3. LITERATURE REVIEW

3.1 Introduction

A fundamental question in structural geology is what controls the geometric characteristics of joint patterns in rocks. Fracture sets and their development are an important factor for engineering and petroleum geologists. The resulting structure is a function of the mutual orientation of intersecting sets of discontinuities (including fractures, joints, faults, bedding planes, foliation,…).

There exists a wealth of published studies on this topic. First of all, the work of Cox (1952) and D. W. Hobbs (1967) has to be mentioned, because they are the first major studies in this field. The Model of Hobbs, based on a simple theoretical explanation, has subsequently been used by a large number of authors. He provided a first explanation for the formation of tension joints in sedimentary rocks.

3.2 Summary

3.2.1 Empirical data

Concerning the data used by the different analyses done, it has been found two different ways in the line of work. There are several articles that use data from field studies (e.g. Gross et al., 1995; Bai and Pollard, 1999, 2000) whereas some other authors use experimental data (from the laboratory) in order to apply the different methods (e.g. Ladeira et al., 1981; Huang et al., 1989; Narr et al., 1991; Gross, 1993; Mandal et al., 1994; Wu et al., 1995; Gross, 1995; Becker et al., 1996; Gross et al., 1997; Odling, 1997; Gross et al., 1997; Ruf et al., 1998).

3.2.2 Methods

Empirical methods. Some authors use statistical methods to analyze the joint data (Huang et al., 1989; Gillespie et al., 1993; Becker et al., 1996; Renshaw, 1997; Odling, 1997; Ji et al., 1998; Ruf et al., 1998). There are some comments to do in this part, inasmuch as a lot of different variations are used. For example, Huang et al. (1989) use a Gamma distribution instead of the normal and log-normal distributions used by many other authors.

Experiments. A large number of authors worked with a three-layer model (e.g. Gross et al., 1995; Bai et al., 1999), in which they only can study the behaviour of the fractured layer (the middle layer, normally), and in this way they can not observe the behaviour of the neighbouring layers.

Simulations. Some different authors have opted to apply numerical modelling based on finite element methods. One of the most used ones is FRANC (FRacture ANalysis Code), which has served to a lot of authors in order to carry out their studies and applications (Gross et al., 1995; Bai et al., 1999; Bai et al., 2000; Bai et al., 2000; Bai et al., 2000).

3.2.3 Interpretation

Concerning the results obtained, generally the interpretation of them is done by plots, profiles or something similar, but H. Wu and D. D. Pollard (1995) consider two different methods to analyze joint sets depending on their development. Thus, the Line Method (for well–developed joint sets) and the Area Method (for both poorly- and well–developed joint sets) are presented in their papers.

Gross (1995) applies the Mohr-Coulomb failure criterion to analyze the fracture data and compares the fracture characteristics with lithologic parameters. He is of the opinion that compositional purity or, conversely, the amount of impurities in a rock unit is a potential factor controlling failure mode.

There is a big number of authors who carry out the application of their data, or the interpretation of their results by means of empirical relationships, it means plotting the results by means of plots or rose diagrams (e.g. Ladeira et al., 1981; Gillespie et al., 1993; Becker et al., 1996; Gross et al., 1997; Renshaw, 1997; Gross et al., 1997; Ruf et al., 1998). Some other ones work with the FSI (Fracture Spacing Index), the FSR (Fracture Spacing Ratio) and the concept of Fracture Saturation to deal about or to arrive at their conclusions (e.g. Gross, 1993; Wu et al., 1995; Becker et al., 1996; Gross et al., 1997; Ruf et al., 1998; Bai et al., 1999). In contrast, Odling (1997) interprets fracture distribution in terms of scale laws.

Several authors (e.g. Wu et al., 1995; Bai et al., 2000) use the spacing to layer thickness ratio, which is the result of dividing the average fracture spacing in the layer by the thickness of that layer. The ratio can vary in values between 0.8 and 1.2. Also the concept of critical spacing to layer thickness ratio, which defines a lower limit for fractures driven by extension in a material without significant flaws, is used by these authors and some other ones.

3.2.4 Discussion

Concerning to the results obtained with the different applications and methods used in the different papers, different points of view are found. A large number of authors arrive to the conclusion that a linear relationship between joint spacing and layer thickness exists, and can be assumed like that. This is the most common thought by the authors. Nonetheless, some authors think that a non-linear relationship between joint spacing and layer thickness exists or, that at least, the linear relationship does not exist totally in all the behaviours depending on the different rock types (Mandal et al., 1994). Some others (i.e., Odling, 1997) observe a power law governing the behaviour in these different studied relationships.

The concept of fracture saturation (or joint saturation, or saturation density…) has been used by several authors to explain joint and fracture development and growth (Becker et al., 1996; Bai et al., 1999; Bai et al., 2000; Bai et al., 2000). Experimental studies of this phenomenon show that the spacing initially decreases as extensional strain perpendicular to the fractures increases. At a certain ratio of spacing to layer thickness, no new fractures form and the additional strain is accommodated by further opening of existing fractures: the spacing then simply scales with layer thickness, which is called fracture saturation. The concept of fracture saturation is a condition for the observation of any systematic relationship between joint spacing and layer thickness. **Figure 2** is a schematic figure showing the comparison of the different behaviour of a thinner and a thicker bed.

The fracture saturation concept is in marked contrast to some theories of fracture, such as the stress-transfer theory (Cox, 1952), which predict that spacing should decrease with increasing strain *ad infinitum*.

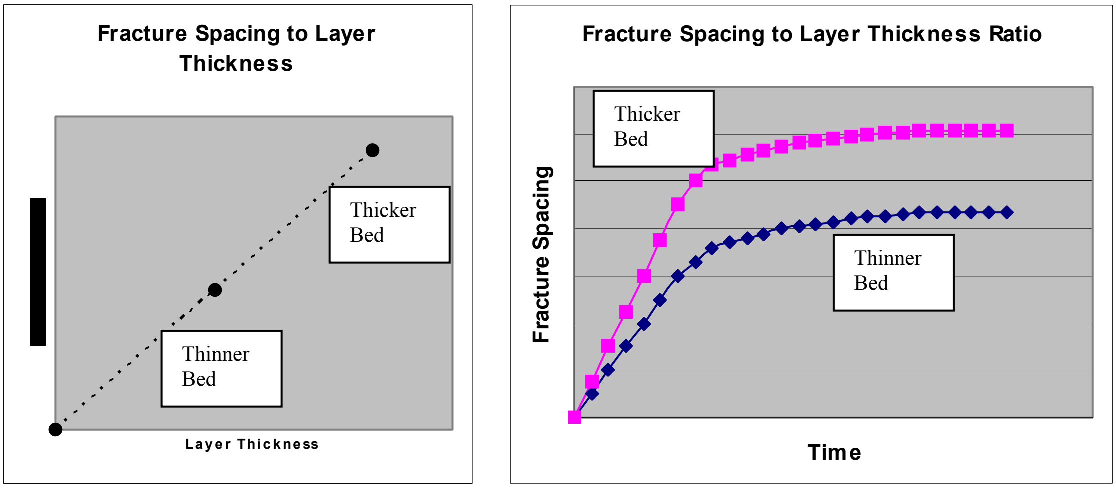

Figure 2. Different general ratio for a thinner and for a thicker bed, and the comparison of the different behaviour of a thinner and a thicker bed.

The commonly used stress-transfer theory (Cox, 1952) considers a three-layer model with a central layer containing equally-spaced fractures. Extension parallel to the layers induces a tensile stress, σ_{xx}. Because of the traction-free condition at the fracture surfaces, the stress σ_{xx} in the fractured layer falls to zero at these surfaces. In the region between adjacent fractures, the stress is transferred from the intact neighbouring layers. As the applied strain increases, the stress midway between adjacent fractures will reach the tensile strength; thus new fractures are induced and the spacing is reduced by half. As the strain increases to infinity, the spacing decreases to an infinitesimal value, with no apparent lower limit. Therefore, this theory does not predict fracture saturation.

3.3 Paper Summaries

3.3.1 Joint spacing vs. layer thickness

D. W. Hobbs (1967), "**The Formation of Tension Joints in Sedimentary Rocks: An Explanation**".
Method: Elastic Models and theory of elasticity. Similar to that given by Cox (1952).
Data: Theoretical models.
Results: Joint frequency is proportional to:

- The inverse of the bed thickness

- The inverse of the square root of the Young's Modulus of the bed
- The square root of the Shear Modulus of the neighbouring beds

Joint frequency increases with increasing tectonic deformation, and the formation of new joint planes does not occur continuously. It depends on the stress history.

F. L. Ladeira and **N. J. Price (1981)**, "**Relationship between Fracture Spacing and Bed Thickness**".
Method: Graphical presentation. Data are expressed as the number of fractures per unit length of traverse against bed thickness on a log-log plot.
Data: Obtained from widely spaced localities in different folds in the Carboniferous turbidites of the Alentejo area (Portugal), in the Carboniferous flysch of Devon and Cornwall (U.K.) and in the Jurassic limestones of Figueira da Foz (Portugal). Hence, variations in lithology and the degree of tectonic deformation will have influenced the fracture separation.
Results: Hydraulic failure mechanism will contribute to the ultimate failure of the rocks, and they postulate that some fractures mainly result from high fluid pressures which occur within the beds prior to the development of the fractures. Searching for a relationship, they find that the distance "d" (separation of fractures) is closely linked to the gradient of the fluid pressure in the surrounding of already existing fractures. Regarding bed thicknesses, they conclude that the thickness of the adjacent incompetent layers surrounding the competent layer has a slight influence on the spacing of fractures in the thicker beds: when adjacent layers are "relatively thick", the fractures in the competent layers are slightly wider spaced than when the adjoining incompetent layers are thin.

Q. Huang and **J. Angelier (1989)**, "**Fracture Spacing and its Relation to Bed Thickness**".
Method: Statistical methods (Gamma distribution (continuous cases), Probability Density Function (PDF)…).
Data: They have recorded joint spacings in two geodynamically contrasting areas: near Sisteron (Alpes de Haute-Provence, France), where compressional tectonics dominate in the outer Alpine arc, and around the Gulf of Suez (Egypt), in a rift system with widespread extensional tectonism.
Results: Gamma distribution may be the most natural distribution for occurrence of joints (and its spacing, density…) in layered beds. The average spacing of tension joints is linearly proportional to the bed thickness, for thicknesses up to a few metres. Additionally, this relationship is controlled by rock properties, including the degree of consolidation of the rocks during jointing. They finish concluding that the frequency distribution of tectonic joint spacing may have no direct relation to tectonic regime.

W. Narr and **J. Suppe (1991)**, "**Joint Spacing in Sedimentary Rocks**".
Method: Hobbs' model (1967) intuitively predicts a constant ratio of bed thickness to joint spacing; however, a simulation based on this model predicts a multimodal distribution of joint spacing. By adding the effect of a limited number of flaws to the model, which weaken the bed at random sites along its length, a simulated distribution of joint spacing is obtained that is similar to the observed log-normal distribution. Thus, Hobbs' model, modified to include the effect of flaws, seems capable of predicting the observed statistics of joint spacing as a function of layer thickness in sedimentary strata. They also use statistical processes (distributions and plots).

Data: Joints of the Monterey Formation in well exposed beach outcrops in the Santa Maria basin and Santa Ynez Mountains of the Transverse Ranges province of California. The Monterey Formation is an approximately 700 m thick sequence of interbedded siliceous shale, chert, phosphatic shale, mudstone and dolostone of Miocene age.
Results: Relatively hard, cohesive rocks of the Monterey Formation show a constant ratio of layer thickness to joint spacing of about 1.3. This ratio is called Fracture-Spacing Index. The frequency distribution of the ratio of joint spacing to median spacing is log-normal. Relatively soft, non-cohesive mudstones do not have regular joint sets but are mechanically important because they form the boundaries to the jointed, cohesive strata. Otherwise, Hobbs' model of the controls on joint spacing qualitatively predicts a constant ratio of layer thickness to joint spacing in an interstratified sequence of rocks with different elastic properties. However, a simulation based on this model gives a multimodal spacing frequency distribution. The addition of macroscopic flaws, which weaken the jointed bed at random sites along its length, results in a simulated frequency distribution that is similar in form to the observed log-normal distribution.

N. Mandal, **S. Krishna Deb** and **D. Khan (1994)**, "**Evidence for a Non-Linear Relationship between Fracture Spacing and Layer Thickness**".
Method: Analogue models (experimental method). Theoretical analysis.
Data: Experimental results from published experimental data (rigid layers of Plaster of Paris resting on a ductile substratum of pitch).
Results: They arrive at the conclusion that in rock sequences of contrasting rheology, fractures in stiff layers of large lateral extent grow at a mechanically favoured spacing in response to layer-parallel traction by the weaker interbeds, and they conclude that fracture spacing in this kind of situation has a non-linear relationship to layer thickness (**Figure 3**). Their mechanical model yields a proportionality of fracture spacing to the square root of the bed thickness, which implies low sensitivity to layer thickness differences for large thicknesses.

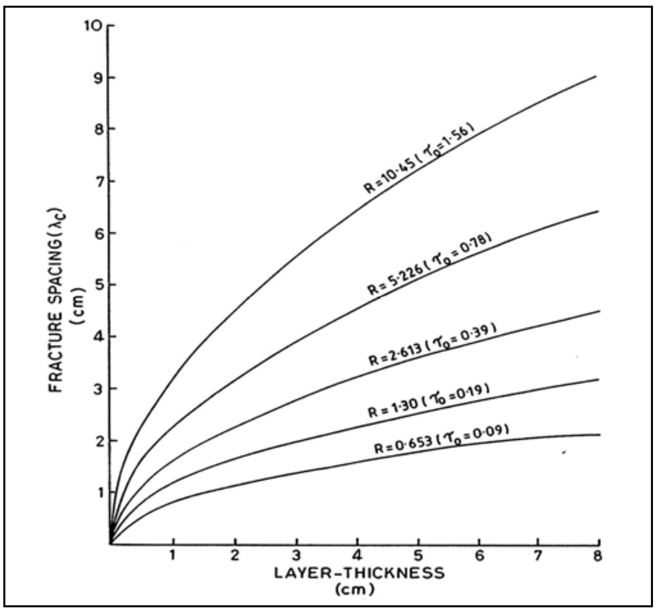

Figure 3. General view of the fracture spacing vs. layer thickness relationship; from Mandal et al. (1994).

H. Wu and **D. D. Pollard (1995)**, "**An Experimental Study of the Relationship between Joint Spacing and Layer Thickness**".

Method: Two methods for measuring joint spacing are described and compared (the Area method and the Line method). Two kinds of joint sets are distinguished on bedding surfaces: the poorly-developed and the well-developed. They assume that the poorly-developed joint sets have been developed in early stages, whereas the well-developed joint sets have been developed in later stages. Experimental modelling is applied to determine the searched relationship; a four-point bending device is used to produce a fracture set in a brittle coating (methylene chloride) on a PMMA (polymethyl methacrylate) substrate.

Data: Collected data from several structural geology publications (outcrops in Russia, France…).

Results: The accuracy of spacing measurements depends on the size of the measured area. If the area is too small the sample will not be representative of the joint set; if the area is too big it may include real spatial variations in spacing. Measurements of spacing from two outcrops in the same rock unit with the same thickness and a non-saturated joint set could be quite different because of minor differences in strain produce major differences in spacing.

Wu and Pollard use the concept of fracture saturation; this is here attributed to stress relaxation caused by fracture opening without significant fracture propagation.

An approximately linear relationship between joint spacing and layer thickness is deduced (for a linear relationship see **Figure 4**).

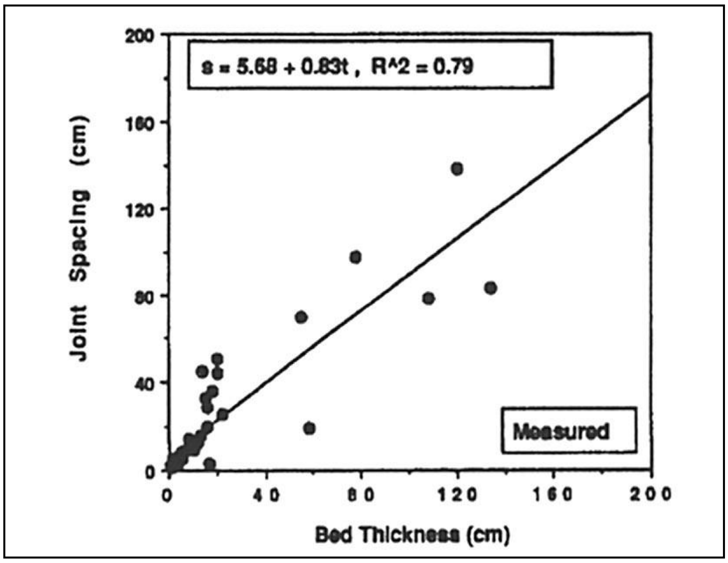

Figure 4. Plot of median joint spacing vs. layer thickness of sandstone (from Ji et al., 1998). The authors deduce a linear relationship between joint spacing and bed thickness from their data. Note, however, that the data may possibly equally well be represented by a non-linear function such as in Figure 3.

S. Ji and **K. Saruwatari (1998)**, "**A Revised Model for the Relationship between Joint Spacing and Layer Thickness**".

Method: Revised analytical model from Hobbs' model (1967), using statistical tools.

Data: Collected from the St-Roch Formation of Lower Cambrian age in continuous exposures at Plage Victor along the Saint-Lawrence river near Saint-Jean-Port-Joli, which is 113 km northeast Quebec city.

Results: A linear relationship for joint spacing and layer thickness, as proposed by Hobbs (1967) is accepted, but for some individual measurements this relationship is only statistically linear, as it could be expected. The authors propose a revised model with some new assumptions with respect to Hobbs (1967) and Mandal et al. (1994). These assumptions are:

1. There is no slip on the layer/matrix interfaces
2. The relationship between joint spacing and layer thickness depends on the actual mode of the shear stress decay constant in the bed matrix; this actual mode should be studied by well-designed experiments
3. The competent layer has a unique tensile strength whereas in a natural sedimentary bed, a fairly wide distribution of strengths is expected along the layer due to the random nature of defects
4. The principal limitation to the theory presented in this paper is the assumption that the two incompetent layers bounding the jointed layer are of equal thickness
5. The model is 2D and implicitly assumes that joints are infinite in the third direction. Thus, the interaction between joints in this direction is ignored.

Their model depends on the selection of material constants (E_f, E_m, ν_m, C_0) and fracture saturation strain for the rocks.

3.3.2 Mechanisms and kinematics

M. R. Gross (1993), "**The Origin and Spacing of Cross Joints: Examples from the Monterey Formation, Santa Barbara Coastline, USA**".
Method: A model is proposed for cross joint propagation based on the analysis of stress reduction in the vicinity of a newly-formed joint. In this model, cross joint development follows a sequential infilling process as remote tensile stress increases with time. According to the model, the first cross joints (with FSI=0.32) propagate under a remote tensile stress of approximately -14 MPa. A second episode of cross jointing (with FSI=0.65) initiates when remote tensile stress reaches -27 MPa, and a third generation of cross joints (with FSI=1.30) develops at -57 MPa. Joints in each successive episode initiate in the midregion between existing joints where local tensile stress is highest. High remote tensile stresses may develop due to differential horizontal contraction among adjacent stratigraphic beds upon uplift and erosion. He also uses the knowledge of some field observations, plots and profiles.
Data: Outcrops in the clayey-siliceous member of the Miocene Monterey Formation of Coastal California (USA).
Results: He arrives at several conclusions:

- A set of pre-existing joints may act as mechanical layer boundaries during subsequent jointing events in much the same manner as lithologic contacts restrict joint propagation.
- Spacing of cross joints (joints which terminate against a series of pre-existing systematic strike perpendicular joints) is directly proportional to the distance between these pre-existing strike-perpendicular joints. Joint termination geometry indicates that cross joints initiated in the midregion between strike-perpendicular joints.

- Crack driving stress is reached first at midpoints between earlier generations of cross joints since they experience the highest values of local tensile stress.
- Stress conditions for cross joint propagation may arise due to differential contraction of adjacent stratigraphic horizons during uplift and erosion.

M. R. Gross, **M. P. Fischer**, **T. Engelder** and **R. J. Greenfield (1995)**, "**Factors Controlling Joint Spacing in Interbedded Sedimentary Rocks: Integrating Numerical Models with Field Observations from the Monterey Formation, USA**".
Method: Numerical modelling (several finite element simulations using a two-dimensional finite element code named FRANC (FRacture ANalysis Code)).
Data: Outcrops in the Monterey Formation of Coastal California (USA).
Results: They explain that joint spacing models try to predict the location of subsequent joints, and they find that stress distributions derived from finite element simulations compare favourably with theoretical predictions of the classical paper of Hobbs (1967). During studying all the factors controlling joint spacing, they infer that an increase of the Elastic Modulus (E) implies longer stress reduction shadows, and therefore wider joint spacing. Their finite element simulations show that "the dependence of the stress reduction shadow on E in the jointing bed is weaker than the square root dependence" predicted by Hobbs (1967). Furthermore, they conclude that bed thickness is the primary factor, but E, Extensional Strain and Flaw Size are important parameters determining joint spacing. They finish concluding that the linear correlation between median joint spacing and bed thickness is remarkably strong.

T. Bai and **D. D. Pollard (2000)**, "**Closely Spaced Fractures in Layered Rocks: Initiation Mechanisms and Propagation Kinematics**".
Method: Numerical modelling, using FRANC (FRacture ANalysis Code).
Data: Three-layer model, introducing several kinds of fractures in the fractured central layer.
Results: They investigate formation of fractures in rocks that have already reached fracture saturation (fracture spacing to layer thickness ratio less than a critical value). They find that the initiation points of infilling fractures are more likely to be found near the interfaces than in the middle of the fractured layer. In order to get a propagation of a fracture, some conditions related to a critical size of that fracture, revealed in the paper, have to be fulfilled. Moreover, an infilling fracture can cut through the fractured layer only if it satisfies some specified conditions, displayed in the paper, related to the fracture spacing to layer thickness ratio. They finish concluding that the propagation of a crack always depends either on hydraulic fracturing and the position of the flaw (small crack) from which it has originated. Hydraulic fracturing occurs when the fluid pressure in a flaw exceeds the least compressive stress by an amount necessary to raise the stress intensity at the crack tip to the fracture toughness of the rock. This condition depends on the size of the flaw. As the fracture develops, there will be a fluid pressure gradient from the lower pressure in the fracture to the ambient pressure at a certain distance from the fracture. Thus, at this distance a second fracture may develop from a similarly sized flaw.

3.3.3 Fracture spacing and fracture saturation

A. Becker and **M. R. Gross (1996)**, "**Mechanism for Joint Saturation in Mechanically Layered Rocks: An Example from Southern Israel**".
Method: Statistical processes and plots, rose diagrams…, using Fracture-Spacing Ratio (FSR) and Fracture-Spacing Index (FSI).
Data: Field measurements obtained from a well exposed outcrop of the Gerofit Formation in southern Israel that affords the opportunity to measure joint spacing in a single bed of uniform thickness and lithology. This outcrop is a set of well-bedded carbonates of the Turonian Gerofit Formation, which consists of jointed limestone and dolostone interbedded with non-jointing marl and shale.
Results: They observe that the spacing of a systematic, mechanically confined joint set varies along the length of a single bed of uniform thickness and lithology. The intensity of joint set development corresponds directly to the presence of throughgoing fracture zones, which in turn likely will indicate regions of relatively high strain. In this way, increasing joint set development is characterized by a shift from broad multimodal to narrow unimodal spacing distributions, decrease in median spacing, decrease in standard deviation and an increase in FSR. Furthermore, portions of the bed subjected to less strain may remain in the sequential infilling phase of confined jointing, whereas regions of higher deformation may be at or near saturation, and this saturation may effectively be achieved by the growth of throughgoing joints (cutting across several beds), which take up further strain and inhibit additional bedding-confined jointing.

M. R. Gross, **D. Bahat** and **A. Becker (1997)**, "**Relations between Jointing and Faulting Based on Fracture-Spacing Ratios and Fault-Slip Profiles; a New Method to Estimate Strain in Layered Rocks**".
Method: Using FSI, FSR, plots and profiles.
Data: Empirical data. The distribution and geometry of joints adjacent to a normal-fault zone were investigated in a road cut through the Lower Eocene Mor Formation, 5 km south of Beer Sheva, Israel. These flat-lying rocks, subjected to considerable brittle deformation, consist of interbedded chalk and nodular chert within structural downwarps of the Syrian arc fold belt.
Results: They find that densely spaced, confined joints in a chalk bed correlate directly to structural position in the hanging-wall block of a normal-fault zone. Deficits in fault slip may result in unrelieved elastic strain stored in parts of the wall rock; this strain surplus may be released during a subsequent jointing event, resulting in locally high FSR (Fracture Spacing Ratio) values. They observe that localized strain around faults and folds may result in anomalously high FSR values, and conclude advising that FSR may provide field and exploration geologists with an effective tool to map local variations in strain around structures when factors such as bed thickness and mechanical properties are well constrained, and when joint apertures scale approximately with joint height.

T. Bai and **D. D. Pollard (1999)**, "**Spacing of Fractures in a Multilayer at Fracture Saturation**"
Method: Numerical modelling, using a two-dimensional finite element code named FRANC (FRacture ANalysis Code), and assuming plane strain conditions for all the models. They study the critical spacing to layer thickness ratio in two different cases using a three-layer model. In the first case, the model contains a fractured competent

central layer, and two softer neighbouring layers of the same thickness. They study the change of critical ratio as a function of the thickness of the neighbouring layers. This is called the symmetric case. In the second case, the model contains a thick bottom layer and a top layer of variable thickness. This case is called the unsymmetrical case.
Results: They conclude, after using a three-layer model, that for both symmetric and asymmetric cases, the critical fracture spacing to layer thickness ratio $[(S/T_f)_{cr}]$ decreases very rapidly with increasing thickness of the neighbouring layer(s). As long as the thickness of the neighbouring layers is 1.5 times the thickness of the fractured layer or greater, the critical ratio is the same as that for the system with both thick top and bottom layers.

T. Bai and **D. D. Pollard (2000)**, "**Fracture Spacing in Layered Rocks: A New Explanation Based on the Stress Transition**".
Method: Numerical modelling, using a two-dimensional finite element code named FRANC (FRacture ANalysis Code) based on the theory of linear and non-linear elastic fracture mechanics, and an experimental verification, using Plexiglas (PMMA) plate specimens. They take into account the stress state transition and the critical spacing to layer thickness ratio. Next figure (**Figure 5**) shows the critical fracture spacing to layer thickness ratio.
Data: Three-layer model, introducing several kinds of fractures in the fractured central layer, and joint spacing data from the literature.
Results: They work about the changes from tensile to compressive due to a critical fracture spacing to layer thickness ratio, and its variations. There is a state stress transition between two adjacent opening-mode fractures in both a homogeneous material and a layered material under extension. Opening-mode fractures form in response to tensile stress in the direction perpendicular to the fracture plane and/or internal fluid pressure. The stress state transition implies that an opening-mode fracture cannot form between two fractures with a spacing to layer thickness ratio less than the critical value unless a locally perturbed tensile stress field exists somewhere between the fractures, or a mechanism exists to overcome the compressive stress.

T. Bai, **D. D. Pollard** and **H. Gao (2000)**, "**Explanations for Fracture Spacing in Layered Materials**".
Method: Numerical modelling, using a two-dimensional finite element code named FRANC (FRacture ANalysis Code).
Data: Three-layer model, introducing several kinds of fractures in the fractured more competent central layer.
Results: The authors offer to us a general view of the fractures' behaviour. They conclude that the spacing of opening-mode fractures in layered materials is often proportional to the thickness of the fractured layer. They conclude that Stress-transfer theory (Hobbs, 1967):

- Fails to predict fracture saturation, and does not satisfy the fundamental equations of equilibrium for an elastic boundary-value problem.
- Fails to predict the stress-state transition.
- Should be abandoned.

Finally, they explain that stress state between two fractures is determined by three mechanisms:

1. Transfer of stress from the neighbouring layers.
2. Contraction involved of the fractured layer in the vertical direction because the fractures shorten as they open. This mechanism should be discussed inasmuch as it is not so clearly explained in the paper.
3. The effect of the traction-free fracture surface.

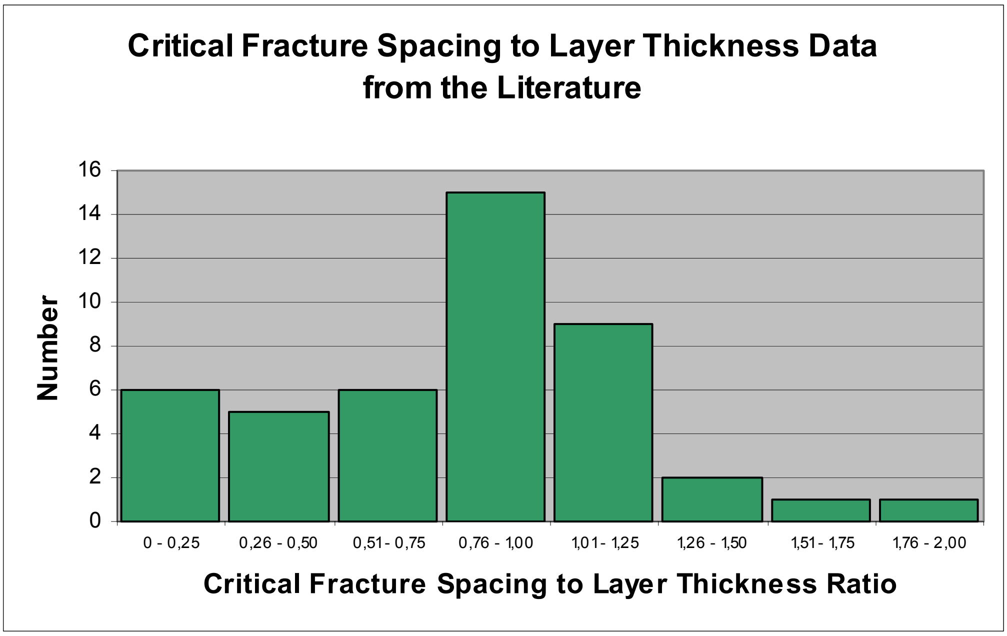

Figure 5. Critical spacing to layer thickness ratio from a literature survey by Bai and Pollard (2000). These ratios were calculated using the inverse of the Fracture Spacing Index (FSI) or the Fracture Spacing Ratio (FSR). Different spacing to layer thickness ratios are from different layers. Note the abundance of values between 0.76 and 1.25.

3.3.4 Mechanical Discontinuities

J. C. Ruf, **K. A. Rust** and **T. Engelder (1998)**, "**Investigating the Effect of Mechanical Discontinuities on Joint Spacing**".
Method: Statistical methods and plots of FSI (strike joints and cross joints).
Data: Empirical data from a large outcrop of the Upper Devonian Brallier Formation, a distal turbidite sequence.
Results: They find that joint spacing in well-bedded sedimentary rocks is more tightly clustered about the mode than a perfect log-normal distribution and is, therefore, statistically different from joint spacing in mechanically isotropic rocks for which, according to the theory, a log-normal distribution would be expected. Furthermore, they observe that cross-joint spacing correlates better with the spacing of pre-existing, systematic joints they grow between, rather than with the thickness of the bed in which they propagate.

3.3.5 Spatial distributions

P. A. Gillespie, **C. B. Howard**, **J. J. Walsh** and **J. Watterson (1993)**, "**Measurement and Characterisation of Spatial Distributions of Fractures**".
Method: Statistical methods (spacing population plots) and several plots.
Data: Line sample (1D) and map datasets (2D) of faults and joints, and synthetics datasets. Datasets have been derived from a regional seismic line across an extensional basin, from a 2D seismic survey of an oil and gas field, from a published map and from outcrops, proceeding from geological literature. The datasets cover a range of scales and are for either normal fault or for joint arrays. Lithologies are, basically, from:

- Triassic, Jurassic and Upper Carboniferous sandstones and shales,
- Recent glacial sands,
- And Tertiary volcanics.

Results: They find a basic difference between fault and joint patterns. They interpret the datasets to indicate that joint systems have more regular, nonfractal, geometries on the scales examined, and they have hierarchical distributions of both size and spacing, arising from the varied thicknesses of the mechanical units which control each particular size of joint.

M. R. Gross, **G. Gutierrez-Alonso**, **T. Bai**, **M. A. Wacker**, **K. B. Collinsworth** and **R. J. Behl (1997)**, "**Influence of Mechanical Stratigraphy and Kinematics on Fault Scaling Relations**".
Method: Using plots of density, stereo plots of poles and profiles.
Data: Empirical data. Geometries and dimensions of normal faults were investigated in the Miocene Monterey Formation exposed along Arroyo Burro Beach in Santa Barbara, California.
Results: They find that small faults display a linear correlation between displacement and length, with the relatively high D/L (Displacement/Length (parallel to the displacement)) ratio attributable to a low shear modulus for mudstone. In contrast, displacement across larger faults that extend across multiple beds is independent of fault length. The lack of correlation between displacement and length for large faults arises from a number of local geologic factors related to lithology and tectonic history of rocks. Finally they conclude that regional tectonic forces lead to the development of a fault system whose growth is locally controlled by mechanical stratigraphy and structural style. Once faults extend beyond the confines of mudstone beds, fault growth is influenced by numerous geologic factors such that displacement no longer correlates with length. Thus, a lot of large faults do not propagate as if in homogeneous medium according to a universal growth model. Because lithologic diversity and structural complexity will vary among rock types and tectonic environments, they emphasize the importance of characterizing the influence of local mechanical anisotropies and deformation styles on fault development.

C. E. Renshaw (1997), "**Mechanical Controls on the Spatial Density of Opening-Mode Fracture Networks**".
Method: Analyses of fracture trace maps and seismic inversions methods, using plots and statistical process.
Data: From more than 30 published fracture trace maps of different lithologies ranging in scale over 14 orders of magnitude.

Results: First of all, he assumes that understanding the controls on fracture density is critical to interpreting the geologic evolution, permeability and mechanical properties of jointed rock. He postulates density-limiting mechanisms; there is a state of fracture criticality that marks the transition from relatively intact to heavily fractured rock. Analyses reveal that near-surface fracture densities are generally less than 1-2 over a range of 14 orders of magnitude. The observed densities are approximately an order of magnitude greater than the range typical of deeper (>500 m) formations and may indicate that surficial controls on fracture growth are different than those at depth. The development of greater densities at the surface may be limited by the significant decrease in effective elastic stiffness associated with fracture densities near unity. As fracture densities approach 1.0, additional strain accommodated by the fractures decreases the driving tension, limiting further fracture growth. He also observes that calculation of the effective stiffness of an elastic medium is straightforward for small fracture densities, whereas for higher fracture densities, several methods have been proposed to account for the mechanical interaction of the fractures, like self-consistent scheme and the second order formulation.

Noelle E. Odling (1997), "**Scaling and Connectivity of Joint Systems in Sandstones from Western Norway**".
Method: Observation height and fracture trace length (seven fracture trace maps of data with different scales) and statistical processes for resolution effects.
Data: Empirical data. The fracture system studied occurs in Devonian-age sandstones and conglomerates of Hornelen in western Norway, approximately 200 km north of Bergen.
Results: She does a study of several joint systems, concluding, for instance, that only the orientations of the major fracture sets were found to be scale-independent. On the contrary, various features like trace-length, distribution, density, connectivity and nature of junctions were all found to be scale-dependent. Furthermore, she does an overview about the critical observation height (maximum height at which a trace can be identified) to study the joint systems by photo interpretation, and she concludes that the critical observation height is related by a power law to fracture trace lengths. Finally, she observes that the nature of connectivity suggests that a scale exists beyond which the fractures controlling flow are scale-independent.