Thrust Zone underwent deformation at a burial depth of 2–3 km, as evidenced by integration of thermal maturity data and stratigraphic data summarized above. Following workers who suggest that aseismic faulting dominates the upper 3 km of the crust (Sibson 1986, Marone & Scholz 1988), it is suggested here that the exposed portion of the Rencurel Thrust is unlikely to have hosted significantly-sized earthquakes. The exposed portion of the Rencurel Thrust may have accumulated displacements by stable sliding of unconsolidated gouges so that releases of seismic energy during fault-slip were small. This is in agreement with the deformation mechanisms reported for the exposed portions of the Rencurel Thrust (Roberts 1991a,b), where displacement was accommodated by initial cataclastic grain-size reduction and subsequent periods of frictional grain-boundary sliding within unconsolidated gouges.

Interconnected fracture–fault networks did not form in the hanging-wall rocks during displacements within the Central Gouge Zone of the Rencurel Thrust. One explanation for this may be that, in accordance with Byerlee's law, the low confining pressure that existed at 2–3 km depth resulted in a low frictional strength within the Central Gouge Zone. The low frictional strength would allow only relatively small pre-seismic stresses to accumulate, so that dilatant fracturing and/or faulting of the rocks in the volume surrounding the fault surface did not occur. Aseismic slip seems the most likely explanation for the lack of fracturing in the hanging-wall during fault slip, and this agrees with the observation that the exposed portion of the Rencurel Thrust underwent deformation at less than ~3 km depth, a depth that is dominated by aseismic faulting.

However, Byerlee's law states that the deeper portions of faults have a greater frictional strength than the shallower portions due to the increase in confining pressure with depth. Using this information it seems sensible to suggest that the deeper, unexposed portions of the Rencurel Thrust may have hosted significantly-sized earthquakes. The cross-section shown in Fig. 1 indicates that the Rencurel Thrust continues to depth. Post-thrusting isostatic uplift in the order of 2–3 km has occurred within the Vercors. Portions of the Rencurel Thrust shown on the cross-section (see Fig. 1) that currently lie between 1 and 7.5 km underwent deformation at 3–10.5 km and, therefore, lay at depths where faulting may have involved large stress drops and significantly-sized earthquakes (Sibson 1986, Marone & Scholz 1988). The implication is that the strain accumulation history for the exposed portion of the Rencurel Thrust described in this paper may not be relevant in discussions of the deeper, unexposed portions of the Rencurel Thrust. In particular, there may exist a transition with regard to the way in which fault–fracture systems develop around the major fault, the spatial distribution of fracture-filling cements and the palaeo-seismicity down-dip along the trace of the Rencurel Thrust.

It is suggested here that mapping syn-kinematic cement generations within fault zones, and collecting kinematic data from localities which host different cement generations may give insights into the strain history, fault-population dynamics and palaeoseismicity of the exposed portions of fault zones. In this paper, using the contrast in strain histories between the Rencurel Thrust and other seismogenic faults described in the literature, it is suggested that shallow, aseismic levels of fault zones above ~3 km may have different strain histories and fault population dynamics than the deeper seismogenic portions of fault zones below ~3 km. A fruitful approach with which to test this hypothesis and the interpretations presented in this paper would be to examine numerous exposures of fault zones in similar lithologies which have been exhumed from crustal depths above and below ~3 km.

CONCLUSIONS

(1) Fracture-filling ferroan calcite cements which show $\delta^{13}C$ values between −1 and 1 and $\delta^{18}O$ values between −6 and −8 are restricted to the Central Gouge Zone of the Rencurel Thrust Zone. Non-ferroan syn-kinematic calcite cements with isotopic values around −4.0 per mil $\delta^{13}C$ and −8.5 per mil $\delta^{18}O$ are only found along minor thrusts in the hanging-wall of the Rencurel Thrust Zone.

(2) Cross-cutting relationships observed within the microtextures of the Rencurel Thrust indicate that the minor thrusts in the hanging-wall to the Rencurel Thrust Zone formed prior to the localization of displacements within the material that was to become the Central Gouge Zone.

(3) No fracture-filling ferroan calcite cements with isotopic compositions of −1 to 1 $\delta^{13}C$ and −6 to −8 $\delta^{18}O$ were found within the hanging-wall of the Rencurel Thrust. The lack of ferroan cements in the hanging-wall is interpreted to mean that the deformation which produced the Central Gouge Zone did not fracture the hanging-wall. The minor thrusts within the hanging-wall represent the 'frozen-in remnants' of the early deformation that was carried passively during displacements within Central Gouge Zone and preserved as the Hanging-wall Fault Array.

(4) Fault planes within the Hanging-wall Fault Array show a greater variety of orientations than fault planes within the Central Gouge Zone. Thus, during the early history of the Rencurel Thrust, strain was accommodated by displacements on minor fault surfaces (displacements <50 cm) having the geometry of frontal, oblique and lateral ramps as well as faults dipping in the direction of movement. During the later history of the Rencurel Thrust, when displacements were localized within the portion of the fault zone preserved today in the Central Gouge Zone, strain was accommodated by displacements on minor fault surfaces having the geometry of frontal ramps and on faults dipping in the direction of movement. Lineation data from the Central

Gouge Zone and from the Hanging-wall Fault Array both indicate that the dominant thrusting direction was towards the west-north-west and that deformation occurred during a single phase of thrusting.

(5) Variation in fault plane orientations and synkinematic cement compositions between the Central Gouge Zone and the Hanging-wall Fault Array indicate that a change occurred in the mechanisms of strain accommodation during the displacement history of the Rencurel Thrust Zone. During deformation within the embryonic form of the thrust, strain was accommodated across an array of minor faults that became abandoned when displacements became localized onto a single thrust surface. During displacement on the single thrust surface, permanent strain within the rocks surrounding the thrust surface did not increase.

(6) The deformation of the exposed portion of Rencurel Thrust can be contrasted with examples of deformation around seismogenic faults described in the literature, where the permanent strain within the rocks surrounding a major fault surface increases during displacements on the major fault. The exposed portion of the Rencurel Thrust may have an anomalous strain history compared to known seismogenic faults because it underwent deformation within the upper 3 km of the crust, where aseismic deformation is prevalent. The fault may have been relatively weak and unable to store large stresses. The deeper, unexposed portions of the Rencurel Thrust may have been able to support greater stresses because of the increase in strength of the fault zone with increased confining pressure, and strain accumulation within the hanging-wall rocks may have accompanied episodic fault slip associated with significantly-sized earthquakes.

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