ELSEVIER

Journal of Structural Geology 29 (2007) 746–758

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.com/locate/jsg

The relationship between joint aperture, spacing distribution, vertical dimension and carbonate stratification: An example from the Kimmeridgian limestones of Pointe-du-Chay (France)

Francis Odonne [a,*], Carine Lézin [a], Gérard Massonnat [b], Gilles Escadeillas [c]

[a] LMTG—UMR 5563, CNRS/IRD, Université Toulouse 3, 14 avenue E. Belin, F-31400 Toulouse, France
[b] TOTAL, CSTJF, avenue Larribau, 64018 Pau Cedex, France
[c] LMDC, INSA Toulouse, 135 avenue de Rangueil, 31077 Toulouse Cedex, France

Received 12 September 2006; received in revised form 11 December 2006; accepted 12 December 2006
Available online 28 December 2006

Abstract

Joint aperture and joint development have been studied in the Kimmeridgian limestones of the Pointe-du-Chay, at the northern boundary of the Jurassic Biscay Basin (France). At Belette outcrop, in some layers the mean joint spacing of the N120° joint set is close to mean layer thickness. There, the classical spacing to thickness relationship appears to be valid in the competent carbonate layers that are included in a more argillaceous matrix. At Pillar outcrop, the N10° joint set is characterised by a high level of joint density and a non-saturated spacing distribution as indicated by the mode/mean ratio values and the C_v values; C_v is the ratio of standard deviation to mean fracture spacing. The classical relationship between layer thickness and fracture spacing has not been observed at the Pillar outcrop. Joint aperture reaches larger values at the Pillar outcrop than at the Belette outcrop where aperture is more homogeneously distributed. Almost all the joints are opened with moderate aperture values at Belette outcrop whereas most joints with large vertical dimension have large apertures at Pillar outcrop, and smaller fractures are closed or poorly opened. From two outcrops that have been subjected to the same geological conditions, apertures of non-stratabound joints appear to be controlled by the vertical dimension of the joints whereas stratabound joints are more regularly spaced and opened.

Keywords: Joints; Joint aperture; Spacing distribution; Vertical dimension; Carbonate stratification

1. Introduction

Joints are simple fractures that do not show any evidence of shear or mineralisation and that typically occur perpendicular to bedding of sedimentary rocks (Hodgson, 1961; Price, 1966; Hancock, 1985; Pollard and Aydin, 1988). In many cases more than one joint set can be recognised, and the abutting relationships are used to establish the chronological formation of the different joint sets (Dunne and Hancock, 1994).

It has been shown, from field data, that the thickness of the mechanical layer can be related to the spacing of systematic joints (Price, 1966; Huang and Angelier, 1989; Narr and Suppe, 1991; Engelder et al., 1997) and to the nature of the rock in which they develop (Ladeira and Price, 1981; Wu and Pollard, 1995). In many cases the joint spacing is close to the layer thickness (Gross et al., 1995; Engelder et al., 1997) and the mechanical discontinuities are considered to be one of the first parameters that control joint development (Narr and Suppe, 1991; Gross et al., 1995; Ruf et al., 1998; Gillespie et al., 2001).

The relationship between joint spacing and layer thickness have been described in competent layers isolated in an incompetent matrix, both in thin layers (Ladeira and Price, 1981; Ji et al., 1998) and thick layers up to 10 m (Engelder et al., 1997). Such a situation corresponds to the model proposed

* Corresponding author.
E-mail address: odonne@lmtg.obs-mip.fr (F. Odonne).

0191-8141/$ - see front matter
doi:10.1016/j.jsg.2006.12.005

by Hobbs (1967) to explain the formation of tension joints in sedimentary rocks.

Hobbs (1967) has proposed a theoretical model based on the elastic strain in a mechanical layer to explain joint spacing. Probabilistic models have been proposed (Pascal et al., 1997; Hoffmann et al., 2004) but most of the models are mechanical models based on the limit of the elastic deformation of layers. Wu and Pollard (1995) and Bai and Pollard (2000a) have developed such a model that proposes the explanation of joint spacing based on the stress transition. The strength of the competent layer has been recognised as an important parameter (Price and Cosgrove, 1990) but Bai and Pollard (2000a) have shown that the joint spacing of a layer may be controlled by its Young's modulus and that of the adjacent layers. Observations of strain in adjacent layers and interbed slip between fractured competent layers have led Ji and Saruwatari (1998) and Ji et al. (1998) to propose a revised theoretical model between joint spacing and bed thickness. Nevertheless, the often cited spacing to layer thickness relationship is not valid in clustered joint patterns. Bai and Pollard (2000b) have proposed a numerical model to explain such closely spaced joints from the propagation of flaws. Analogue experiments have provided particular insights into the progressive development of joint sets (Rives et al., 1992; Gross et al., 1995; Wu and Pollard, 1995; Sagy et al., 2001) and show that spatial change in joint spacing and joint geometry can be related to the stress field in the fractured layers (Goodwin, 1995; Sagy et al., 2001). Joint aperture has been studied from a numerical model using the theory of elasticity (Bai et al., 2000) but it has been poorly documented from field work.

In this work, our aim was to look for relationships between the spacing and vertical dimensions of the joints, the lithology of the carbonate rocks and the aperture of the joints. Using elastic modelling, Bai et al. (2000) have shown that numerous parameters may influence fracture aperture, and it may be inferred that large fractures have larger apertures than the small ones or that fractures have smaller apertures in case of a high fracture density because the extensional deformation is distributed in a more homogeneous way. For this reason joint data were collected in natural areas that have been affected by multi-scale fracture patterns.

At the northern boundary of the Jurassic Biscay Basin, two outcrops have been selected around the Pointe-du-Chay where the lower Kimmeridgian carbonates are well exposed. Numerous joints can be easily measured in a number of places and the two outcrops are two end members of the same structural style in which some variations have been looked for.

At north of the Pointe-du-Chay, the Pillar outcrop is composed of layers of mudstones to wackestones according to Dunham (1962). The carbonate sedimentation was a continuous process without argillaceous layers. This is completely different to the Belette outcrop, where the carbonate layers are included in thick argillaceous interbeds.

To estimate the fracture density, Narr (1991) has proposed an indicator that is independent of the layer thickness, namely the Fracture Spacing Index, FSI. It is defined as the slope of the regression line of the mechanical layer thickness vs. median joint spacing for a range of different layers. The FSR, Fracture Spacing Ratio, can be calculated for each layer as the ratio of the mechanical layer thickness to median joint spacing (Gross, 1993). Gross (1993) and Ruf et al. (1998) have shown that the spacing of cross-joints can be related to the spacing of the systematic joint sets between which they develop. Hence, while layer thickness controls systematic joint spacing, layer thickness has only an indirect control in cross joint spacing. To avoid any ambiguity, only the systematic joint sets have been studied and compared from Pillar and Belette outcrops.

Joints have been studied from eight layers at the Pillar outcrop and four at the Belette outcrop. Measurements have been collected of orientation, spacing, position, size and aperture parameters for all fractures on the vertical cliff of the outcrop.

Two sets of joints are present throughout the Kimmeridgian limestones of the Pointe-du-Chay, striking at N10°E and N120°E, respectively. Both are observed everywhere in the Biscay Basin (Arthaud and Choukroune, 1972) where they are interpreted as resulting of the reactivation of hercynian structural directions.

2. The Kimmeridgian limestones of Pointe-du-Chay

The outcrops of the Pointe-du-Chay are located five kilometres south of La Rochelle, France (Fig. 1). They are composed of carbonates of Lower Kimmeridgian age occurring on the northern boundary of the Jurassic Biscay Basin. Sediments deposited in this area consist of fine mudstones in which small isolated patch reefs have developed that are mainly composed of corals. The distribution of these reefs is partly controlled by faults inherited from Hercynian structures (Hantzpergue, 1985). Bioclast accumulations can develop around the patch reefs, due to the protection of the reef or because of its partial destruction (Olivier et al., 2003). As a result, the carbonate rock types that can be observed at the Pointe-du-Chay vary from mudstone to boundstone, including oolithic limestones. However, because of the few occurrences of bioclastic arrivals in the sediments, mudstones comprise the majority of the succession.

We have selected two outcrops around the Pointe-du-Chay in which the fractures are well exposed and result clearly from natural origins, that is to say without human intervention such as road works or quarry explosions. The Pillar outcrop, in the north, is a large cliff in which eight mudstone to locally wackestone layers have been studied. The Belette outcrop is located at south of the Pointe-du-Chay, it is a smaller area in which four layers have been studied.

3. Stratabound joint set at Belette outcrop

At the southern end of the Pointe-du-Chay area, the Belette outcrop is composed of limestones interbedded with marls (Fig. 2). Competent layers are mudstones in which stratabound joints have developed, incompetent argillaceous interbeds are not fractured. Both the N10° and N120° joint sets may be observed. The abutting relationships indicate that the N120° joint

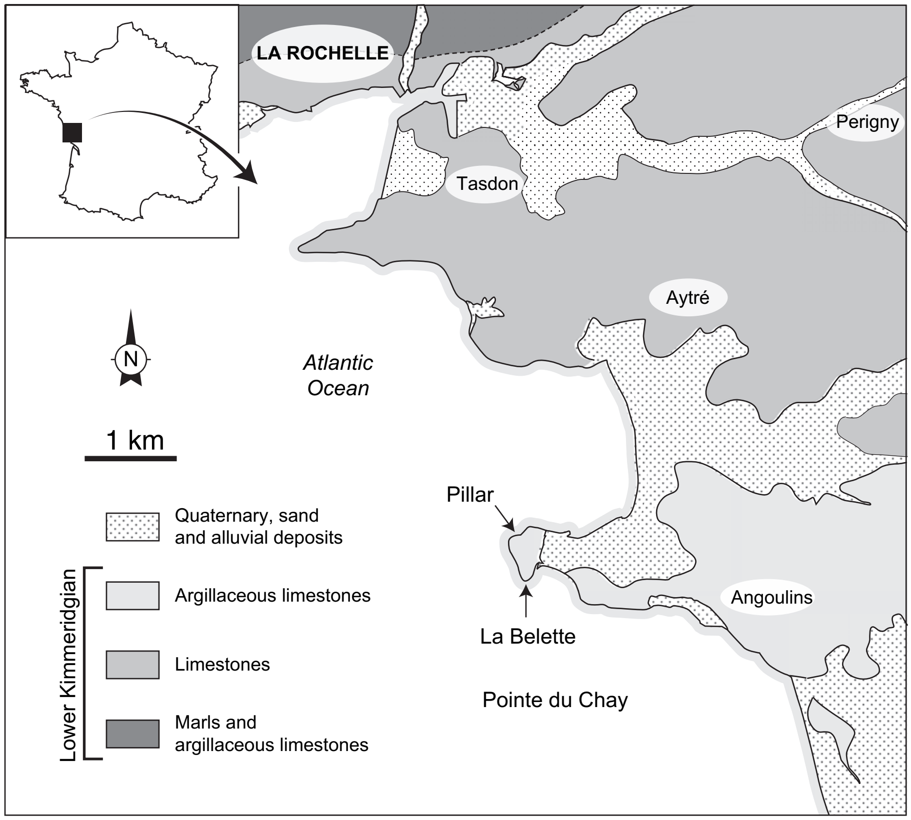

Fig. 1. Location of Pointe-du-Chay near La Rochelle (France) and simplified geological map. The Kimmeridgian limestones are partly covered with Quaternary beach sand and shore swamps. Limestones are well exposed in coastal cliffs around the Pointe-du-Chay.

set appears to be the systematic joint set and measurements have been collected on this joint set (Fig. 3). Accurate mean value of orientation is 126.8°, standard deviation is 24.8°. Joint spacing, orientation and vertical dimension have been studied from four layers.

The spacing distributions of joints have been studied using the histograms shown in Fig. 4. They seem to correspond to log-normal to almost normal distributions in the four layers. In a joint set, the distribution of spacing has been considered as an indication of the joint saturation (Rives et al., 1992). It has been proposed that the mode/mean ratio could indicate the saturation level of the set (Rives et al., 1992). Layers in which saturation is reached may continue to strain by opening of existing joints only (Narr and Suppe, 1991). The mode to mean ratio give values that range from 0.39 to 0.93. In layer 3, which is completely isolated in an argillaceous matrix, the histogram of spacing data is close to that of a normal distribution law and the mode to mean ratio is 0.83. The spacing standard deviation and the mean spacing values of these layers (Table 1) are clearly different, the spacing standard deviation being about the half of the mean joint spacing. The spacing distribution at the Belette outcrop is regular and probably saturated, especially in layer 3 where the coefficient of variation C_v is 0.44 (Fig. 5). C_v is the standard deviation to mean ratio

Fig. 2. View of the Belette outcrop at South of the Pointe-du-Chay and schematic stratigraphic column. Layers 1 to 4 are composed of fine grain carbonate rocks (mudstones) included in more argillaceous layers. Stratabound joints are limited to the carbonate beds only.

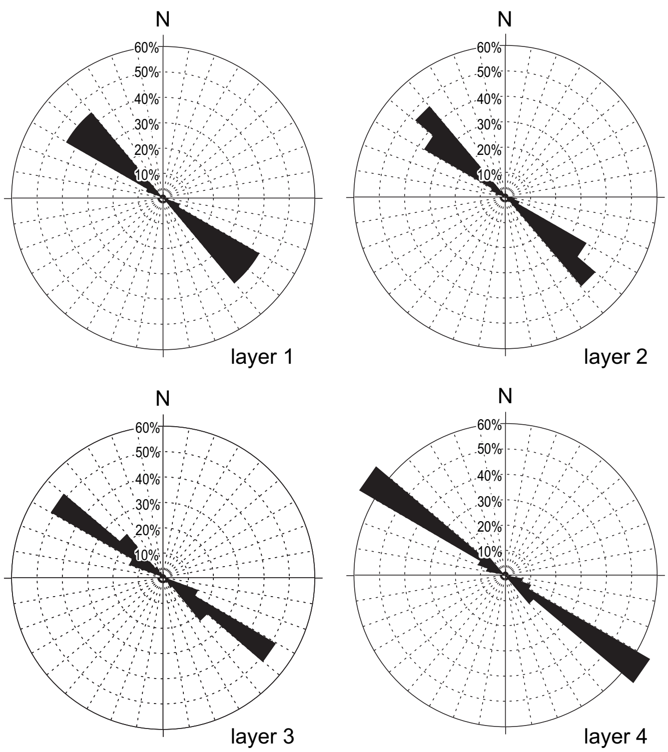

Fig. 3. Orientations of N120° joints in four layers of Belette outcrop. Joints appear to be well organised along this direction.

(Cox and Lewis, 1966). A low value of C_v indicates an anti-cluster spacing distribution (Gillespie, 2003).

The median joint spacing to mean layer thickness diagram (Fig. 6) shows that joint spacing and layer thickness both increase. An FSI value can be calculated, as proposed by Narr (1991), but it is not of significant value due to the small number of layers; nevertheless individual FSR values can be calculated (Table 1)—values are about 1 and show that joint spacing is close to mean layer thickness for layers 1 to 3. In layer 4, the joint spacing is about twice the layer thickness with a FSR value of 0.441.

At the Belette outcrop the N120° joint set appears to be well organised, joint density is low but spacing is regular and low values of $C_v < 1.0$ characterise saturated joint spacing distributions (Gillespie, 2003).

4. Multi-scale non-stratabound jointing in the Pillar outcrop

At the Pillar outcrop (Fig. 7), joint character, orientation and distribution have been studied from eight layers. According to the description proposed by Bai et al. (2000), many joints are unconfined inside a sedimentary bed, some are confined between two layer boundaries and others are multilayer joints that cross several layers. As a result, we cannot consider the eight layers as perfect mechanical layers as defined by Narr and Suppe (1991) and Gross (1993). This is probably related to the fact that there is no sedimentary interbed that could transmit a significant part of the stresses and permit the vertical propagation of the joints. Some of the layers are composed of smaller sedimentary beds that can be characterised by different carbonate content, porosity or micrite to sparite ratio (Fig. 8). All the data, joint spacing, aperture and vertical dimension, have been reported for these small

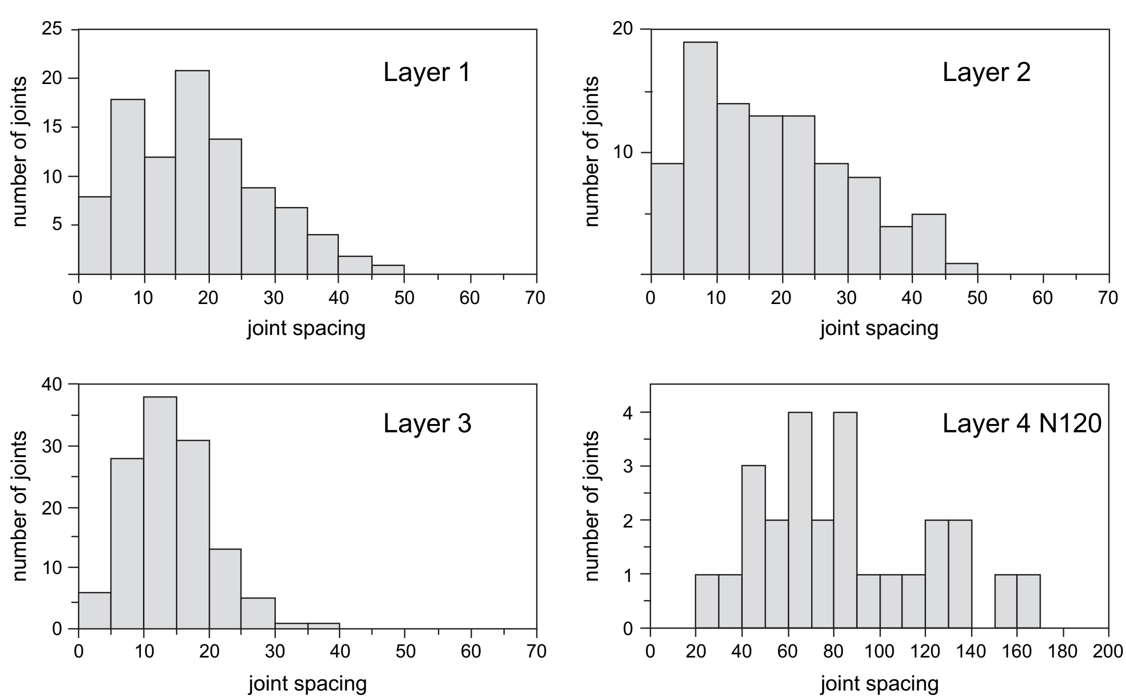

Fig. 4. Spacing distributions of joints in layers 1 to 4 from the Belette outcrop which appears to correspond to log-normal to normal distributions. In layer 3 that is completely isolated in an argillaceous matrix, the histogram is close to that of a normal distribution law.

Table 1
Standard deviation and mean spacing values of joints in layers 1 to 4 from the Belette outcrop

Layer	Mean layer thickness	Mean joint spacing	Spacing standard deviation	FSR	C_v
Belette 1	16.732	18.760	10.35	0.93	0.552
Belette 2	18.042	19.037	11.58	1.00	0.608
Belette 3	16.021	14.528	6.39	1.14	0.44
Belette 4	35.000	86.385	38.11	0.44	0.441

The coefficient of variation, C_v, is the spacing standard deviation to mean spacing ratio. The FSR values that are close to 1.0 show clear fracture spacing and layer thickness relationships in Belette layers 1 to 3. Low values of C_v indicate anti-clustering.

sedimentary beds because they constitute reference units for calculation of joint density.

On top surface of some layers, the abutting relationships can be observed between the joint sets (Fig. 9). At the Pillar outcrop the N10° joint set appears to be the systematic joint set that predates the almost perpendicular N120° joint set. As for the Belette outcrop we have chosen to study the systematic joint set only. In all the layers, joints are well organised around the N10° direction (Fig. 10) with accurate mean value of 14.6° and a standard deviation of 11.9°. On the Pillar outcrop 2332 joints were measured; each one has been characterised by its direction, spacing, aperture and upwards and downwards persistence.

The joint spacing distributions that are reflected by the histograms of Fig. 11 seem to correspond to a log-normal distribution in most of the eight layers. In all the cases presented in Fig. 11, the value of the mode/mean ratio is between 0.23 and 0.7, far from the value of 1 that indicates the normal distribution of the set. The C_v values (Gillespie, 2003) are from 0.72 to 1.25 with a mean value of 0.82 and standard deviation of 0.14. All this suggests the non-saturation of the joint set in all the layers at the Pillar outcrop but a joint spacing that is more clustered at the Pillar outcrop than at the Belette.

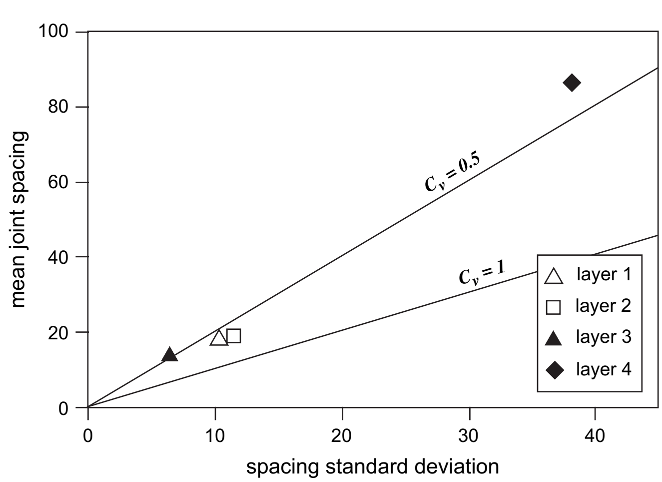

Fig. 5. Mean joint spacing against standard deviation of spacing at Belette outcrop. All the C_v values are below 1.0.

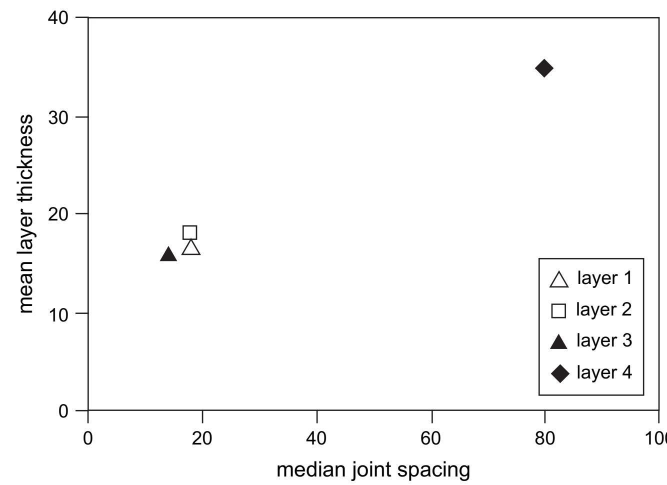

Fig. 6. The median joint spacing against mean layer thickness diagram shows that joint spacing and layer thickness both tend to increase at Belette outcrop.

The bedding normalised fracture density has been estimated using the FSI (Narr, 1991) and the FSR (Gross, 1993). For example, Gross (1993) has measured FSR values that range from 0.61 to 1.38 and Narr (1991) presents FSI values that are close to 1.3. In the Pillar outcrop, the mechanical limits of the layers are not clear and FSR measurements do not correspond exactly to the conditions proposed by Narr (1991). Nevertheless, we have calculated FSR values from the mean thickness of the elementary sedimentary layers. Since the thickness of the sedimentary layers is often less than the complete layer thickness, e.g. layer 7 is composed of sedimentary layers 7a, 7b and 7c, we should have values that are less than that of Narr (1991). In fact, our FSR results range from 0.61 to 3.39 and they indicate a very high level of joint density at Pillar outcrop. In the same way, it is not possible to calculate a FSI value from the mean layer thickness and the median joint spacing data of all layers when they are plotted on the same diagram (Fig. 12). Layers 1, 7 and 8 where the spacing is smaller than the thickness of the layer appear to be densely fractured whereas layer 6 is poorly fractured. The classical relationship between layer thickness and joint spacing (Price, 1966; Engelder et al., 1997) was not observed at the Pillar outcrop, probably because the mechanical layers cannot be clearly identified.

As a first result, the N10° joint set appears to be characterised by both a high level of joint density and a non-saturated spacing distribution shown by the C_v values, which does not fit with the classical idea of the progressive saturation of a joint set with the progressive increasing of joint density. This result has led us to look at the vertical dimension of the joints that compose the joint set. Many joints have a vertical dimension that is larger than the layer thickness and we have looked to see if there is a relationship between the vertical dimension and the saturation of the joint set. In order to focus on the distribution of joints of specific sizes, some joint measurements have been progressively subtracted from the data file. When a joint was subtracted from the file, a correction of the spacing

Fig. 7. Pillar outcrop view at North-West of Pointe-du-Chay. Pictures faces the N10° joint set. Scale is given by the metal scale on the ground (2.7 m). The studied layers (1 to 8) are between the two horizontal white lines.

values was calculated at each time by replacing the two previous spacing values into a single new one.

We present the results of three layers, 1, 4 and 8, as being representative of all the layers in Fig. 13. For each layer, four spacing distributions are shown: (a) the spacing distribution of all the joints of the layer; (b) the distribution of the small joints, the vertical dimension of which is less or equal to the layer thickness; (c) the distribution of large joints that have vertical dimension larger than the layer thickness, that is to say all the joints that propagate outside of a layer; (d) the distribution of very large joints with vertical dimension larger than twice the layer thickness.

In all the layers, the spacing distributions of the small joints, the single bed joints, are close to that of the distribution of all the joints, they seem to show log-normal distributions and all the calculated C_v that range from 0.73 to 0.84 do not indicate the saturation of the joint set. C_v have been calculated for different vertical dimensions but no relationship has been established between the joint spacing and the joint height. The spacing distributions of large joints and very large joints that cross several beds (Fig. 13c,d) do not correspond to clearly identified distribution laws and no organisation can be clearly deduced from data of layers 4a and 8a.

The spacing standard deviation and the mean spacing values of the different fracture sizes in layers 1, 4a, 5a and 8 (Fig. 14) both progressively increase together. Such distributions, in which the arithmetic mean and the standard deviation have equal values, correspond to exponential distributions (Baecher, 1983). Most of the C_v results that range from 0.5 to 1.0 indicate low clustering and are consistent with a random distribution. This result can be illustrated by the line drawing of the joints that cut layer 4 (Fig. 15); it is difficult to show a regular joint spacing from Fig. 15, either for small joints or large joints. This is probably because a dominant joint size cannot develop in such layers where sedimentary interbeds do not act like discontinuities stopping the vertical propagation of the non-stratabound joints.

5. Joint aperture in Pointe-du-Chay limestones

Joint aperture has been measured on layers 6, 7a, 7b and 7c of the Pillar outcrop and layer 3 of the Belette outcrop. Each measurement corresponds to the maximum aperture that can be observed in the middle of the joint. In order to avoid rounding effects along the eroded joint edges on outcrop surfaces, a thickness gauge composed of 20 different iron strips with perfectly calibrated thicknesses from 0.02 to 2 mm has been used to make measurements at depth, inside the joint plane. Closed joints, in which it has not been possible to introduce the smaller strip of the gauge, are assigned an aperture of zero.

On the joint aperture to minimum joint spacing diagrams (Fig. 16), the joint aperture has been plotted against the smaller of the two spaces either side of the joint. Scattering of data is more important in layer 7 of Pillar outcrop than in layer 3 of Belette outcrop but there is no clear relationship between joint spacing and joint aperture. Nevertheless it can be noticed that almost all the joints of layer 3 at the Belette outcrop are open when a large part of the joints of layer 7 at the Pillar outcrop are nearly closed.

The joint aperture has been plotted against the vertical dimension of joints of layers 6 and 7 of the Pillar outcrop (Fig. 17). It appears that higher aperture values are observed in joints with higher vertical dimensions; the linear correlation coefficients are 0.65 and 0.5 for layers 6 and 7, respectively. This is not a good linear correlation but it is an indication that joint aperture generally tends to increase with the vertical dimension of joints. In layer 3 of the Belette outcrop, all the joints are strictly confined to the competent carbonate layers,

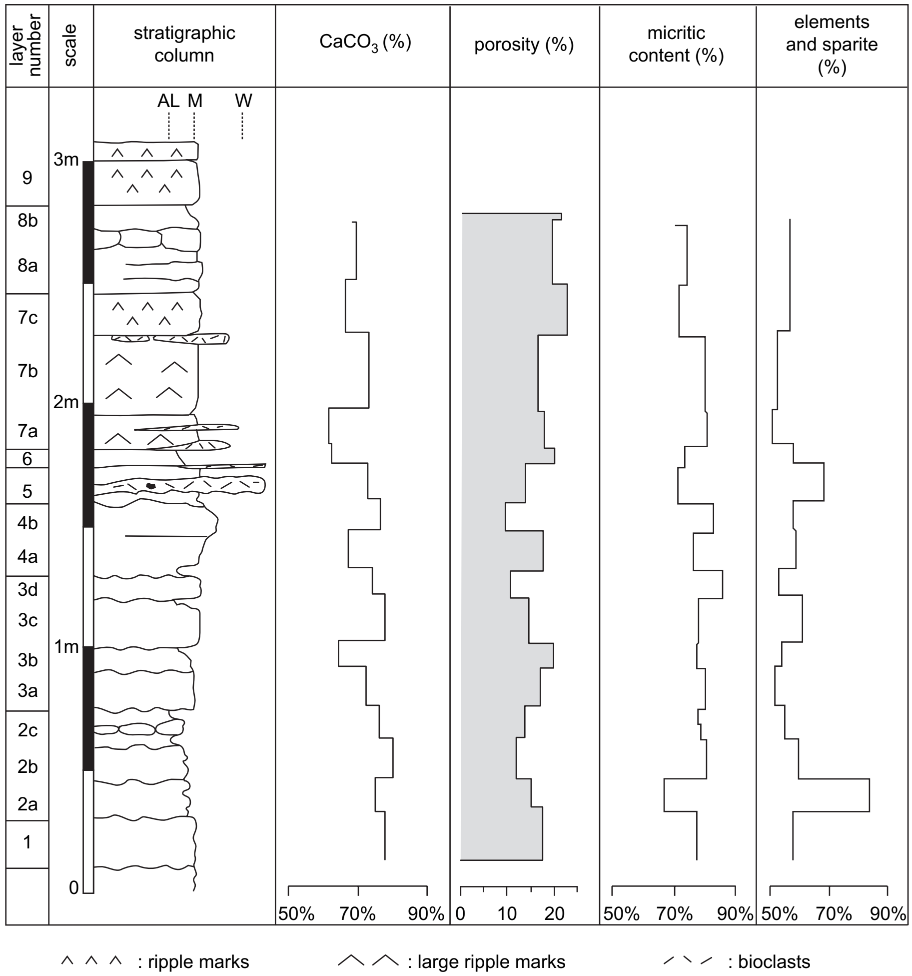

Fig. 8. Stratigraphic column of the base of the Pillar outcrop. The beds are divided in small sedimentary layers. They are distinguished by different carbonate content, porosity or micritic to sparitic ratios.

all having the same vertical dimension, and it would not make any sense to plot these values.

To investigate more accurately the relationship between vertical dimension and joint aperture, the aperture of the joints has been plotted against their position along the layer, the distance (Fig. 18). For layers 6 and 7 of the Pillar outcrop the diagrams can be subdivided in two parts, the left part with some joints of high aperture and the right part without. In layer 6, it can be seen that the joints with high vertical dimension have also large aperture values, up to 10 mm, while the small joints between these large joints have very small aperture values or are completely closed (Fig. 18a,b,d). On the right side, without large joints, some moderate aperture values can be observed but it is difficult to find any organisation. Cumulative aperture diagrams (Fig. 18c,e) show that high aperture values are limited to the left part of the Pillar outcrop.

In layer 3 of the Belette outcrop there are no large joints (Fig. 18f) and the joint aperture is more homogeneously distributed along the layer as shown by the cumulative aperture diagram (Fig. 18g). On layer 3 of the Belette outcrop the arithmetic mean of the joint aperture values is 0.49 mm, and it is respectively from 0.61 mm to 0.93 mm for layers 6 and 7 of the Pillar outcrop (Table 2). The median values of this aperture are more variable: they are 0.45 mm in Belette layer 3 when they are from 0.05 to 0.2 mm in layers 6 and 7 at Pillar outcrop (Table 2). The mean aperture is not large in Belette layer 3 but a greater number of joints is opened with moderate aperture values.

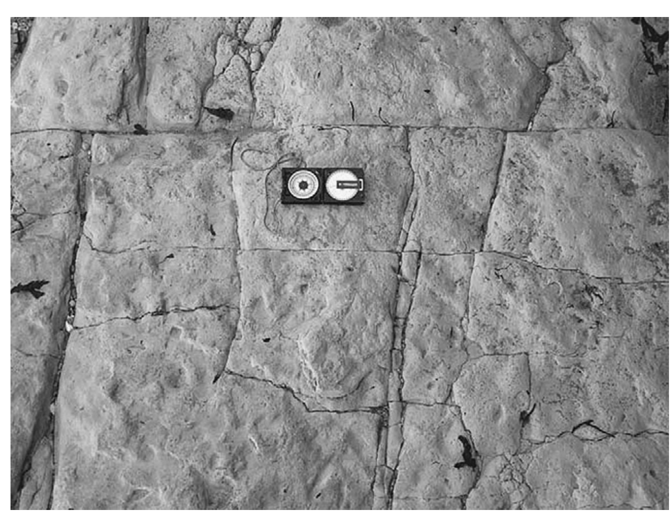

Fig. 9. Top view of a layer at the Pillar outcrop, the systematic joint set is the N10° joint set, parallel to the long side of the compass. Most, but not all, of the N120° joints abut on the first joint set.

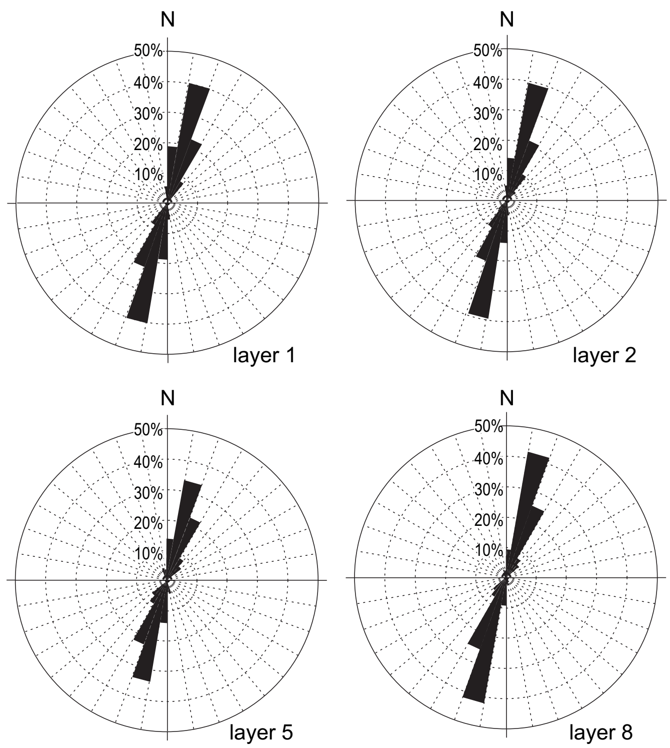

Fig. 10. Orientations of N10° joints in four layers of Pillar outcrop. Joints appear to be well organised along this direction.

6. Discussion

Based on their abutting relationships, the N10° and the N120° joint sets represent in turn the systematic joint set, N10° at the Pillar outcrop and N120° at the Belette outcrop. Both affect the Kimmeridgian limestones of the Pointe-du-Chay and they are considered to have formed before the Upper Cretaceous from the reactivation of hercynian structural directions (Arthaud and Choukroune, 1972).

The large joint density of the Pillar outcrop could be related to a specific behaviour of the layers rather than to a high level of deformation. This hypothesis is strengthened by the examination of the cumulative joint aperture per metre along the layer (Table 2). The difference is higher between the data of the layer 6 and 7 of the Pillar outcrop than between layer 6 of the Pillar and layer 3 of the Belette outcrop.

A high level of joint density has been observed at Pillar outcrop where sedimentary layers are not separated by any interbed. Conversely, at the Belette outcrop where layers are included in a thick (>5 cm) argillaceous matrix, the layers show lower joint density and more regular joint spacing.

Ladeira and Price (1981), Huang and Angelier (1989) and Ji and Saruwatari (1998) have shown that joint density in a competent layer decreases when the thickness of the incompetent layer increases. Huang and Angelier (1989) have described joints in limestone beds of the French Alps interbedded with thick shales, they have shown that this situation facilitates a regular joint spacing. Gillespie et al. (1999) have described such a regular spacing of stratabound veins, the width of the stress shadow is often proportional to the mechanical layer thickness (Hobbs, 1967; Gross et al., 1995) and when the veins have reached a regular spacing the layer is said to be saturated (Rives et al., 1992). This is what is observed at the Belette outcrop with joints.

The situation is different at the Pillar outcrop where joint density is higher. Pascal et al. (1997) have shown a log-normal law of spacing distribution in a well stratified outcrop of Wales with micritic limestones and some mudstone interbeds. This also corresponds to what is generally observed in unbedded rocks (Ruf et al., 1998). Nevertheless, the log-normal spacing distribution that is observed at the Pillar outcrop cannot be compared exactly to isotropic rocks where joint orientations are widely scattered. Most of the joints that are observed at Pillar outcrop are almost vertical and orientated N10° for the systematic joint set or N120° for the cross-joint set. The state of stress controls joint orientation, in flat-lying rocks joints are normal to bedding because the principal stresses are orthogonal to bedding (Strömgard, 1973; Treagus, 1981, 1988; Watkinson and Cobbold, 1981). This is why joint direction can be related to sediment anisotropy (Winsor, 1979). At Pillar outcrop the sedimentary anisotropy imposes principal stresses to be parallel and perpendicular to bedding where they form vertical joints, but the carbonate interbeds are unable to stop the vertical propagation of joints. This is probably

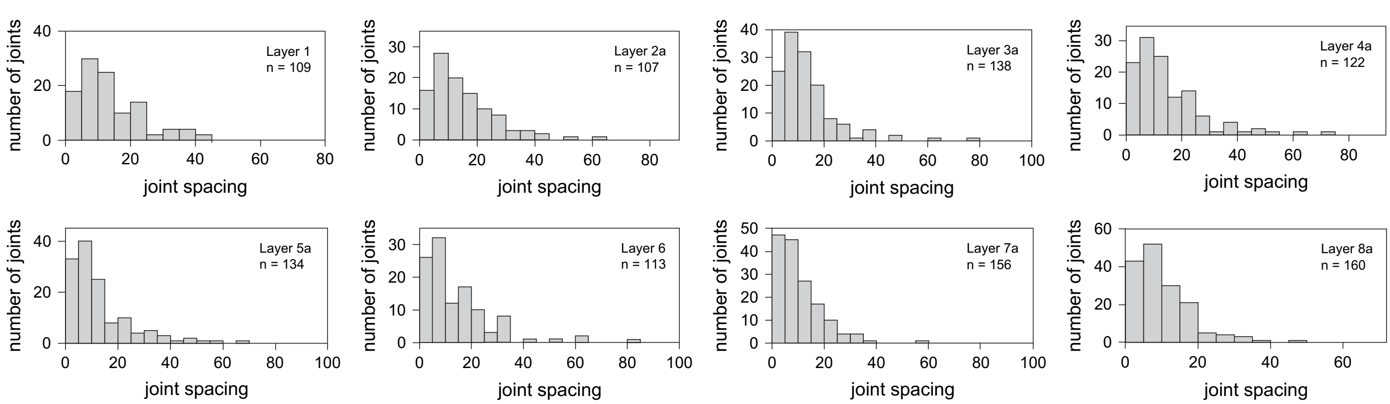

Fig. 11. Spacing distributions of joints in eight layers of the Pillar outcrop. Most of the histograms appear to correspond to a log-normal distribution.

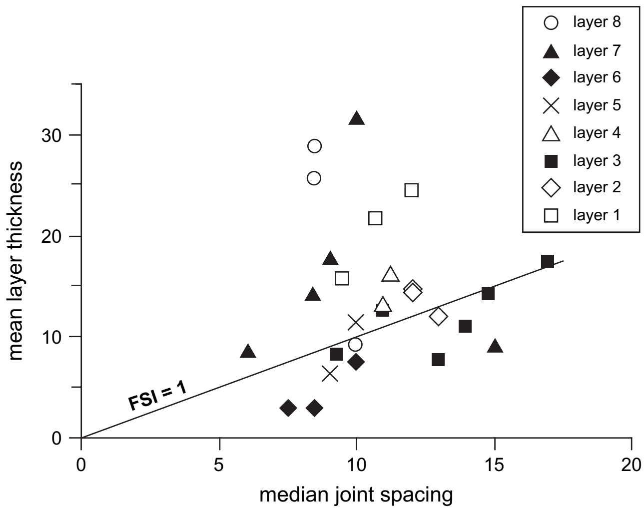

Fig. 12. Mean layer thickness against median joint spacing diagram of Pillar outcrop layers. Layers 1, 7 and 8 where spacing is smaller than the thickness of the layer appear to be densely fractured when layer 6 is poorly fractured. The scattering of the data does not permit the calculation of a significant FSI, the FSI = 1 line has been drawn as a reference mark. The classical relationship between layer thickness and joint spacing is not observed at Pillar outcrop.

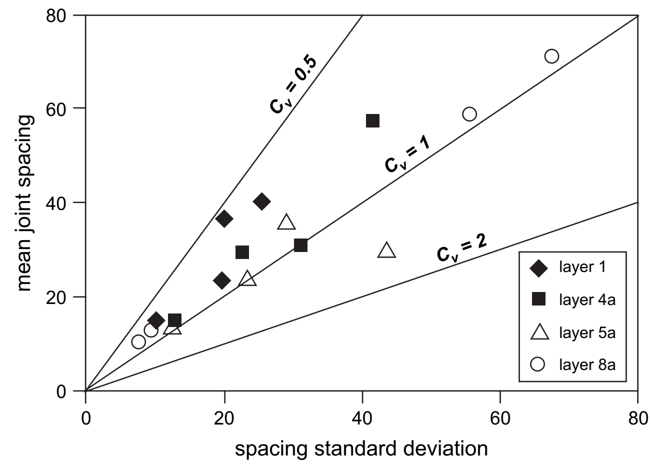

Fig. 14. Standard deviation vs. mean joint spacing values of layers 1, 4a, 5a and 8a from the Pillar outcrop. Most of the C_v values range from 0.5 to 1.0. In most layers, the arithmetic mean and the standard deviation have equal values. Such distributions have been recognised as exponential distributions.

why log-normal distributions of the set and moderate C_v values (0.8) are observed. Non-stratabound fractures (Odling et al., 1999) have no regular spacing. Large fractures are supposed to develop large stress shadows, as they propagate they put more and more of the smaller fractures into their stress shadows and these smaller fractures stop to develop (Gillespie et al., 1999). The high joint density of the Pillar outcrop with an irregular spacing appears to be due to the lack of incompetent layer between the carbonate layers and the development of non-stratabound joints.

Thick marl layers appear to entirely inhibit the vertical propagation at Belette outcrop whereas the lack of interbeds permit such a propagation at Pillar outcrop. As has been proposed by Helgeson and Aydin (1991), the vertical propagation of joints, out of the stiff layers, is controlled by interbeds. Hoffmann et al. (2004) confirm this result with a probabilistic-mechanistic simulation.

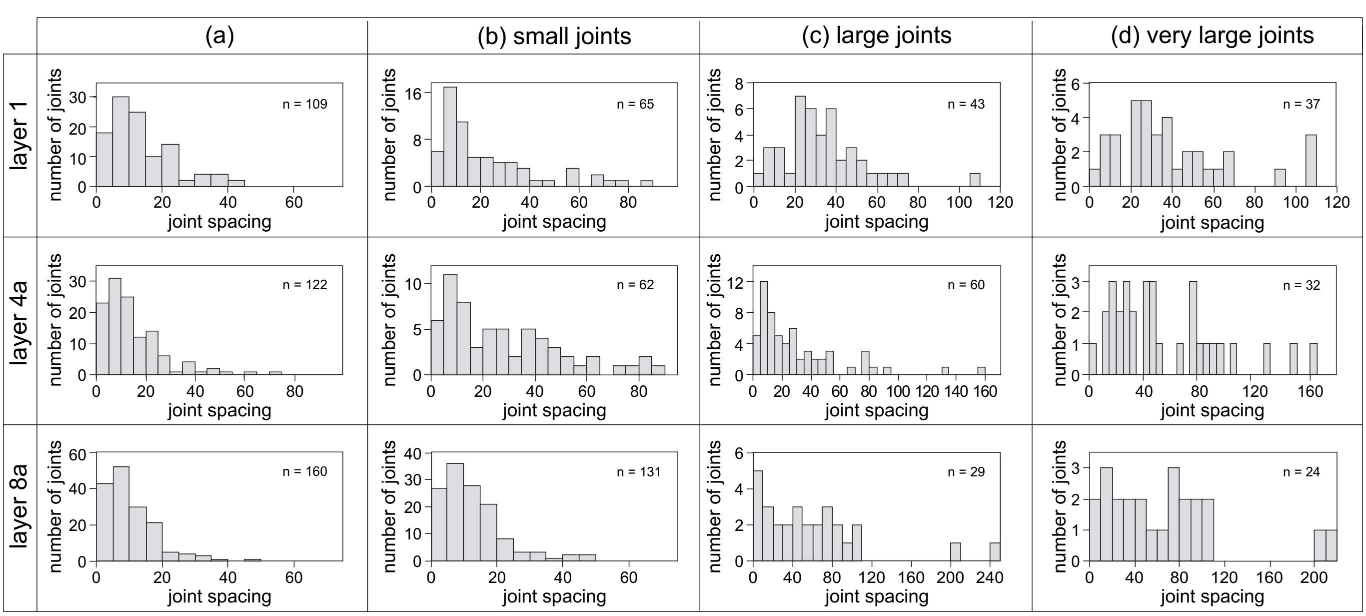

Fig. 13. From layers 1, 4a and 8a of the Pillar outcrop, four joint spacing distributions have been calculated: (a) the spacing distribution of all the joints of the layer; (b) the distribution of the small joints the vertical dimension of which being less or equal to the layer thickness; (c) the distribution of large joints that have vertical dimension larger than the layer thickness; (d) the distribution of very large joints with vertical dimension larger than twice the layer thickness. In the three layers, both the spacing distribution of the small joints and that of all the joints appear as log-normal distributions. The spacing distributions of the largest joints do not correspond to clearly identified distribution laws and no organisation can be clearly deduced, especially from the data of layers 4a and 8a.

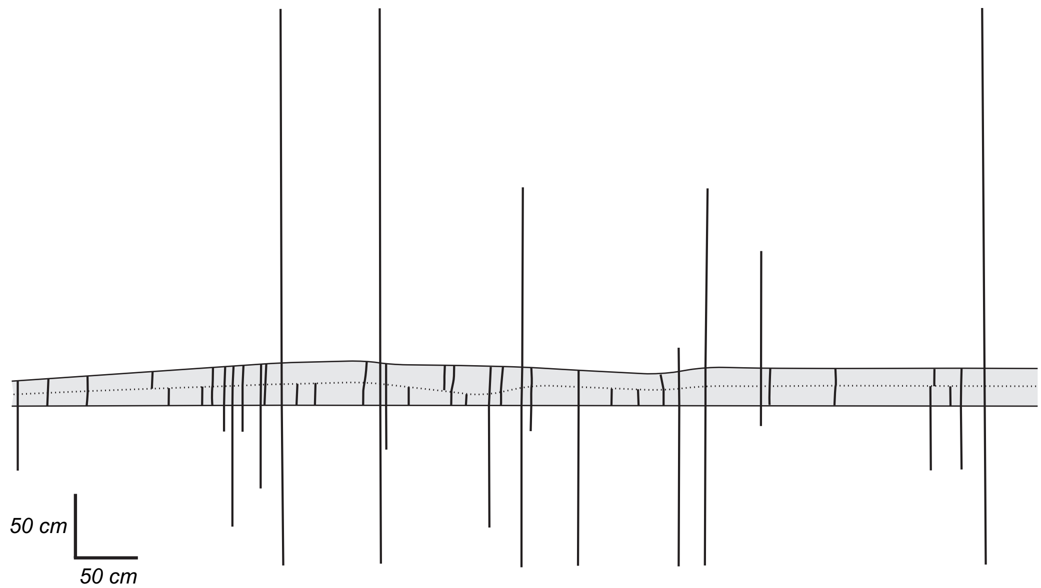

Fig. 15. Line drawing of the joints of layer 4, no regular joint spacing can be observed either for small joints or for large joints.

The joint aperture is regular in Belette outcrop where all the joints cross completely the layer but do not propagate through the incompetent marl layers. At Pillar outcrop joint aperture is larger but it does not appear to be correlated to the density or to the saturation of the joint set distribution in a layer. It is more clearly related to the vertical dimension of the joint. This corresponds to what Bai et al. (2000) describe as non-confined fractures, they show that in such a situation the fracture aperture is larger in fractures with large vertical dimension and in layers with high fracture density. Layer 7b

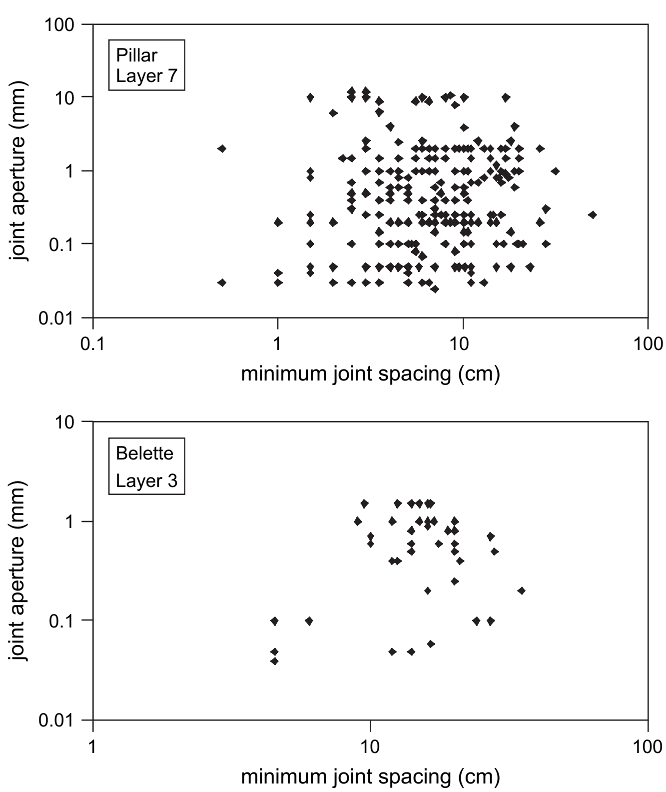

Fig. 16. Joint aperture vs. minimum joint spacing diagrams of layer 7 at the Pillar outcrop and of layer 3 at the Belette outcrop. The minimum joint spacing is the smaller of the two spaces either side of the joint. The highest aperture values are reached in layer 7 of Pillar outcrop but a great number of these joints are completely closed. Almost all of the joints of layer 3 from Belette outcrop are opened with moderate apertures.

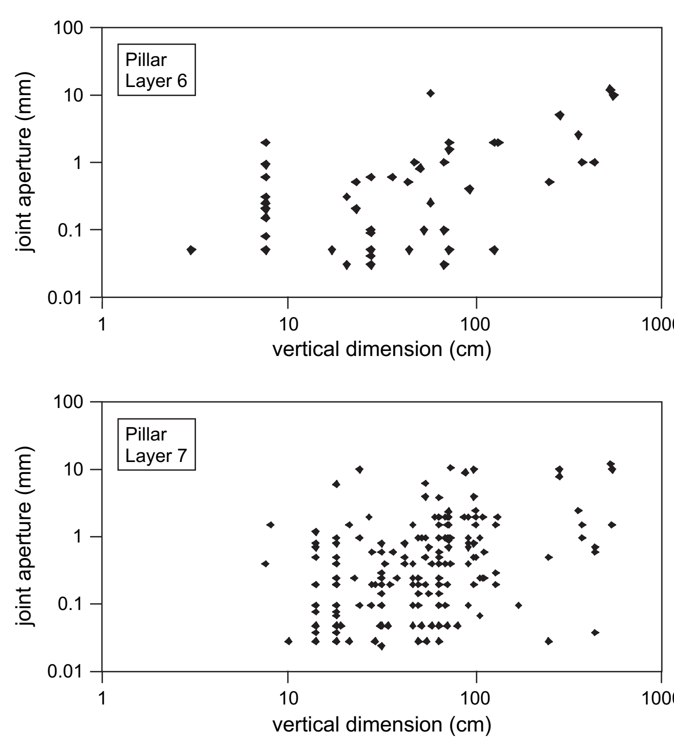

Fig. 17. Joint aperture and vertical dimension of fractures of layers 6 and 7 of the Pillar outcrop. The joint aperture weakly tend to increase with the vertical dimension, the linear correlation coefficients are 0.65 and 0.5 for layers 6 and 7, respectively.

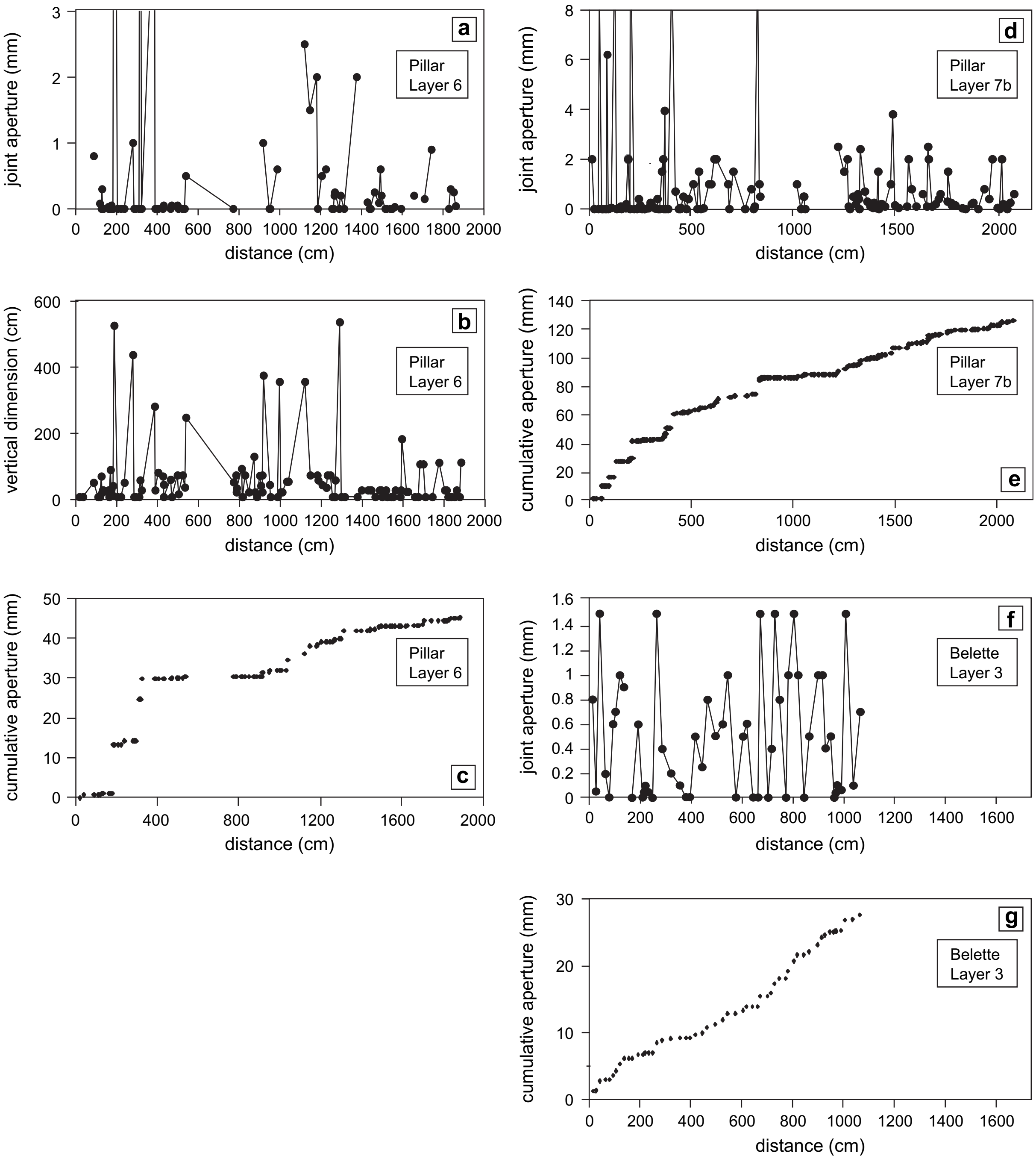

Fig. 18. (a–c) In layers 6 of Pillar outcrop, joint aperture, vertical dimension and cumulative aperture of joints as function of their position along the layer, the distance. (d, e) In layers 7b of Pillar outcrop, joint aperture and cumulative aperture of joints against the distance. (f, g) In layer 3 of the Belette outcrop, joint aperture and cumulative aperture of joints against the distance. At Pillar outcrop, in the left part of the diagrams only the joints with large vertical dimensions can show large aperture values. At Belette outcrop, fracture apertures are more regularly organised, the mean aperture is low but almost all the fractures are opened with moderate aperture values, whatever their position along the layer may be.

(located in the middle part of layer 7) is the layer in which cumulative joint aperture reaches the highest values (Table 2), probably because a great number of joints completely cross layer 7 and because the mid part of a joint is generally more opened than the joint tips. Such a relationship between length and aperture has already been described with joints in chalk (Goodwin, 1995) or for vein aperture (Vermilye and Scholz, 1995) even if the conditions of vein formation may be somewhat different from those of joints (Gillespie et al., 2001; Cosgrove, 1995).

We can suppose a simple sequence of events for the joints formation in the Belette outcrop: the joints appear, their number increases to reach the saturation of the joint set, after that they only open to accommodate the progressing deformation. At the Pillar outcrop a different sequence must be proposed: the joint number progressively increases, the progressive

Table 2
Mean and median apertures of joints in layers 6 and 7 of the Pillar outcrop and layer 3 of the Belette outcrop

Layer	Mean aperture (mm)	Median aperture (mm)	Aperture/ metre (mm)	Orientation
Pillar 6	0.61	0.05	3.8	N10°
Pillar 7a	0.75	0.05	5.77	N10°
Pillar 7b	0.93	0.2	7.2	N10°
Pillar 7c	0.80	0.2	5.85	N10°
Belette 3	0.49	0.45	2.59	N120°

Aperture of fractures per metre is the cumulative aperture of all fractures in the layer divided by the length of the layer. The difference is higher between the data of the layers 6 and 7 of the Pillar outcrop than between layer 6 of the Pillar and layer 3 of the Belette outcrop.

deformation creates new joints that gradually infill between old joints. Some joints propagate vertically in the surrounding layers; with a higher vertical dimension they develop larger stress shadows and stop the development of smaller fractures around them. The joints with a higher vertical dimension open more than the small ones and the cumulative aperture increases with the joint density. At the Pillar outcrop the system has not reached any saturation: joints have increased in number, size and aperture.

7. Conclusion

Joint development and joint aperture have been studied in the Kimmeridgian limestones of the Pointe-du-Chay. At the Pillar outcrop the N10° joint set appears to be the systematic joint set while the N120° joint set is that of the Belette outcrop.

At the Belette outcrop, a relationship can be observed between the median joint spacing and the layer thickness. The FSR values that are about 1 show that joint spacing is close to mean layer thickness for layers 1 to 3 and low values of $C_v < 1.0$ characterise saturated joint spacing distributions. The spacing to thickness relationship appears to be valid in the carbonate layers of the Belette outcrop that are composed of typical stratabound competent layers included in a more argillaceous matrix.

At the Pillar outcrop, the joint set is characterised by a high level of joint density and a non-saturated spacing distribution. The C_v values are about 1.0, suggesting the non-saturation of the joint set in all the layers at the Pillar outcrop but a joint spacing that is more clustered at the Pillar outcrop than at the Belette. FSR values ranging from 0.61 to 3.39 indicate a very high level of joint density in most of the layers. At the same time the values of the mode/mean ratio are between 0.23 and 0.7, that is to say far from the value of 1 that indicates the saturation of the set. The log-normal law of the spacing distribution and the value of the mode/mean ratio both indicate the non-saturation of the joint set in all the layers at the Pillar outcrop. The classical relationship between layer thickness and bed thickness has not been observed at the Pillar outcrop.

When looking at particular joint sizes, the spacing distributions show log-normal distributions or negative exponential distributions and indicate the non-saturation of the joint sets. At the Pillar outcrop, the joint spacing distributions appear to be undersaturated in all layers and for large and small joints.

Joint aperture is larger at the Pillar outcrop than at the Belette outcrop but it is more homogeneously distributed in the latter. There, the mean aperture is not large but a great number of joints are opened with moderate aperture values, which correspond to the aperture associated with a saturated distribution of the joint set. Conversely, the joint aperture is concentrated in some joints at the Pillar outcrop. Joints with large vertical dimension are more opened than small joints. A relationship can be established between these two parameters, even if it is not a perfect linear correlation, but no relationship appears between joint spacing and joint aperture in a layer. It can be deduced that joint aperture is better controlled by the size of the joints than by the joint spacing. Nevertheless it has been observed around large and well-opened joints that there is no other opened joint. The opening of a joint seems to prevent its neighbour from opening.

The presence of an argillaceous layer around a competent carbonate layer is clearly one of the most important parameters in controlling the distribution and aperture of joints. When the competent layer is included in a matrix the joint spacing and joint aperture are homogeneously distributed, as is the case of a stratabound joint set. In the case of a succession of layers without argillaceous layers, the non-stratabound joints are not confined to one layer, their distribution is less regular and the aperture seems to be controlled by the vertical dimension and position of the joint relative to the larger joints.

Acknowledgements

This research was funded by TOTAL, which is also thanked for permission to publish this work. Comments and suggestions made by Mark Jessell led to significant improvements in the paper. We thank Christiane Cavaré-Hester for her assistance in the line drawing of figures. Careful and constructive reviews of Terry Engelder and Paul Gillespie have significantly improved the manuscript.

References

Arthaud, F., Choukroune, P., 1972. Méthode d'analyse de la tectonique cassante à l'aide des microstructures dans les zones peu déformées: exemple de la plate-forme nord-Aquitaine. Revue de l'IFP 27, 715–732.

Baecher, G.B., 1983. Statistical analysis of rock mass fracturing. Mathematical Geology 15, 329–348.

Bai, T., Pollard, D.D., 2000a. Fracture spacing in layered rocks: a new explanation based on the stress transition. J. Struct. Geol. 22, 43–57.

Bai, T., Pollard, D.D., 2000b. Closely spaced fractures in layered rocks: initiation mechanism and propagation kinematics. J. Struct. Geol. 22, 1409–1425.

Bai, T., Pollard, D.D., Gross, M.R., 2000. Mechanical prediction of fracture aperture in layered rocks. J. Geophys. Res. 105, 707–721.

Cosgrove, J.W., 1995. The expression of hydraulic fracturing in rocks and sediments. In: Ameen, M.S. (Ed.), Fractography: Fracture Topography as a Tool in Fracture Mechanics and Stress Analysis. Geological Society, London, Special Publications, vol. 92, pp. 187–196.

Cox, D.R., Lewis, P.A.W., 1966. The Statistical Analysis of Series of Events. Chapman and Hall, London.

Dunham, R.J., 1962. Classification of carbonate rocks according to depositional texture. In: Hamm, W.E. (Ed.), Classification of Carbonate Rocks, 1. Mem. Am. Ass. Petrol. Geol., Tulsa, pp. 108–121.

Dunne, W.M., Hancock, P.L., 1994. Palaeostress analysis of small-scale brittle structures. In: Hancock, P.L. (Ed.), Continental Deformation. Pergamon Press, pp. 101–120.

Engelder, T., Gross, M.R., Pinkerton, P., 1997. An analysis of joint development in thick sandstone beds of the Elk basin anticline, Montana-Wyoming. In: Fractured Reservoirs: Characterization and Modelling Guidebook. Rocky Mountain Association of Geologists, pp. 1–18.

Gillespie, P.A., Johnston, J.D., Loriga, M.A., McCaffrey, K.J.W., Walsh, J.J., Watterson, J., 1999. Influence of layering on vein systematics in line samples. In: McCaffrey, K.J.W., Lonergan, L., Wilkinson, J.J. (Eds.), Fractures, Fluid Flow and Mineralization. Geological Society, London, Special Publications, vol. 155, pp. 35–56.

Gillespie, P.A., 2003. Comment on "The geometric and statistical evolution of normal fault systems: an experimental study of the effects of mechanical layer thickness on scaling laws" by R.V. Ackermann, R.W. Schlische and M.O. Withjack. J. Struct. Geol. 25, 819–822.

Gillespie, P.A., Walsh, J.J., Watterson, J., Bonson, C.G., Manzochi, T., 2001. Scaling relationships of joint and vein arrays from The Burren, Co. Clare, Ireland. J. Struct. Geol. 23, 183–201.

Goodwin, A.M., 1995. Spatial change in joint geometry in the Chalk of eastern England. In: Ameen, M.S. (Ed.), Fractography: Fracture Topography as a Tool in Fracture Mechanics and Stress Analysis. Geological Society, London, Special Publications, vol. 92, pp. 197–213.

Gross, M.R., 1993. The origin and spacing of cross joints: examples from the Monterey formation, Santa Barbara coastline, California. J. Struct. Geol. 15, 737–751.

Gross, M.R., Fischer, M.P., Engelder, T., Greenfield, R.J., 1995. Factors controlling joint spacing in interbedded sedimentary rocks: integrating numerical models with field observations from the Monterey formation, USA. In: Ameen, M.S. (Ed.), Fractography: Fracture Topography as a Tool in Fracture Mechanics and Stress Analysis. Geological Society, London, Special Publications, vol. 92, pp. 215–233.

Hancock, P.L., 1985. Brittle microtectonics: principle and practice. J. Struct. Geol. 7, 437–457.

Hantzpergue, P., 1985. L'héritage hercynien dans la paléógéographie récifale du Jurassique supérieur nord-aquitain (France). C.R. Acad. Sci. Paris II 301 (15), 1147–1150.

Helgeson, D.E., Aydin, A., 1991. Characteristics of joint propagation across layer interfaces in sedimentary rocks. J. Struct. Geol. 13, 897–911.

Hobbs, D.W., 1967. The formation of tension joints in sedimentary rocks: an explanation. Geol. Mag. 104, 550–556.

Hodgson, R.A., 1961. Classification of structures on joint surfaces. Am. J. Sci. 259, 493–502.

Hoffmann, W., Dunne, W.M., Mauldon, M., 2004. Probabilistic-mechanistic simulation of bed-normal joint patterns. In: Cosgrove, J.W., Engelder, T. (Eds.), The Initiation, Propagation, and Arrest of Joints and Other Fractures. Geological Society, London, Special Publications, vol. 231, pp. 269–284.

Huang, Q., Angelier, J., 1989. Fracture spacing and its relation to bed thickness. Geol. Mag. 126, 335–362.

Ji, S., Zhu, Z., Wang, Z., 1998. Relationship between joint spacing and bed thickness in sedimentary rocks: effects of interbed slip. Geol. Mag. 135, 637–655.

Ji, S., Saruwatari, K., 1998. A revised model for the relationship between joint spacing and layer thickness. J. Struct. Geol. 20, 1495–1508.

Ladeira, F.L., Price, N.J., 1981. Relationship between fracture spacing and bed thickness. J. Struct. Geol. 3, 179–183.

Narr, W., 1991. Fracture density in the deep subsurface: techniques with application to Point Arguello Oil Field. Am. Assoc. Petrol. Geol. Bull. 75, 1300–1323.

Narr, W., Suppe, J., 1991. Joint spacing in sedimentary rocks. J. Struct. Geol. 13, 1037–1048.

Odling, N.E., Gillespie, P., Bourgine, B., Castaing, C., Chilès, J.-P., Christensen, N.P., Fillion, E., Genter, A., Olsen, C., Thrane, L., Trice, R., Aarseth, E., Walsh, J.J., Watterson, J., 1999. Variations in fracture system geometry and their implications for fluid flow in fractured hydrocarbons reservoirs. Petrol. Geosci. 5, 373–384.

Olivier, N., Hantzpergue, P., Gaillard, C., Pittet, B., Leinfelder, R.R., Schmid, D.U., Werner, W., 2003. Microbialite morphology, structure and growth: a model of the Upper Jurassic reefs of the Chay Peninsula (Western France). Palaeogeogr. Palaeoclimatol. Palaeoecol. 193, 383–404.

Pascal, C., Angelier, J., Cacas, M.C., Hancock, P.L., 1997. Distribution of joints: probabilistic modelling and case study near Cardiff (Wales, U.K.). J. Struct. Geol. 19, 1273–1284.

Pollard, D.D., Aydin, A., 1988. Progress in understanding jointing over the past century. Geol. Soc. Am. Bull. 100, 1181–1204.

Price, N.J., 1966. Fault and Joint Development in Brittle and Semi-Brittle Rock. Pergamon Press, New York, 568 pp.

Price, N.J., Cosgrove, J.W., 1990. Analysis of Geological Structures. Cambridge University Press, 502 pp.

Rives, T., Razack, M., Petit, J.P., Rawnsley, K.D., 1992. Joint spacing: analogue and numerical simulations. J. Struct. Geol. 14, 925–937.

Ruf, J.C., Rust, K.A., Engelder, T., 1998. Investigating the effect of mechanical discontinuities on joint spacing. Tectonophysics 295, 245–257.

Sagy, A., Reches, Z., Roman, I., 2001. Dynamic fracturing: field and experimental observations. J. Struct. Geol. 23, 1223–1239.

Strömgard, K.E., 1973. Stress distribution during formation of boudinage and pressure shadows. Tectonophysics 16, 215–248.

Treagus, S.H., 1981. A theory of stress and strain variations in viscous layers, and its geological implications. Tectonophysics 72, 75–103.

Treagus, S.H., 1988. Strain refraction in layered systems. J. Struct. Geol. 10, 517–527.

Vermilye, J.M., Scholz, C.H., 1995. Relation between vein length and aperture. J. Struct. Geol. 17, 423–434.

Watkinson, A.J., Cobbold, P.R., 1981. Axial directions of folds in rock with linear/planar fabrics. J. Struct. Geol. 3, 211–217.

Winsor, C.N., 1979. The correlation of fracture directions with sediment anisotropy in folded rocks of the Delamerian fold belt at Port Germein gorge, South Australia. J. Struct. Geol. 1, 245–254.

Wu, H., Pollard, D.D., 1995. An experimental study of the relationship between joint spacing and layer thickness. J. Struct. Geol. 17, 887–905.