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Predicting variability in joint frequencies from boreholes

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Abstract

Joints in rock are not evenly spaced, but commonly show clustering. This suggests that boreholes that are a short distance apart can intersect very different numbers of joints. A simple 1D model is used to illustrate variability in joint frequencies from vertical wells intersecting steeply dipping joints. The model indicates that raw joint frequencies logged from core or borehole images can give unreliable inputs into reservoir models, especially when the joints are clustered and variations occur over scales that are much smaller than the resolution of seismic surveys or the grid blocks used in reservoir simulations. Variability in joint frequencies from deviated or horizontal wells can be used, however, to test the variability in joint frequencies from vertical wells.

Keywords: Boreholes; Joints; Joint frequencies; Prediction

1. Introduction

Fractured reservoirs can be difficult to model and to exploit. The key to a better understanding of sub-seismic structures lies in well data, but commonly limited use is made of the vital data collected from core and borehole images, even though these data provide the only direct information about joints in hydrocarbon reservoirs. Furthermore, collecting such joint data costs considerable time and money. The challenge lies in the translation of such data to a full-field reservoir model. Are the wells representative, and how do we build a 3D model from isolated wells?

Much recent work has focussed on correlating joint data from wells with seismic or surface attributes, with the aim of developing joint distribution maps and models (e.g. Hennings et al., 2000). For example, Ouenes (2000) uses a neural network to find the possible underlying relation that may exist between various seismic (e.g. time dip, edge, azimuth, variance, amplitude) or geological (e.g. structure, bed thickness, lithology) drivers and the joint intensity, enabling maps of joint intensity to be created.

There are problems, however, with interpreting joint *frequencies* (number per unit distance) from wells. First, joint sets that are at a low angle to the well are under-sampled (e.g. Terzaghi, 1965; Mauldon and Mauldon, 1997; Peacock et al., 2003). This is a particular problem, for example, where deviated or horizontal wells are drilled at a low angle to the strike of a dominant set of joints. Wells are commonly drilled vertically and steeply dipping (and bed-perpendicular) joints are common (Fig. 1), so this situation is emphasised in this paper. Anderson's (1951) theory explains why vertical joints are commonly developed within a few hundred metres of the Earth's surface. Second, joints are not evenly spaced, but tend to show some clustering (e.g. Priest and Hudson, 1976), so variations in the numbers of joints intersected can occur over short distances (Fig. 1). Third, as much of the limited joint data as possible should be used in any analysis, so core and borehole image data commonly have to be combined, even though they sample joints differently. Borehole image data may reveal different joint frequencies than are seen in cores (e.g. Committee on Fracture Characterization and Fluid Flow, 1996). It is, therefore, undesirable to combine core and borehole image data, although the different types of data sometimes reveal similar joint *distributions* (variability in the spacings between joints).

This paper presents a simple method for studying the variability in joint frequencies measured in wells. For simplicity, vertical wells and a single set of sub-vertical

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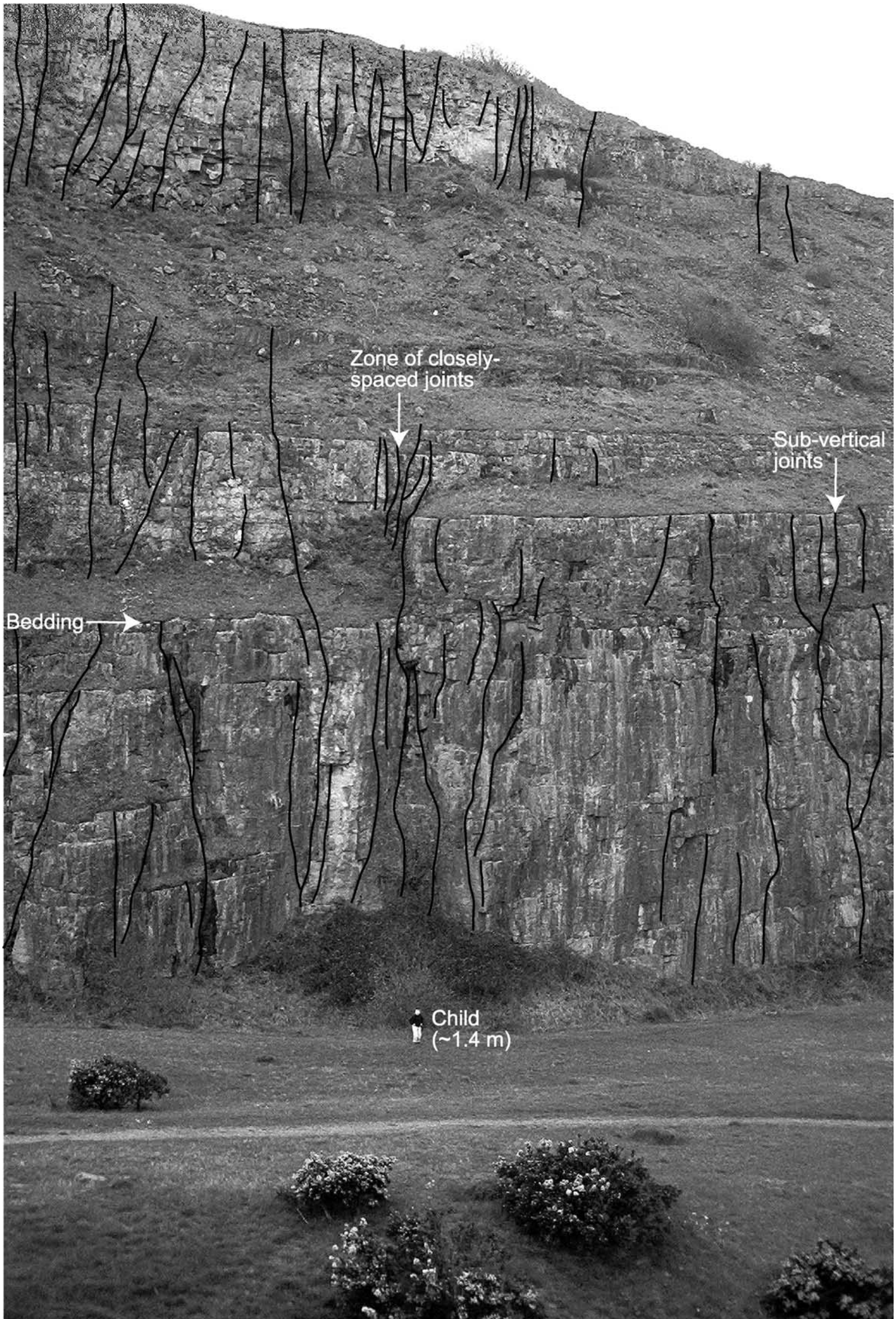

Fig. 1. Photograph of gently dipping Carboniferous Limestone and sub-vertical joints (highlighted in black), Colwyn Bay, North Wales. Zones of relatively closely spaced joints occur in the cliff, illustrating how different numbers of joints can be intersected by wells that are a short distance apart. A deviated well with an azimuth at a high angle to the strike of the joints would give a better measure of the joint distribution through the rock mass than would vertical wells.

joints are modelled to test variability in joint frequencies using different joint spacing distributions. The methodology would apply equally to deviated or horizontal wells at a low angle to joint sets. The model is tested using a field example, which indicates how data from deviated or horizontal wells can be used to test variability in joint frequencies from vertical wells.

2. Different types of joint distributions

Much work has been carried out on joint spacings (e.g. Priest and Hudson, 1976; Wheeler and Dixon, 1980; Rouleau and Gale, 1985; Huang and Angelier, 1989; Rives et al., 1992; Gillespie et al., 1993, 2001; Gross et al., 1995; Becker and Gross, 1996; Narr, 1996; Cooke, 1997; Dholakia et al., 1998), and this work has illustrated the complexity that occurs in how joints are distributed within a rock mass. Fig. 2 illustrates three types of joint spacing distributions, based on a spectrum from evenly spaced to strongly clustered (also see Priest and Hudson, 1976, fig. 1). If joints are approximately evenly spaced (Fig. 2a), joint spacings would be within a narrow range and each borehole would intersect the same intensity of joints (e.g. Fig. 3a). If the joints are randomly distributed (Fig. 2b), joint spacings would occur within a range of values such that there is no correlation between successive values. In this case, some joints are closely spaced and some are widely spaced (e.g. Fig. 3b), so different boreholes may intersect a significantly different numbers of joints. If the joints are clustered (Fig. 2c), zones of closely spaced joints occur within an area with a lower background level of jointing (Fig. 3c), so different boreholes would intersect many or few joints. These three types of distribution are compared in this paper.

3. Method used for modelling variability in joint distributions

Modelling has been carried out using spreadsheet software. The modelling simulates jointing in a 3D rock mass using a simple 1D approach (Fig. 4). The procedure is as follows:

1. A single set of simulated 'joints' is distributed along a horizontal scanline (Fig. 4). A 2000-m-long scanline with ~2000 joints was used for the modelling presented in Fig. 5. Either a real distribution can be used, or the type of distribution can be selected, e.g. regular, random or clustered (Figs. 2 and 5). The random distribution function in the spreadsheet software is used to generate random joint spacings. This function generates a uniformly distributed random number.
2. The thickness of the 'rock mass' must then be specified. A thickness of 100 m was used for the modelling presented in Fig. 5.
3. Each joint is assigned a dip, either on the basis of real data or an assigned distribution. For example, joint dips of 70° were used for the modelling presented in Fig. 5.
4. The dip of a joint and the thickness of the rock mass controls the length of scanline over which it would be intersected by a vertical well, i.e. each joint has a 'width' along the scanline. It is assumed that each joint extends through the entire rock mass. The width of a joint along the scanline is given by the thickness of the rock mass divided by the tangent of the joint dip. Each modelled joint has the same 'width' because joint dips of 70° were used for the modelling presented in Fig. 5.
5. Simulated 'wells' are placed at intervals along the scanline. They are placed at 1 m intervals in the models presented in Fig. 5.
6. The numbers of joints intersected by each well are counted. The number of joints intersected by each well is controlled by: (a) mean joint spacing, (b) variations in joint spacing, (c) joint dip, and (d) thickness of the rock mass.
7. Wells are generated only for the middle 1000 m part of the 2-km-long scanline to avoid edge effects.
8. The maximum, minimum, mean and standard deviations of the number of joints per well are measured (Table 1). These can be used to make simple comparisons between different distributions.

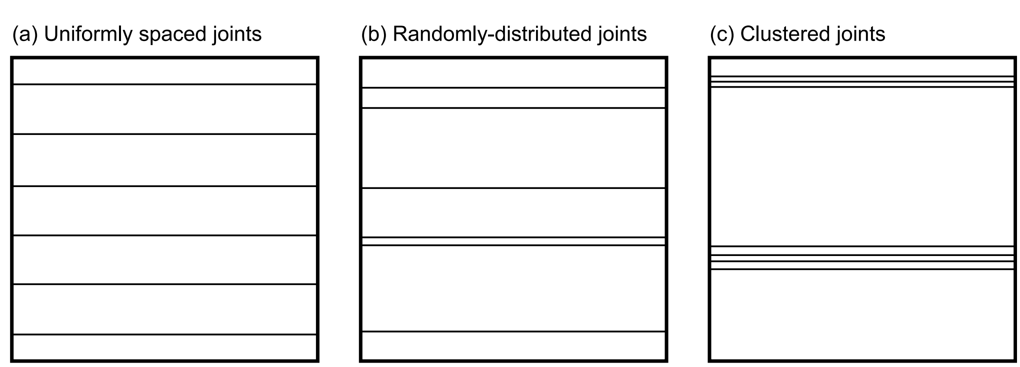

Fig. 2. Different types of joint distributions. (a) Uniformly-spaced joints, which may equate to a normal distribution. (b) Randomly-distributed joints, which may equate to a lognormal distribution. (c) Clustered joints.

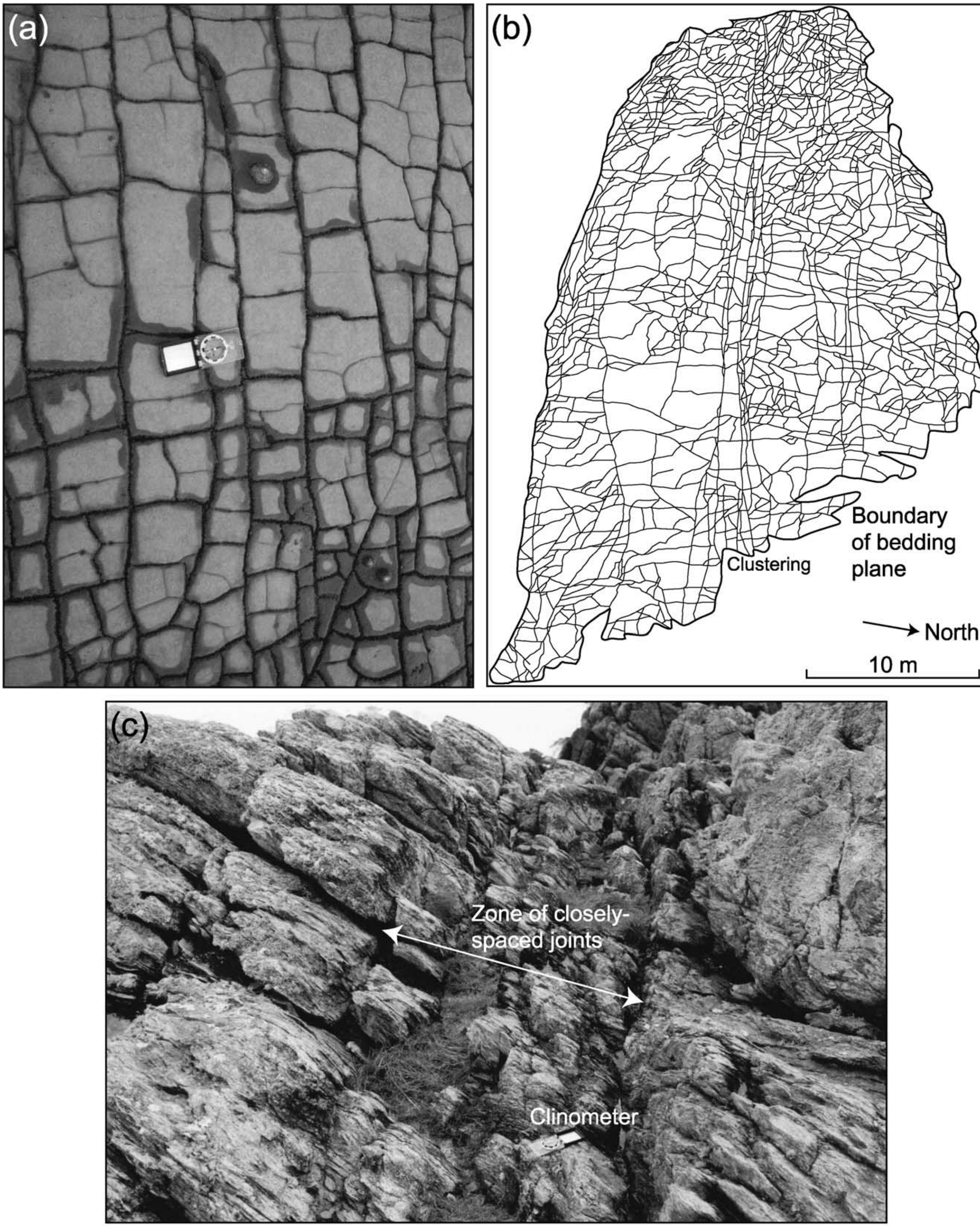

Fig. 3. Examples of different types of joint distribution. (a) Photograph of approximately uniformly spaced joints (top to bottom in this photograph) on a Liassic limestone bedding plane at Kilve, Somerset. (b) Map showing both approximately randomly distributed and clustered joints exposed on a limestone bedding plane, Oman. (c) Photograph of a zone of clustered joints in Precambrian metasediments, Rhoscolyn, Anglesey, UK.

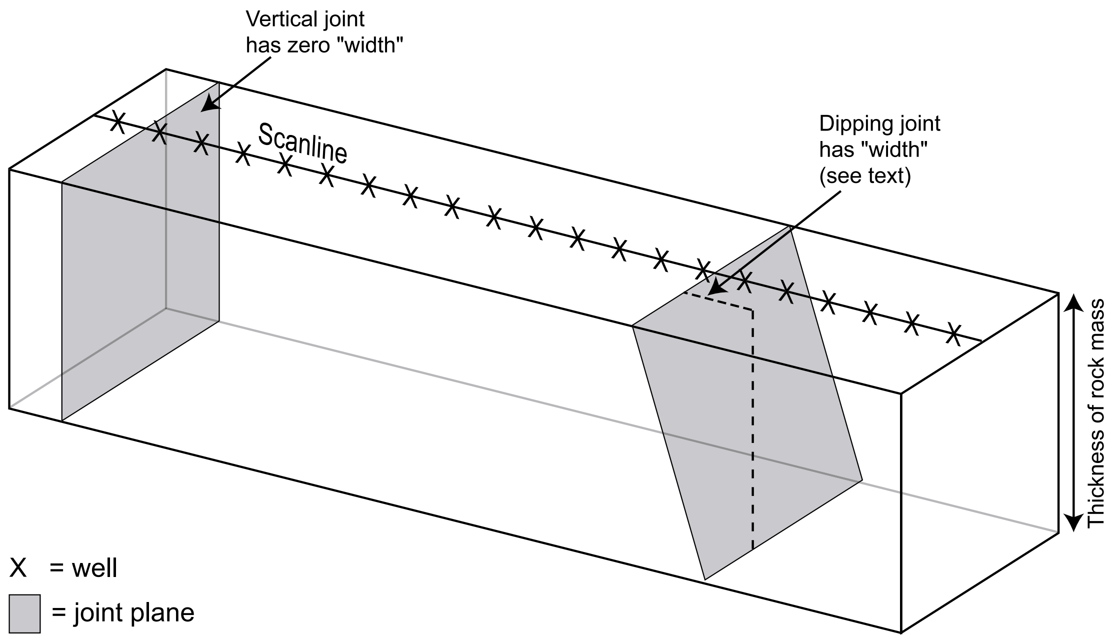

Fig. 4. Schematic diagram of the modelling presented in this paper. A 1D model is used to simulate joints in a 3D rock mass, with 'joints' distributed along the horizontal scanline. The rationale is as follows. (1) Assume a vertical sample plane intersecting a set of joints. (2) Joint spacings and joint dips are used to determine start and end points of each joint in a unit of specified thickness. The widths of the joints are related to their dips and to the thickness of the modelled unit, representing the vertical extent of each joint. Greater widths represent more gently dipping joints or thicker sequences. It is assumed that each joint crosses the whole unit. (3) Vertical 'wells' are placed along the sample plane and the numbers of joints intersected by each 'well' are counted. (4) Results are plotted (Fig. 5).

Distributions can also be compared by plotting graphs of percent number of wells against percent numbers of joints (Fig. 5c).

9. Twenty-five realisations of each joint distribution type have been generated to test the variability in the results (Table 1).

Three types of distribution are modelled (Fig. 5). Approximately evenly distributed joints are modelled using the random distribution function in the spreadsheet software within a very narrow range of spacings, from 0.8 to 1.2 m (Fig. 5a). Randomly distributed joints are modelled having random spacings over the wider range of 0–2 m. Clustered joints are modelled using a fractal distribution with a power-law exponent of 1, and a spacing range of 0.159–317.5 m. A fractal distribution is used because it is a simple method for producing high variability in joint spacings, with many joints being closely spaced and a few joints being widely spaced.

4. Results of modelling

Fig. 5b shows graphs of the cumulative numbers of joints against distance along a scanline for different joint distributions. Both the evenly- and randomly-spaced joints plot as straight lines at this scale of observation, indicating limited variability will occur in the numbers of joints intersected by the wells. The clustered joints do not plot as a straight line, indicating much greater variability in the numbers of joints intersected by the wells.

Fig. 5c shows graphs of percent number of wells against percent numbers of joints predicted by the method to be intersected by the wells. The evenly-spaced joints show a relatively narrow range of joint frequencies intersected by the wells (Fig. 5c), the randomly-distributed joints show a wider range of joint frequencies, while the clustered joints show the widest range of joint frequencies.

Modelled results for the three different distributions are presented in Table 1. The variation in the numbers of joints

Table 1
Results from the modelling of three different joint distributions (Figs. 4 and 5). Mean values shown from 25 realisations of each model, with the range of values shown in brackets

Numbers of joints intersected by wells	Evenly-distributed	Randomly-distributed	Clustered
Maximum	38.96 (38–40)	47.32 (45–50)	96.68 (80–112)
Minimum	33.64 (33–34)	27.72 (25–30)	0
Mean	36.37 (36–36.86)	36.54 (35.55–37.97)	34.02 (21–48.23)
Standard deviation	0.965 (0.87–1.08)	3.456 (2.71–4.20)	27.896 (23.48–31.66)

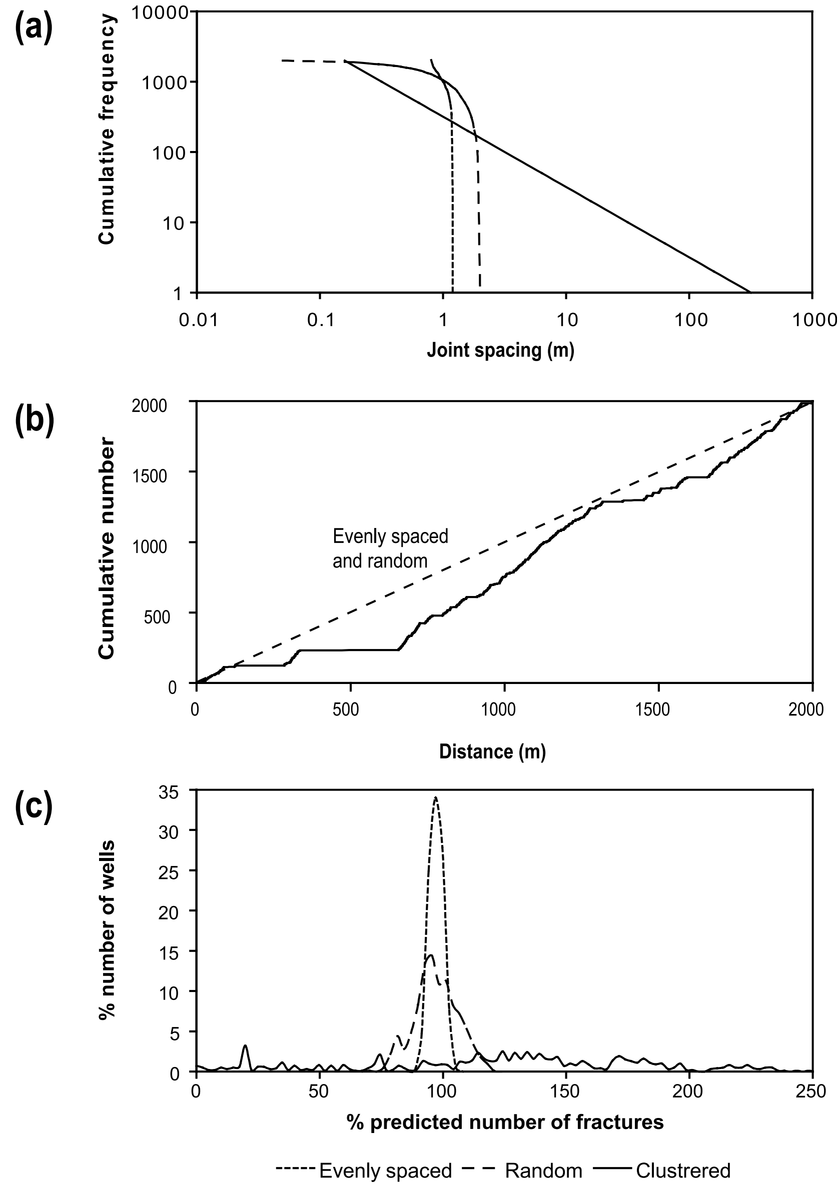

Fig. 5. (a) Cumulative frequency of joints against joint spacing for the different joint distributions. The approximately evenly distributed joints have a very narrow range of spacings, from 0.8 to 1.2 m. The randomly distributed joints have random spacings over the range of 0–2 m. The clustered joints have a fractal distribution with a power-law exponent of 1, and a spacing range of 0.159–317.5 m. (b) Graph of the cumulative numbers of joints against distance along a scanline for different joint distributions. The approximately evenly spaced and randomly distributed joints both plot as straight lines at this scale of observation, indicating limited variability in the numbers of joints intersected by the wells. The clustered joints do not plot as a straight line and indicate much greater variability in the numbers of joints intersected by the wells. (c) Graph of percent number of wells against percent numbers of joints intersected by the wells. The mean number of predicted joints is used as 100% on the x-axis. The approximately evenly spaced joints show a relatively narrow range of joint frequencies intersected by the wells. The randomly distributed joints show a wider range of joint frequencies intersected by the wells, and the clustered joints show the widest range of joint frequencies.

intersected by wells increases as the spacing becomes more uneven, i.e. as the clustering increases.

5. Field example of joints

A map of joints exposed on a limestone bedding plane (Fig. 6a) is used as a test of the technique presented in Figs. 4 and 5. This example allows modelling based on the joint distribution measured along a scanline to be compared with the numbers of joints measured along perpendicular scanlines. This situation is equivalent to using a horizontal well to simulate vertical wells.

Fig. 6b shows the cumulative number of joints against distance along scanline A–A′ (Fig. 6a). The approximate straight line indicates a fairly even distribution of joints along scanline A–A′ at the scale of observation. Gillespie et al. (2001) show that these joints have an approximately

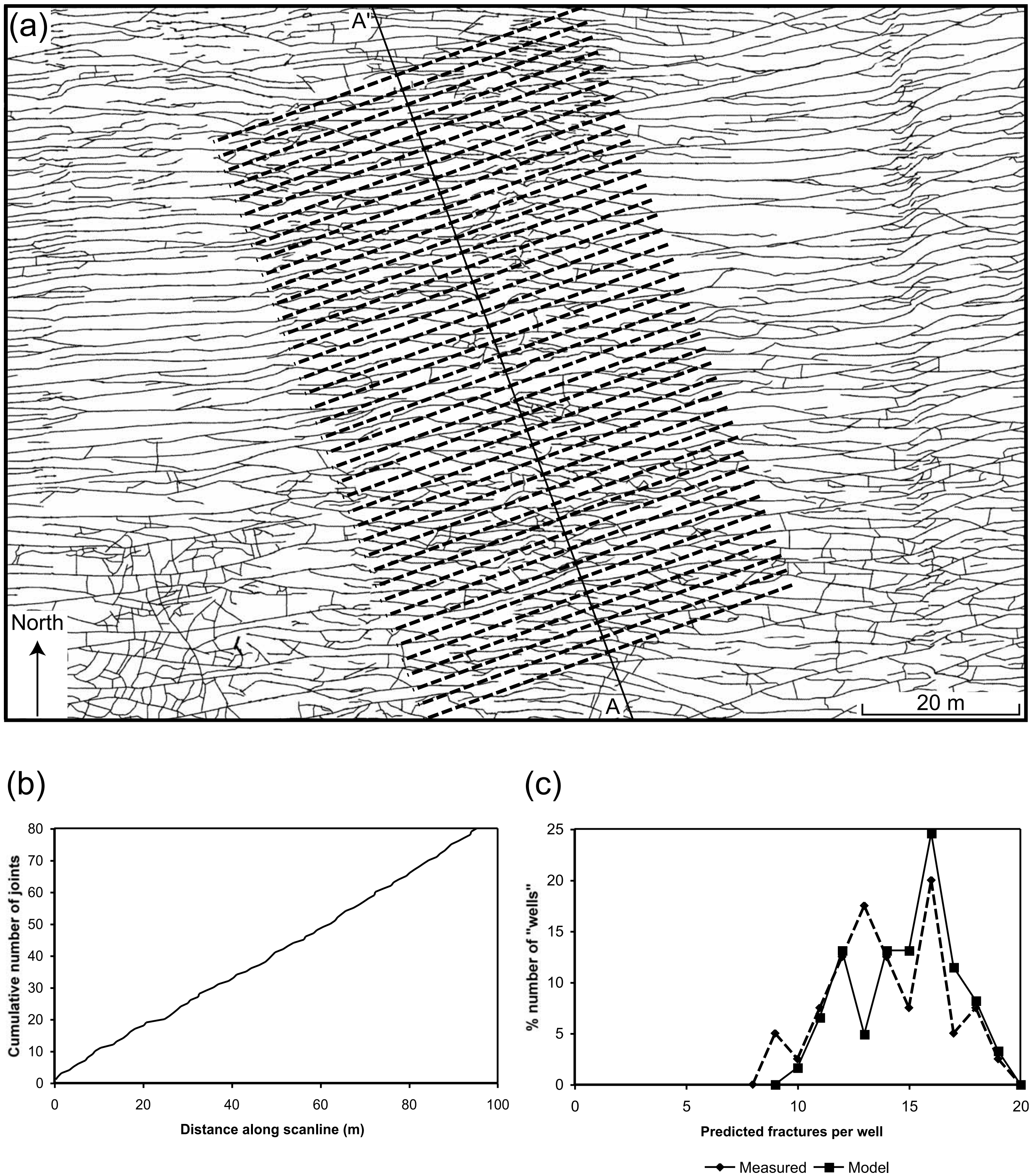

Fig. 6. (a) Map of joints from the Burren, western Ireland (from Gillespie et al., 2001, fig. 5b). The set of ∼N–S striking veins have been removed from the map. The joint distribution has been measured along scanline A–A′. Forty other scanlines (dashed) are drawn as simulated wells, and the numbers of joints intersected by these of perpendicular scanlines are counted. (b) Cumulative number of joints against distance along scanline A–A′. There appears to be an approximately even distribution of joints along the scanline at this scale of observation, as indicated by the straight line. (c) Number of wells against numbers of joints intersected for the model and for the perpendicular scanlines. The modelled results are similar to the counted numbers from the perpendicular lines, with the maximum number of wells intersecting 16 joints. The mean number of joints intersected is 14.89 for the model and 14.05 for the perpendicular scanlines. Standard deviations are 2.24 for the model and 2.51 for the perpendicular scanlines. Differences between the count and the model are probably caused by the irregular traces of the joints.

normal spacing distribution, with an approximately regular spacing. This spacing distribution and the measured strikes of the joints relative to scanline A–A′ have been used to model the number of joints that would be intersected along wells that would be perpendicular to scanline A–A′, and these are compared with numbers of joints measured along the perpendicular scanlines (Fig. 6c). The modelled results are similar to the counted numbers from the perpendicular scanlines, with the maximum number of wells intersecting 16 joints. The example shown in Fig. 6 indicates how deviated or horizontal wells may be used to predict variations in joint frequencies from vertical wells (Section 6).

There are problems in comparing joint data from differently orientated wells, even if data are corrected using the Terzaghi (1965) function (also see Mauldon and Mauldon, 1997). For example, vertical wells in gently dipping beds will intersect a greater variety of lithologies than will horizontal wells. Lithological competence can control the nature of joints, with more joints tending to occur in more brittle beds (e.g. Ladeira and Price, 1981; Narr and Suppe, 1991; Hanks et al., 1997). For example, Gross et al. (1995) suggest that joint spacing decreases with increased Young's modulus because beds with higher Young's modulus fail at lower extensional strains. This means that the joint population will be more diverse in a sequence of lithologies than in a single lithology. The mean spacing of the joints that form a joint set within a bed is typically approximately proportional to bed thickness (e.g. Hobbs, 1967; Ladeira and Price, 1981; Huang and Angelier, 1989; Narr and Suppe, 1991; Ji and Saruwatari, 1998; Ruf et al., 1998). Joint frequencies from vertical wells cannot, therefore, be directly compared with joint frequencies from horizontal wells.

6. Improving correlations with seismic attributes and future work

Methods have been developed to correlate measured joint frequencies with various seismic attributes. Such a correlation would allow maps of the seismic attributes to be used as a proxy for variations in joint frequencies across an area (e.g. Hennings et al., 2000). The results of the modelling presented here suggest, however, that data from vertical wells may be misleading because measured joint frequencies may vary over distances that are very small compared with seismic resolution or the scale of grids used in reservoir simulation models.

Joint frequencies from vertical wells are reliable where the joints are approximately evenly spaced (e.g. as revealed by deviated or horizontal wells), but may give unreliable results if joints are clustered. Variability in joint frequency is to be expected in vertical wells through a rock mass with a locally non-uniform distribution of joints. Another well a short distance away will intersect a different number of joints. The modelling presented here does, however, present the possibility of producing 'error bars' for potential variability in measured joint frequencies in each vertical well. For example, variations in joint frequencies obtained from deviated or horizontal wells can be used to predict variability in joint distributions along vertical wells, in the same way as the scanline was used to predict variability in joints along simulated wells in Section 5 (Fig. 6c). Such 'error bars' will allow improved correlation with seismic attributes, allowing improved models for joint distributions.

Sophisticated methods exist for developing 3D discrete fracture network models (e.g. Ezzedine and de Marsily, 1993). The method presented here is, however, a simple approach to test the variability and reliability of fracture data from wells. Further work is needed to expand the method to 3D fracture systems, which will enable improved correlations between well and seismic data, thereby allowing more sophisticated reservoir models.

7. Conclusions

A simple 1D model has been developed to simulate the variability that would be observed in the numbers of joints intersected by wells in a rock mass. The model indicates the following:

1. Variability in numbers of joints intersected by wells increases as the joints become less evenly spaced, i.e. as the joints become more clustered.
2. Much of the variability in joint frequencies observed in wells may be caused by variations in joint spacing that are smaller than the seismic resolution or the scale of grid blocks used for reservoir modelling. Unreliable results may therefore be obtained by correlating the frequencies of vertical joints from vertical wells with seismic attributes to develop a model for the distribution of joints across a field.
3. The modelling presented here allows variations in joint spacing obtained from deviated or horizontal wells to be used to predict the variability in joint frequencies from vertical wells. For example, strongly clustered joints observed in deviated or horizontal wells can be used to quantify the likelihood of a vertical well intersecting a cluster of joints. This would allow 'error bars' to be generated for joint frequencies from vertical wells, thereby improving correlations with seismic attributes and modelling of the distribution of joints within a reservoir.

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