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Models for guiding and ranking well-to-well correlations of channel bodies in fluvial reservoirs

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Abstract

A probabilistic method has been devised to assess the geologic realism of subsurface well-to-well correlations that entail the lateral tracing of geologic bodies across well arrays with constant spacing. Models of geo-body *correlability* (based on the ratio between correlatable and penetrated geo-bodies) are obtained from total probabilities of penetration and correlation, which are themselves dependent on the distribution of lateral extent of the geo-body type. Employing outcrop-analog data to constrain the width distribution of the geo-bodies, it is possible to generate a model that describes realistic well-to-well correlation patterns for given types of depositional systems. This type of correlability model can be applied for checking the quality of correlation-based subsurface interpretations, by assessing their geologic realism as compared with one or more suitable outcrop analogs. The approach is illustrated by generating total-probability curves that refer to fluvial channel complexes and that are categorized on the basis of outcrop-analog classifications (e.g. braided system, system with 20% net-to-gross), employing information from a large fluvial geo-body database (FAKTS) that stores information relating to fluvial architecture. From

these total-probability functions, values can be drawn to adapt the correlability models to any well-array spacing. The method has been specifically applied to rank three published alternative interpretations of a stratigraphic interval of the Travis Peak Formation (Texas, USA) previously interpreted as a braided fluvial depositional system, in terms of realism of correlation patterns as compared to (i) all analogs recorded in FAKTS and considered suitable for large-scale architectural characterization, and (ii) a subset of them including only systems interpreted as braided.

Introduction

For hydrocarbon reservoirs or aquifers that are composed principally of fluvial channel lithosomes, it is desirable to be able to realistically forecast the lateral continuity of sedimentary architectural elements when attempting well-to-well correlations. For this reason several predictive techniques have been proposed in past decades to improve the realism of models of subsurface fluvial sedimentary heterogeneity based on well-to-well correlation panels. For example, it is common to refer to empirical quantitative relationships that relate the lateral extent of channel bodies to their thickness (cf. Fielding and Crane 1987; Dreyer 1993; Mjøs and Prestholm 1993; Robinson and McCabe 1997; Reynolds 1999) or to interpreted paleo-hydrologic parameters of their formative channels (cf. Collinson 1978; Lorenz et al. 1985; Fielding and Crane 1987). One of the underlying themes of these two approaches is a requirement to inform subsurface models by variably making use of architectural data drawn from outcrop or modern analogs, i.e. ancient or modern sedimentary systems displaying sedimentary architecture that is thought to be comparable with the interpreted subsurface system. Another fundamental characteristic shared by these methods is that the information they provide is useful for assessing whether correlation of an individual channel lithosome results in a realistic reconstruction of likely lateral extension; likelihood is independently considered for each single channel unit, but no information is provided to guide correlations by quantifying the realism of heterogeneity patterns of the sedimentary succession as a whole. Therefore, although these approaches inform the lateral tracing of a channel body so that it results in a plausible lateral extent, they do not indicate whether the correlations carried out for all channel bodies in a succession result in a realistic distribution of channel-body lateral extents, i.e. they do not satisfactorily account for geometric variability.

In view of the limitations associated with such past approaches, the aim of this study is to illustrate a new method for guiding well-to-well correlations of fluvial channel bodies. Specific objectives are as follows: (i) to employ a large outcrop-analog database to further evaluate the usefulness and limitations of previously proposed approaches to well correlations of fluvial hydrocarbon reservoirs or aquifers; (ii) to present a new probabilistic method to guide the development of well-to-well correlation panels and to appraise their quality; (iii) to demonstrate the utility of the approach by ranking the geologic realism of three different interpretations of the same system based on the employment of different techniques for the correlation of the same well array.

In terms of the generic application of this type of approach to elucidate subsurface architecture, it is worth noting that, although the approach proposed here specifically refers to well correlation of fluvial channel complexes, the method can be generalized to sand-bodies formed in a variety of depositional environments (e.g. deep-water sand sheets), provided that an appropriate database of the lateral extent of such geo-bodies, as measured from reservoir analogs, is available.

Database

Given that established approaches to guiding subsurface correlations of fluvial channel bodies are based on the derivation of an expected value of width for each individual channel element by using relationships based on either geometry (channel-body thickness) or paleo-hydrology (the inferred depth or width of associated formative channels), this study further tests the applicability of such methods through application of a large architectural knowledge base: the Fluvial Architecture Knowledge Transfer System (FAKTS; Colombera et al. 2012a). Among other things, FAKTS includes geometric and (paleo-) hydrologic data relating to depositional elements that are defined on geometric rules and classified as channel complexes or floodplain units. The geometric criteria that need to be followed to distinguish individual channel complexes among amalgamated channelized deposits consider geometric change across the channel-cluster vertical extension, taking into account the interdigitation of floodplain deposits, mode and rate of change in the lateral extension of contiguous channel deposits along the vertical direction, and existence of lateral offsets where channel bodies are vertically stacked. As of February 2013, the database includes 3345 channel complexes to which geometric information is associated, obtained from 40 different case histories, representing mostly studies from the published literature. FAKTS channel complexes are objects whose geometry is typically lenticular in cross section, and is effectively described by thickness and width (cf. Colombera et al. 2013). Channel-complex width distributions are employed in this study to implement a new assessment of likelihood of correlation (here termed *correlability*, and based on the ratio between the number of likely correlatable and penetrated channel complexes) by making use of data that collectively refer to entire successions or parts thereof, rather than to single channel bodies.

Assessing past approaches to channel-body width prediction

Past correlation approaches are evaluated here with regard to information derived from a large architectural knowledge base (the Fluvial Architecture Knowledge Transfer System – FAKTS – Colombera et al., 2012a). It is not within the scope of this work to provide a full account of the relative merits and drawbacks of analog-based or paleohydrology-based approaches, and neither is this necessary since the principal pitfalls have already been discussed in detail by Bridge and Mackey (1993), Bridge and Tye (2000) and Miall (2006). Instead, this study further highlights the inadequacy of approaches based on relationships for the correlation of each single channel body by focusing once more on the wide architectural variability that might stem from adopting such methods without checking for independent constraints of geologic realism (e.g. resulting sandbody width distribution). This problem is emphasized by the considerable scatter observed in the architectural data presented here, which highlights the difficulty of reliably inferring channel-body width from the formative-channel bankfull depth, or of inferring formative-channel bankfull depth from the thickness of a channel sandstone body, or of inferring channel-body width directly from its thickness. For example, considering bankfull depths observed in the 7 to 23 m range, FAKTS channel-complex widths cover as much as four orders of magnitude (figure 1); overall the two variables yield a Pearson correlation coefficient of 0.341. The architectural database stores both the inferred (for rock-record cases) or measured (for modern river cases) bankfull depth of channels and the geometry of lower-scale units (architectural elements) contained within the channel complexes; since architectural-element thickness, in some cases, may relate to formative channel bankfull depth, some architectural elements whose thickness was interpretable as the entirely preserved thickness of the associated in-channel geomorphic element (barform) were therefore considered to estimate bankfull depth (cf. Bhattacharya and Tye 2004). With regard to the relationship between measured or inferred bankfull depths and channel-complex thickness (figure 2), FAKTS data do not fit well with the relationship given by Fielding and Crane (1987) in the form of *channel depth = 0.55 sandstone thickness*, or with a linear relationship altogether (application of a linear best fit to the full FAKTS dataset returns $R^2 = 0.0656$). The FAKTS channel-complex width-to-thickness scatterplot (figure 3) displays substantial scatter, even if only real widths are considered, with widths varying by three to four order of magnitudes for any corresponding value of thickness. Importantly, the power-regression best fit of all FAKTS channel-complex real-width data shows a significant discrepancy with the *most-likely case* predicted by Fielding and Crane (1987), especially for channel complexes that are thicker than 8 m.

Introducing a new probabilistic method: correlability models

The strict application of quantitative relationships of the type presented above (e.g. width vs. thickness equations), or even a flexible application of analog information (e.g. ranges in width-to-thickness aspect-ratio), would potentially lead to many correlation panels that are architecturally very different but equally plauible, given that they would equally honor geometric constraints.

To add a further constraint to well correlations, the approach taken in this study is not consider relationships that refer to individual elements that need to be correlated over several wells; instead relationships are considered that refer to either the sedimentary succession as a whole, or to specific portions thereof. In particular, this study introduces, explains and utilizes a set of probabilistic tools that can be employed to check the realism of a given fluvial reservoir or aquifer model, so that well correlations can be iteratively adjusted to match with a target quantity that describes the correlability (i.e. likelihood of correlation) of channel bodies over a given inter-well distance. Geometric data on which estimates of target channel-complex correlability are based can be selectively derived from a range of suitable analogs that match with the subsurface succession in terms of interpreted paleo-environmental or system-descriptive parameters (e.g. bankfull discharge, channel pattern). The employment of this approach, however, does not require paleo-environmental or paleo-hydrologic interpretation because it potentially only involves the use of relationships describing associated architectural properties of the preserved record (e.g. geometry and proportions as shown in a specific model below, in the section titled ‘A general probabilistic model based on channel-deposit proportions’).

In subsurface geo-body correlation workflows, the employed method should ideally integrate with other correlation techniques, such that it can be used in conjunction with expressions for estimating the lateral extent of individual bodies; for example, relationships linking channel-body thickness with range in width can be flexibly used to inform the lateral extent of any given sandstone body, provided the resulting width distribution ensures that the correlation panel matches the target correlability given by the model presented below. The approach can be used either to guide or evaluate a model in cases where well spacing is fixed. However, the approach does not provide constraints with which to inform decisions on the tracing of individual sandbodies across adjacent wells at the time that these decisions are being made. Rather, the method can be used to perform *a posteriori* checks of the resulting correlation panels, which can then be iteratively modified by revising correlations to progressively minimize the panel discrepancy from the correlability model. Later in this work, a case example of how this approach can be implemented is illustrated through application to a set of previously-interpreted correlation panels; this illustrates how the technique can be used to perform an example quality check.

Total probability of penetration of a randomly selected channel-complex

The procedure employed herein to guide or rank a correlation framework is based on knowledge of the following: (i) the proportion of channel complexes that are likely penetrated (or equivalently the total probability of penetration of a randomly-chosen channel complex) by a well array with given spacing S; (ii) the proportion of channel complexes that are likely correlatable (or equivalently the total probability of correlation of a random channel complex) over variable inter-well distance (i.e. S, 2S, 3S…), for any channel-complex width distribution. Thus, the adopted approach first obtains the expression for the total probability of channel-complex penetration for a known channel-complex width distribution. Width distributions represent the analog data with which correlation panels need to be compared.

The conditional probability (P) of penetration (p) of a channel-complex of width W for penetration angle θ and well spacing S (figure 4) can be described by the relation given by McCammon (1977) for parallel-line search of a dike by geophysical surveys; for $W \leq S$:

$$P(p/\theta) = \left(\frac{W}{S}\right) \sin\theta$$

the unconditional probability can be written as:

$$P(p) = (2/\pi)(W/S) \int_0^{\pi/2} \sin\theta \, d\theta$$

Although the method can be utilized for any angle of well penetration, for the sake of simplicity this study only considers penetration in an orientation that is orthogonal to floodplain paleo-surfaces, in which case θ = π/2:

$$P(p) = \left(\frac{W}{S}\right)$$

So, the conditional probability of channel-complex penetration for width W can be expressed as follows (cf. figure 5):

$$P(p/w) = \begin{cases} \left(\frac{W}{S}\right) & \forall\, W \leq S \\ 1 & \forall\, W > S \end{cases}$$

Now, the method requires determination of a value of total probability of penetration by a well array of spacing S of a fluvial reservoir with channel-complexes that follow a width distribution with a probability density function *P(w)*; the total probability theorem is then applied:

$$P(p) = \int_{\bar{w}} P(p/w) P(w) \, dw$$

So, the total probability of penetration of a randomly chosen channel-complex (equivalent to the non-volumetric proportion of channel-complexes penetrated) is given by (cf. figure 6):

$$P(p) = \int_0^S \left(\frac{w}{S}\right) P(w)\, dw + \int_S^{W_{max}} P(w)\, dw$$

Database analysis (e.g. figure 7) reveals that for channel-complexes $P(w)$ is typically adequately described by log-normal probability density functions, which take the form:

$$P(w) = (\frac{1}{w\sigma\sqrt{2\pi}})e^{-\frac{(\ln w-\mu)^2}{2\sigma^2}}$$

where μ is the location parameter and σ is the scale parameter of the channel-complex width distribution (parameters μ and σ represent the mean and standard deviation of the natural logarithm of the width, respectively).

For such width distributions the total probability of channel-complex penetration *P(p)* is given by:

$$P(p) = \int_0^S \left(\frac{w}{S}\right) (\frac{1}{w\sigma\sqrt{2\pi}})e^{-\frac{(\ln w-\mu)^2}{2\sigma^2}}\, dw + \int_S^{W_{max}} (\frac{1}{w\sigma\sqrt{2\pi}})e^{-\frac{(\ln w-\mu)^2}{2\sigma^2}}\, dw$$

By operating the definite integral, it is then possible to obtain relationships describing the total probability of penetration for channel complexes belonging to specific fluvial types (i.e. characterized by specific probability density functions) as a function of well spacing S.

From the example given in figures 7 and 8, it is apparent how the choice of the type of synthetic analog (in this particular case, a generic non-categorized fluvial system that includes all FAKTS data, figure 7a, or an ideal fluvial facies model based on FAKTS systems classified as braided, figure 7b) will eventually affect the model describing the total probability of penetration as a function of well spacing (figure 8). It is important to note that the total probability is not representative of a volumetric proportion, but only of the ratio between the number of geometrically defined fluvial channel bodies that are penetrated and the total number of bodies along the section.

Total probability of correlation of a randomly selected channel-complex

Just as the expected proportion of channel complexes penetrated by the well array can be quantified by the total probability of penetration, the proportion of channel complexes that are correlatable between two wells is also quantified by a measure of total probability. To obtain the total probability of *correlation* of a randomly selected channel complex, a method is first employed to obtain the expression for the conditional probability of channel-complex correlation between two adjacent wells for complex width W. Relations by McCammon (1977) are used to obtain the following:

for $\theta = \frac{\pi}{2}\ and\ W \leq S$: $P(c) = 0$;

for $\theta = \frac{\pi}{2}$ $and\ W \geq 2S\colon P(c) = 1;$

for $\theta = \frac{\pi}{2}$ $and\ S \geq W \leq 2S\colon P(c) = \left(\frac{W}{S}\right) - 1$

where θ remains the penetration angle and S the distance between two wells.

So, the conditional probability (P) of channel-complex correlation (c) for width W can be expressed as follows (orange dashed curve in figure 9):

$$P(c/w) = \begin{cases} 0 & \forall\, W \leq S \\ \left(\dfrac{W-S}{S}\right) & \forall\, S < W < 2S \\ 1 & \forall\, W \geq 2S \end{cases}$$

Again, to obtain a value of total probability of channel-complex correlation (i.e. proportion of correlatable channel complexes) between two wells of spacing S in a fluvial reservoir with channel-complexes following a width distribution with probability density function *P(w)*, the total probability theorem is applied:

$$P(c) = \int_{\bar{w}} P(c/w) P(w)\, dw$$

So, the total probability of correlation between a pair of wells spacing S of a randomly chosen channel-complex (i.e. the non-volumetric proportion of channel-complexes correlatable) is given by (hatched area in figure 9):

$$P(c) = \int_0^S 0 \cdot P(w) dw + \int_S^{2S} \left(\frac{w-S}{S}\right) P(w) dw + \int_{2S}^{W_{max}} P(w)\, dw$$

Then:

$$P(c) = \int_S^{2S} \left(\frac{w-S}{S}\right) P(w) dw + \int_{2S}^{W_{max}} P(w)\, dw$$

For a fluvial reservoir with channel-complex widths following a log-normal distribution the total probability of channel-complex correlation between two wells of spacing S is given by:

$$P(c) = \int_S^{2S} \left(\frac{W-S}{S}\right) \left(\frac{1}{w\sigma\sqrt{2\pi}}\right) e^{-\frac{(\ln w - \mu)^2}{2\sigma^2}} dw + \int_{2S}^{W_{max}} \left(\frac{1}{w\sigma\sqrt{2\pi}}\right) e^{-\frac{(\ln w - \mu)^2}{2\sigma^2}}\, dw$$

By operating the definite integral, it is then possible to obtain relationships describing the total probability of correlation for channel complexes belonging to specific fluvial types (i.e. characterized by specific probability density functions) as a function of correlation distance S.

Again, it is evident how differing width distributions, associated with different types of synthetic analogs, will result in differences in the models that describe the total probability of correlation as a function of inter-well correlation distance (figure 10).

Comparison between probability-based models and subsurface interpretations: a quality check

Once knowledge of total probability of penetration and correlation is obtained for a suitable field analog or database-informed synthetic analog (i.e. composite set of quantitative information distilled from several analog case studies; cf. Colombera et al. 2013), it is possible to draw from the curves (i) values of total probability of penetration for the given well spacing and (ii) total probability of correlation for each integer multiple of the well-spacing (figure 11a, b). Then, operating the ratio between the values of total probability of correlation and the total probability of penetration (figure 11c) it is possible to obtain values that quantify the proportion of penetrated channel complexes that are correlatable over a given distance. If these values are plotted as a function of inter-well distance (figure 11c), a curve describing the proportion of penetrated channel bodies that are likely to be correlatable as a function of correlation distance is obtained: this curve will represent the model of correlability against which to test interpretations. This curve can then be plotted together with an analogous curve including the ratios between correlated and penetrated channel complexes, as represented in the panel that is being checked, for all admissible inter-well distances. A first-order comparison between the model of correlability and the subsurface interpretation can be carried out graphically, allowing for recognition of the degree of approximation of the interpretation to the model and whether the interpretation is too conservative or excessively confident (figure 11d, e). Numerically, the degree of approximation of the subsurface interpretation to the correlability model is quantified by a value of cumulative discrepancy, given by the sum of the absolute values of the panel-model discrepancy at each correlation distance: this particular score can be used to rank several alternative correlation panels in terms of geologic realism (inversely proportional to the score), as illustrated in the case study example application below.

Necessarily, the main limitations of the approach lie in the uncertainty connected with the quality of the primary data incorporated in the correlability models, and in the confidence of the degree to which the supposed analogs could match with the subsurface system of interest.

To further explain how the method could be implemented in likely subsurface workflows, it is necessary to highlight several significant points:

- the proposed approach can be independently applied for different stratigraphic intervals of a subsurface succession, employing different correlability models on the assumption that channel-complex width distributions exhibit stationarity in those intervals;
- for a given panel, different realizations resulting from different well-correlation outcomes may attain the same score of cumulative discrepancy from the correlability models, i.e. are equally ‘realistic’, and the number of such realizations will generally increase with number of penetrated channel complexes and wells;
- the same correlation panel can be checked against different correlability models (e.g. a model based on fluvial-fan successions, or a model for 30% net-to-gross), provided that these different models are based on data from suitable analogs.

In view of this last point, it is also of fundamental importance to note that if the same correlation panel is checked against different correlability models that each incorporate different types of analogs, different scores of cumulative discrepancy are likely to be attained (see next section for an example). If these models are based on equally valid analogy between outcropping successions (or modern rivers) and subsurface systems, the variability in correlability across the models would quantify the uncertainty intrinsic in the method. Specifically, if the correlation panels have been adjusted such that the sum of the different cumulative-discrepancy scores is minimized, then the variability in cumulative-discrepancy scores can be used to effectively quantify the uncertainty inherent in considering those scores as quantifiers of geologic realism. It is, however, important to note that a single correlability model could be obtained that matches with the subsurface case study in terms of all available constraints on its architecture, its depositional system parameters and its controls (e.g. correlability model based on all fluvial systems classified as having net-to-gross in the range 20%-30%, being interpreted as embodying river systems with meandering channel pattern, and accumulated under the influence of a wet climate): although this model is expected to embody the closest match with the subsurface case study, it would incorporate reduced variability in sandbody size compared to models based on individual classes of depositional systems, as only analogs matching all the types of analogy would be considered. The amount of data (number of width measurements, number of analogs) included in a model is itself a quantifier of its general value.

It is of paramount importance to only consider the proposed method as a way to quantify geologic realism by comparison against analogs: subsurface practitioners are not supposed to revise well correlations to attain ‘zero’ cumulative discrepancy between correlation panels and correlability models, if this entails lateral geobody correlations that violate geologic rules or constraints (e.g. generation of unrealistic surface gradients).

Case study example application: ranking alternative correlation panels for the subsurface Travis Peak Formation (Texas, USA)

To illustrate an application of this method, it is here used to rank the likelihood of three alternative architectural interpretations proposed by Tye (1991), Bridge and Tye (2000) and Miall (2006) for the same well array, through a stratigraphic interval (Zone 1) of the lower Cretaceous Travis Peak Formation, East Texas (figure 12). In this area, the Travis Peak Formation comprises rocks interpretable as deposited in the context of fluvial and paralic depositional systems (Tye et al. 1989; Dutton et al. 1991; Davies et al. 1993). Variable architectural styles of the fluvial systems have been recognized and related to planform evolution; both high-sinuosity and braided planform types have been interpreted. The interval to which the three correlation panels refer has been interpreted as a dominantly braided fluvial depositional system (cf. Tye 1991; Davies et al. 1993). This dataset was chosen because it is a good published example of different models of fluvial subsurface architecture based on the adoption of different sets of assumptions. However, it is not necessarily the most suitable dataset for the method; first of all, the log interpretation resulting in attribution to channel or floodplain deposits differs slightly for the different panels; moreover, it is necessary to assume that the wells were equally spaced (spacing = 1.54 km) as depicted in figure 12 even though the actual spacing varies between 0.8 and 2.2 km. This last shortcoming has been ignored in the following discussion as this dataset is used merely to illustrate a potential application of the method. However, this limitation could be overcome by either subdividing the correlation panel into segments or by evaluating the approximation of the correlation panel to the model only on a qualitative basis in the form of graphical comparison, as explained at the end of this section.

The proposed method is used here to quantitatively rank the realism of the different interpretations, but could equally fit in a subsurface correlation workflow: practitioners would correlate the sandbodies following established criteria (e.g. as given by Bridge and Tye 2000; and Miall 2006), would check the resulting discrepancy that the panel correlations exhibit from the correlability model, and would revise correlations accordingly, i.e. to minimize the cumulative discrepancy and the discrepancy for any value of correlation distance.

The correlability technique described above is applied to this dataset in order to rank the deterministic models by identifying which of these panels represents the most realistic subsurface fluvial architecture by comparison with an ideal channel-complex width distribution obtained by (i) all FAKTS analogs or (ii) a synthetic analog based on many systems matching the dataset in terms of interpreted planform type (i.e. braided river), so that discrepancies between the results obtained from assuming each of the two types of analogy can also be assessed. Thus, probability density functions describing channel-complex width have been obtained as follows:

- extracted from all analogs contained in the FAKTS database and considered suitable for deriving geometric output (figure 7a);
- extracted from all FAKTS analogs interpreted as representing braided fluvial systems and considered suitable for derivation of required geometric output (figure 7b).

Curves describing the total probability of penetration (figure 8) and correlation (figure 10) have been obtained for the two types of synthetic analogs, and from these values of total probability of penetration for S = 1540 m and total probability of correlation for S and multiples of S were derived. This enables a correlability model based on total probabilities to be plotted as the ratio between total probability of correlation and total probability of penetration for S and its multiples.

The definition of subsurface units must match with the definition of outcrop-analog units. So, the channel bodies depicted in the panels (figure 12) have been subdivided geometrically in agreement with the definition of a channel-complex adopted for the FAKTS database, to ensure that results are comparable with correlability models based on width probability density functions derived from the database. Next, the ratio between the number of correlated channel-complexes and the number of channel-complexes in each panel was computed for multiples of S (up to 7S = 10780 m, for which no channel-complex is correlatable in any of the three panels). Resulting ratios relating to the subsurface interpretations were plotted together with the correlability model based on FAKTS analogs for graphical comparison against correlation distance (figure 13a). This plot permits a straightforward quantitative comparison of the difference between the two correlability models, in terms of proportion of penetrated channel complexes that are likely correlatable over a given distance. Crucially, from this plot it is evident how, compared to either of the other two models, the interpretation by Tye (1991) consisted of lateral correlations that were considerably too optimistic. To facilitate comparison and quantification of the discrepancy between the subsurface interpretations and each of the two correlability models (i.e. all analogs vs. braided systems), the difference between the ratio of correlated and penetrated channel complexes for the interpretation and for the model was also plotted independently for the two models (figure 13b, c). The total discrepancy can then be measured as the sum of the absolute values of the discrepancy at each correlation distance (S to 7S, in this example) to rank the subsurface interpretations in terms of geologic realism. The interpretation panels by Bridge and Tye (2000) and Miall (2006) show comparable results: they both appear to be overly optimistic with well correlations, especially over a single well spacing (i.e. between adjacent wells), and have similar values of discrepancy (0.36 and

0.24, respectively, as evaluated against the all-analogs correlability model). The interpretation panel by Miall (2006) has the lowest total discrepancy values (0.24 and 0.40, as evaluated against the all-analogs and braided models respectively) and therefore ranks highest when compared with both correlability models (see Fig. 13b and 13c).

The same results that have been used here to illustrate the method of quality-checking could be used to inform the correlation panel through iterative adjustment of the interpretations until the panel matches realistic correlation patterns.

Further insight into the realism of the subsurface reconstructions is offered by channel-complex width-to-thickness scatterplots (figure 14), which permit comparison of the dimensions of subsurface channel bodies with the geometry of FAKTS' outcrop analogs. However, because the thickness values associated with well data are obtained from one-dimensional sampling the significance of the comparison is limited, chiefly because channel-complex thicknesses recorded in the FAKTS database refer to maximum thickness, and the thickness of these bodies can be highly variable laterally. In addition, and differently from correlability models, these plots do not permit a quantitative assessment of the effect of the statistical sampling of channel-complex geometries by the well array (i.e. the plots do not exclude geometries associated with channel complexes that are likely non-penetrated). Nevertheless, in case of wide inter-well spacing, these plots can be useful for qualitatively adjusting the likely position of pinch-out of channel bodies between two wells; this could be achieved by narrowing individual sandbodies that plot outside of the analog data-point cloud.

If the approach is followed to guide interpretations, additional attributes that can be inferred in subsurface correlation-based reconstructions are: (i) the percentage (as fractional number) of channel-complexes that are not yet penetrated by the array of wells, which coincides with '1 - total probability of penetration'; (ii) the expected width distribution of those channel complexes, given by the difference between the analog channel-complex width probability density function and the curve obtained as the product between the same probability density function and the conditional probability of penetration. From this information volumetric proportions of non-penetrated channel complexes can then be estimated by relating widths to likely thickness, for example by following common empirical relationships (e.g. Collinson 1978; Fielding and Crane 1987).

Well configurations characterized by constant inter-well distance are common (e.g. He et al. 2013), making this approach of direct use for such situations. Whenever the condition of constant well spacing is not applicable, if there exist adjacent stratigraphic portions within which inter-well distance is roughly constant, the quality-check method presented here could be applied separately for different segments. Instead, if the well spacing is highly variable, correlability models could be obtained for the maximum and minimum values of well spacing, in order to identify a confidence interval – rather than a single correlability curve – with which subsurface interpretations could be compared, for example in terms of discrepancy between the underlying area and the curve given by the ratio between correlated and penetrated units plotted for the average spacing, or even just graphically.

It is noteworthy that if the type of panel-model comparison shown here was carried out against a range of correlability models compiled on data from alternative analogs, and the correlation panels were revised to minimize the sum of the different cumulative-discrepancy scores, then the variability in cumulative discrepancy would offer insight into the uncertainty associated with the method. However, it is necessary to stress that this would only be valid under the assumption that different successions or rivers (or synthetic analogs compiled from the synthesis of information from various case studies; cf. Colombera et al. 2013) could be considered as equally valid analogs to the subsurface succession of interest, which is debatable. A complex interplay of autogenic and allogenic controls act on the wide geometric variety exhibited by fluvial-channel sandbodies, and knowledge-related uncertainty is inevitably associated with the interpretation of a subsurface depositional system (e.g. in terms of depositional setting), with the interpretation of outcropping analogs, and with the degree to which analog sedimentary architecture can be considered a match to subsurface architecture. Each of these factors need to be taken into account in both the application and the validation (e.g. through testing of total-probability curves through outcrop-analog studies) of the proposed method.

A general probabilistic model based on channel-deposit proportions

Total-probability-based models of channel-complex correlability such as the ones presented for braided systems (figure 13a, c) can be customized on any fluvial environmental type (e.g. fluvial coastal plain meandering system developed under the influence of a sub-humid climatic regime; cf. Colombera et al. 2013), provided that a channel-complex width distribution is available. Furthermore, these models can be constructed on architectural properties that are distinctively associated with a given distribution of channel-complex width; it is therefore useful to be able to generate models categorized on properties that can directly be derived from interpreted well data, such as the relative proportion of channel and floodplain deposits.

In the FAKTS database, stratigraphic volumes within a succession are distinguished whenever different classifications of system descriptive parameters or boundary conditions can be assigned (Colombera et al. 2012a). These volumes do not refer to a standard spatial or temporal scale, but they are typically tens of meters thick for case studies that are considered suitable for investigation at the channel-complex scale. So, for each volume for which at least two-dimensional information is available, both descriptive statistics (figure 15) of channel-complex width and the proportion of channel complexes, as based on the product of their thickness and lateral extent have been computed. Such information is useful *per se* as a general constraint to inform well-to-well correlations for adjacent stratigraphic zones with variable channel proportions, but has greater predictive potential if it is incorporated into a correlability model.

By considering only the highest-quality datasets (well exposed outcrop analogs for which comprehensive datasets captured as a product of direct observation are available), empirical relationships linking the mean and standard deviation of channel-complex width with the proportion of channel deposits within each volume can be obtained (figure 15b, c). As would be expected, the average lateral extent of the channel complexes shows a positive relationship with channel-complex proportion, since FAKTS channel complexes are geometrically defined channel bodies, and forms of channel-body amalgamation, including lateral stacking, are expected to become more frequent with increased channel-deposit proportion, regardless of the autogenic or allogenic driver of the change in proportion. It is important to note that some high-quality datasets derived from studies of outcrop analogs with great lateral extent and continuity of exposure (of which channel-complex mean widths are included in figure 15a) are not accounted for by the equations in figure 15b-c, and that the inclusion of all suitable analogs would return a relationship that would predict higher mean widths, especially for low channel-deposit proportions, ultimately suggesting overly optimistic well-penetration and correlation total probabilities.

The empirical relationships derived from exponential regression of the highest-quality datasets are given by:

$$meanW = 42.4e^{3.9P}$$

$$stdevW = 40.7e^{3.8P}$$

where P refers to the proportion of channel deposits and W to the channel-complex width.

Assuming that a log-normal distribution adequately describes channel-complex width distribution for any proportion in the range 10 to 90%, it is possible to express location and scale parameters as a function of proportions, since these parameters are related to width mean and standard deviation:

$$\mu = 2\ln(42.4e^{3.9P}) - \left(\frac{\ln((42.4e^{3.9P})^2 + (40.7e^{3.8P})^2)}{2}\right)$$

$$\sigma = \sqrt{\ln((42.4e^{3.9P})^2 + (40.7e^{3.8P})^2) - 2\ln(42.4e^{3.9P})}$$

These values have been used to obtain probability density functions that are employed for calculating total probabilities of channel-complex penetration (figure 16a) and correlation (figure 16b) by a well array in stratigraphic volumes with channel-deposit proportions variable between 10% and 90%. The resulting models are limited by the assumption of width distributions being log-normal for any value of proportions; however, groups of stratigraphic volumes with variable channel-deposit proportions can be separately analyzed to gain insight into the type of distributions that best describe channel-complex widths in any range of proportions, thereby allowing for a refinement of the total probability curves. Nonetheless, a FAKTS stratigraphic volume containing 32 channel complexes composing 86% of its volume returned a channel-complex width distribution satisfactorily described by a log-normal curve, suggesting that the assumption is reasonable even for high net-to-gross successions. These curves can then be used to generate, for a given well-spacing, a correlability model similar to the ones presented above (i.e. by operating ratios of proportions of correlated and penetrated channel-complexes, as drawn from the curves). The resultant correlability model can then be used to tentatively predict correlation statistics for cases in which only channel-deposit proportion and well-array spacing are known.

It is important to reiterate, once again, that the curve in figure 16b refers to channel-complexes defined on a set of geometric rules (see ‘Database’ section) and that can be variably stacked. Consequently, this curve includes data drawn, for example, from vertically-juxtaposed channel complexes that may be solely distinguished on the recognition of discontinuously-interfingered floodplain deposits: a significant implication is that the curve of total probability of correlation as a function of distance cannot therefore be considered simply in terms of lateral connectivity. In practice, it may be deemed useful to consider dimensional attributes that describe the geometry of interconnected reservoir-quality rocks; using the same database this could be done by quantifying the effect of the juxtaposition of units of the same type on the dimension of the composite bodies (cf. material units of Colombera et al. 2012b). Also, in this specific example, a more readily applicable – and arguably more useful – quality check for subsurface interpretations of systems characterized by a very high proportion of channel deposits would be given by correlability models for fine-grained floodplain units.

Conclusions

The difficulty in developing readily applicable methods to realistically capture the lateral extent of sedimentary bodies when applying deterministic well correlations is still perceived as a major limiting factor for better constraining models of reservoir characterization (cf. Borgomano et al. 2008). The method presented here makes use of total probabilities of well penetration and correlation for guiding and quality-checking subsurface interpretations based on well-to-well correlations of fluvial channel lithosomes, given *a priori* knowledge of a realistic distribution of their lateral extent (in the form of probability density functions) and a well array with constant spacing. The likelihood of the subsurface interpretation is assessed by comparison with dimensional parameters obtained by outcrop analogs not just by considering the most likely width of individual geologic units, but by ensuring geologic realism for the whole succession through consideration of sandstone-width variability. Thus, the approach is not necessarily alternative to, but rather integrative with previous methods based on the use of empirical relationships for deriving channel sandstone body widths from paleo-hydrologic interpretations or measured thicknesses.

The approach illustrated here for channel complexes has general value: it can be applied to the correlation of any geologic units (e.g. deep-water channels, sand sheets, carbonate shoals), provided that a realistic description of their lateral extent can be obtained in the form of a probability density function. This consideration has implications concerning the need for extensive and good-quality outcrop-analog data that are essential for the practical application of this sort of correlability model to subsurface reservoir prediction.

Ranking interpretations by comparing geologic-body correlability with reference patterns can be especially useful if different correlation frameworks equally reproduce geologically-sensible scenarios in terms of depositional features (e.g. distribution of interpreted sub-environments, paleo-surface gradients), and the method can also be used to independently rank stochastic well correlations that involve the lateral tracing of geologic bodies (cf. Lallier et al. 2012), and computer-assisted correlations in general.

The usefulness of the method can be enhanced by generalizing it through reformulation of the expressions of total probabilities of penetration and correlation to account for different angles of well penetration, and by implementing the method as a software-based predictive tool.

Future work is needed to assess the value of correlability models by validating their predictions against outcrop analogs, as these provide the opportunity to benchmark the total-probability curves on which the models are based.

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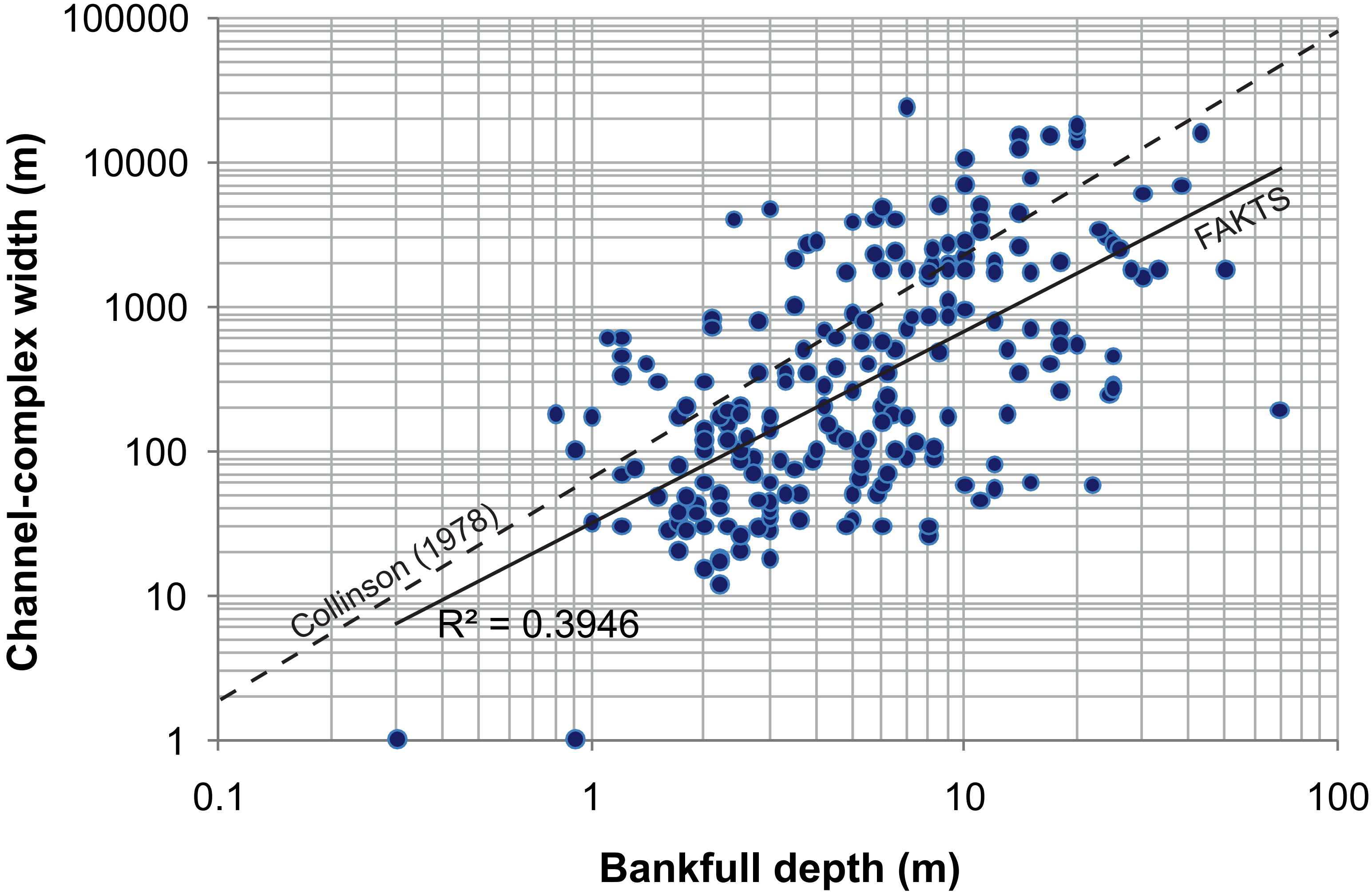
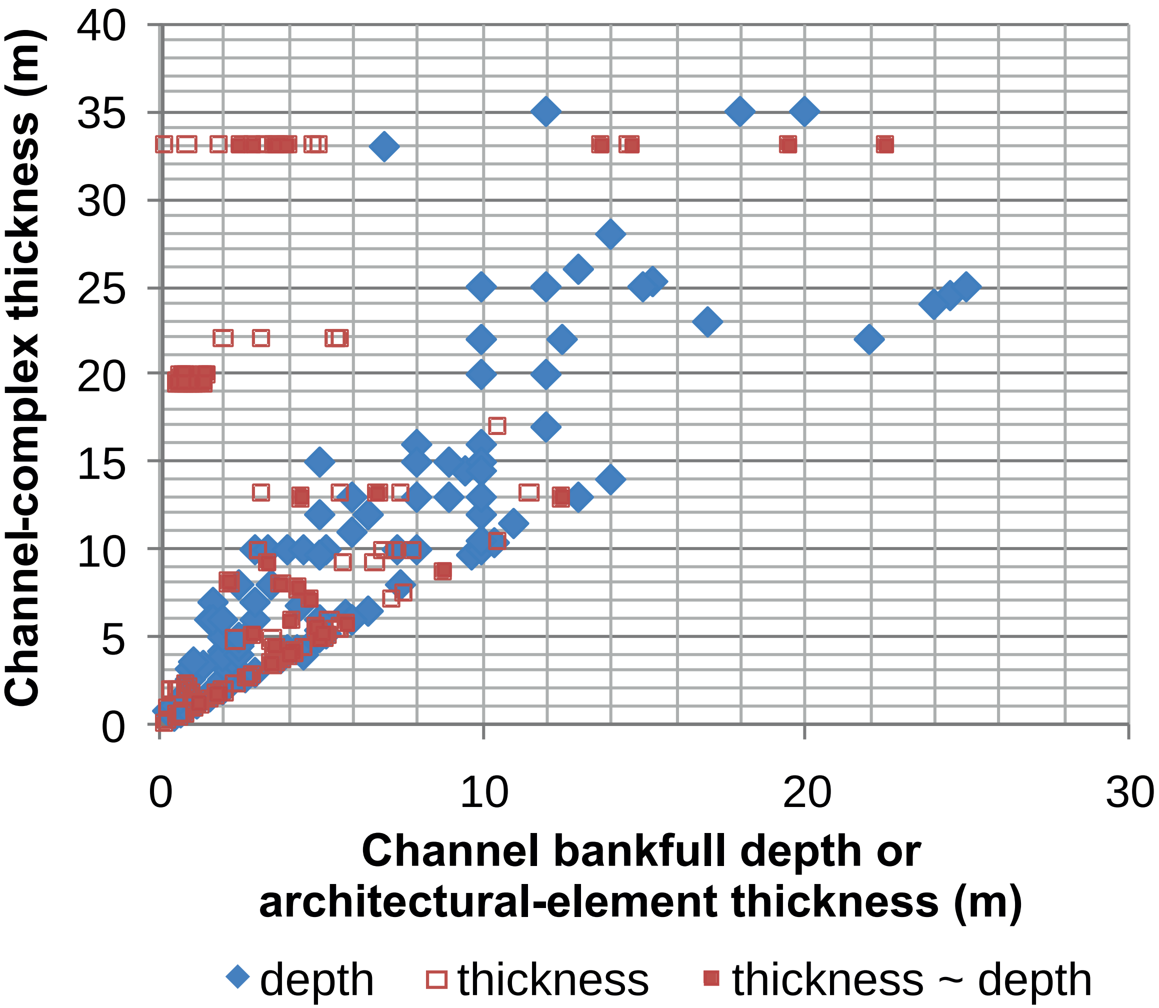

100000
10000
1000
100
10
1
Channel-complex width (m)
0.1
1
10
100
Bankfull depth (m)
Collinson (1978)
FAKTS
R² = 0.3946

FIGURE 1



Channel-complex thickness (m)
0
5
10
15
20
25
30
35
40
0
10
20
30
Channel bankfull depth or architectural-element thickness (m)
◆ depth
□ thickness
■ thickness ~ depth

FIGURE 2

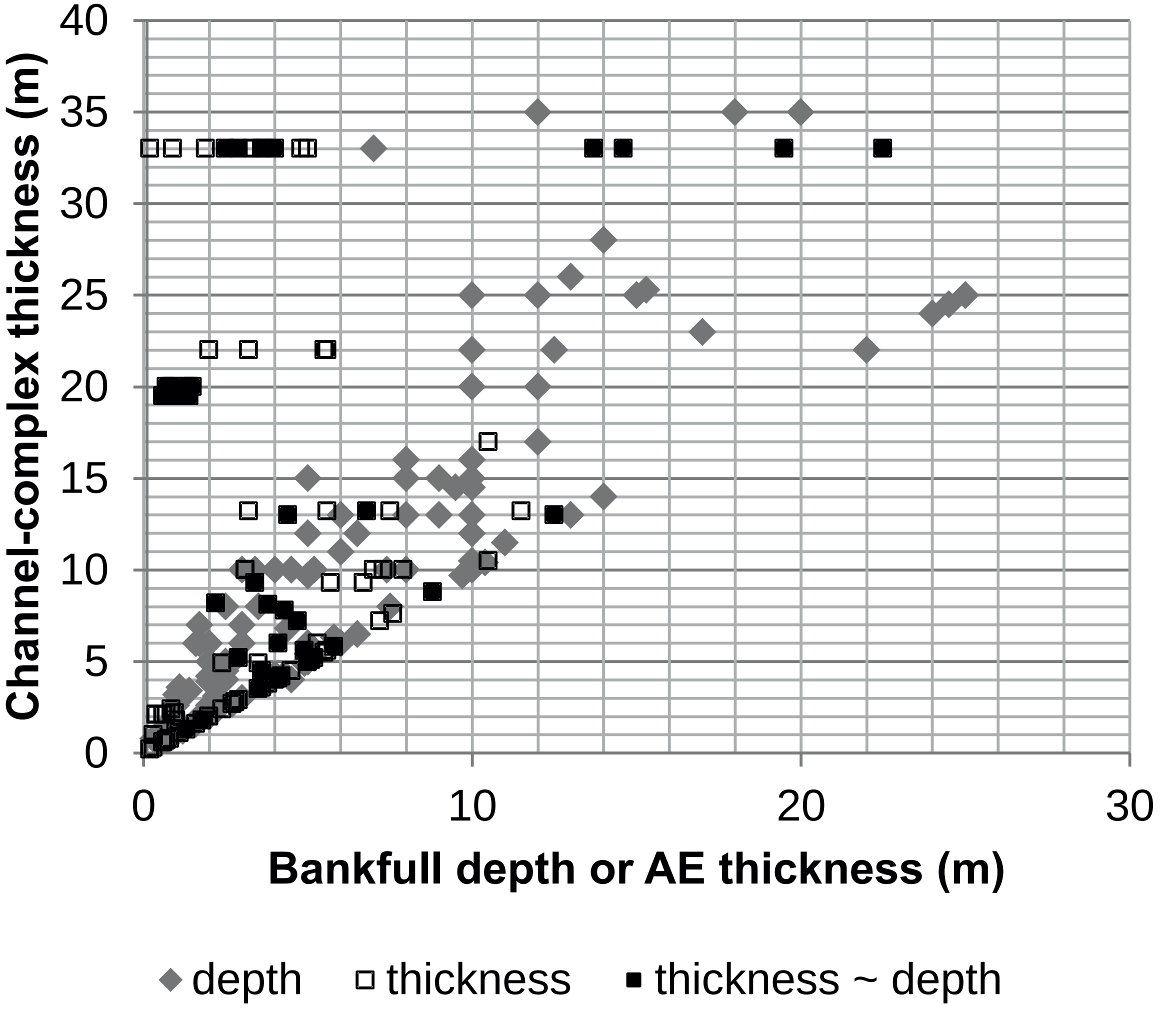
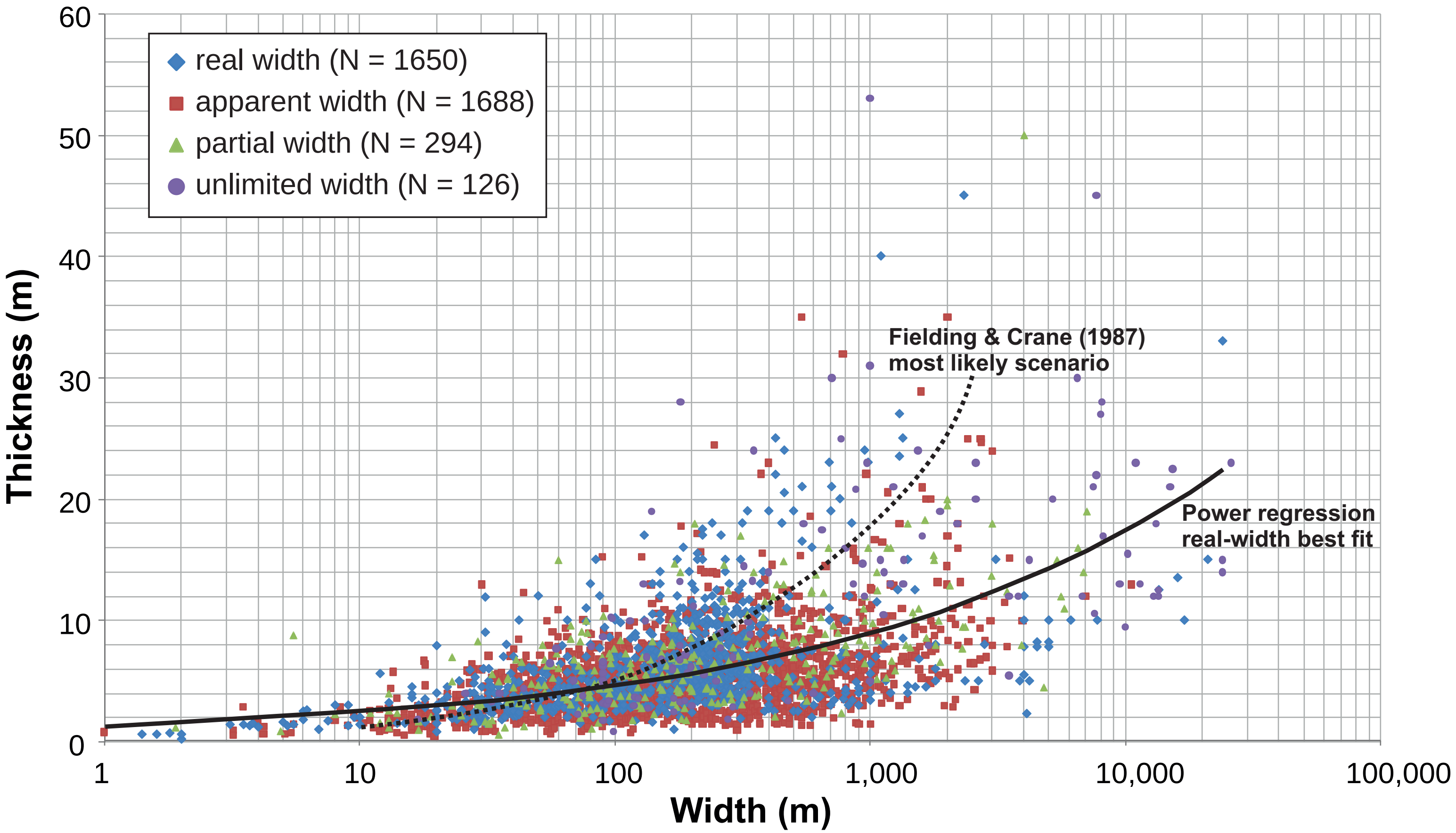

Channel-complex thickness (m)
40
35
30
25
20
15
10
5
0
0
10
20
30
Bankfull depth or AE thickness (m)
◆ depth
☐ thickness
■ thickness ~ depth

FIGURE 2 (b/w)



60
50
40
30
20
10
0
Thickness (m)
◆ real width (N = 1650)
■ apparent width (N = 1688)
▲ partial width (N = 294)
● unlimited width (N = 126)
Fielding & Crane (1987)
most likely scenario
Power regression
real-width best fit
1
10
100
1,000
10,000
100,000
Width (m)

FIGURE 3

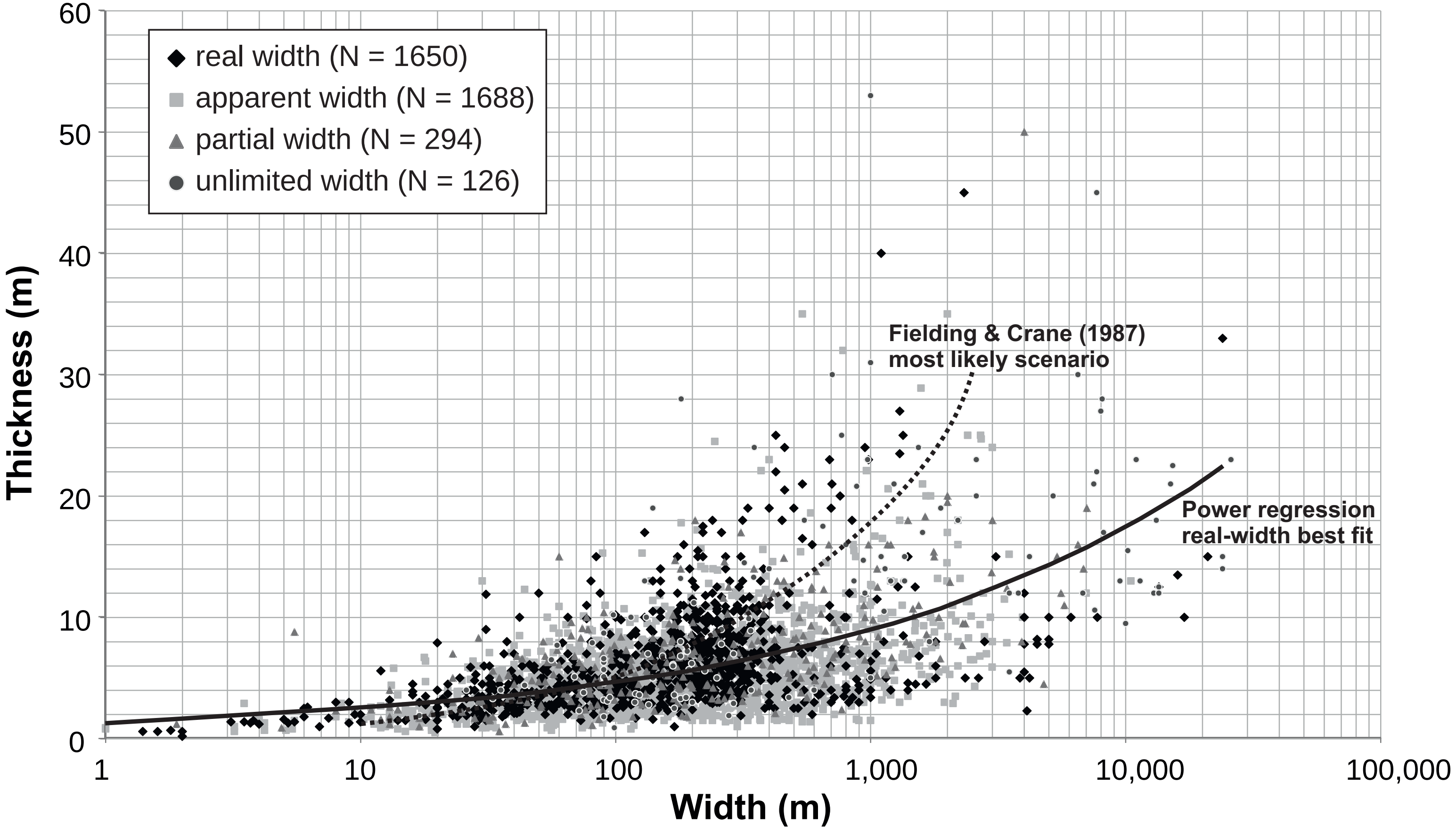

60
50
40
30
20
10
0
Thickness (m)
◆ real width (N = 1650)
■ apparent width (N = 1688)
▲ partial width (N = 294)
● unlimited width (N = 126)
Fielding & Crane (1987) most likely scenario
Power regression real-width best fit
1
10
100
1,000
10,000
100,000
Width (m)

FIGURE 3 (b/w)

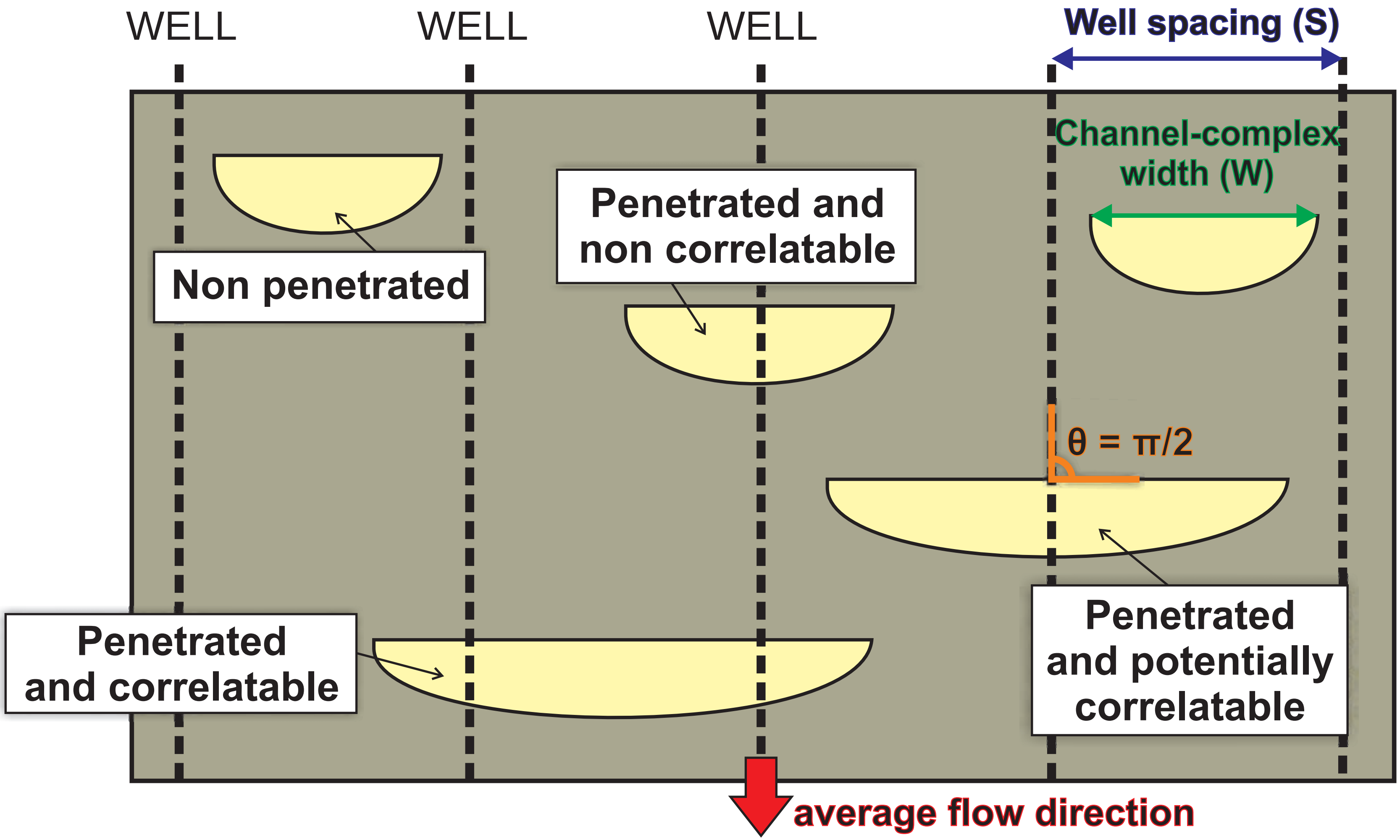

WELL
WELL
WELL
Well spacing (S)
Channel-complex width (W)
Non penetrated
Penetrated and non correlatable
θ = π/2
Penetrated and correlatable
Penetrated and potentially correlatable
average flow direction

FIGURE 4

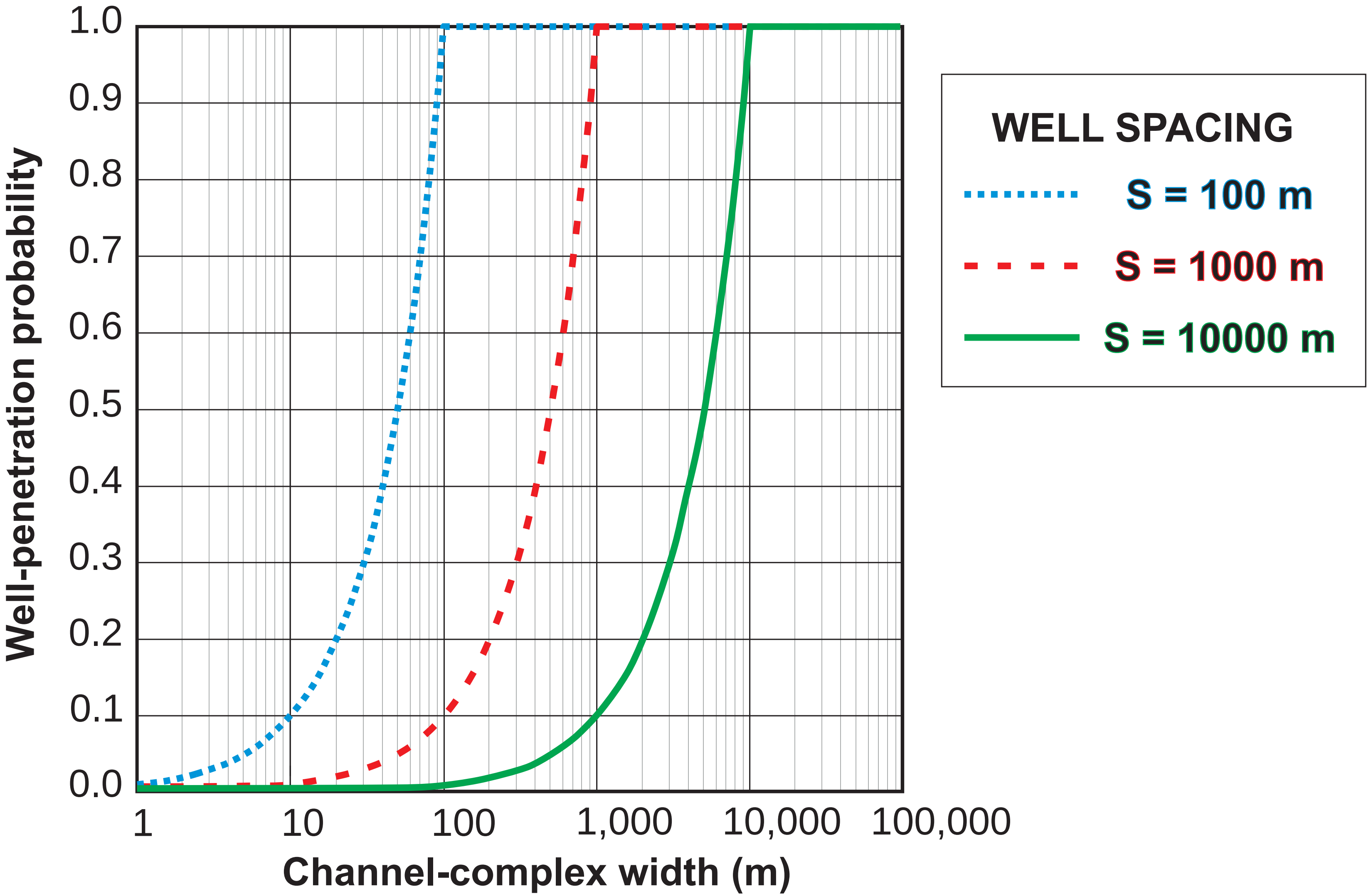

1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Well-penetration probability
1
10
100
1,000
10,000
100,000
Channel-complex width (m)
WELL SPACING
S = 100 m
S = 1000 m
S = 10000 m

FIGURE 5

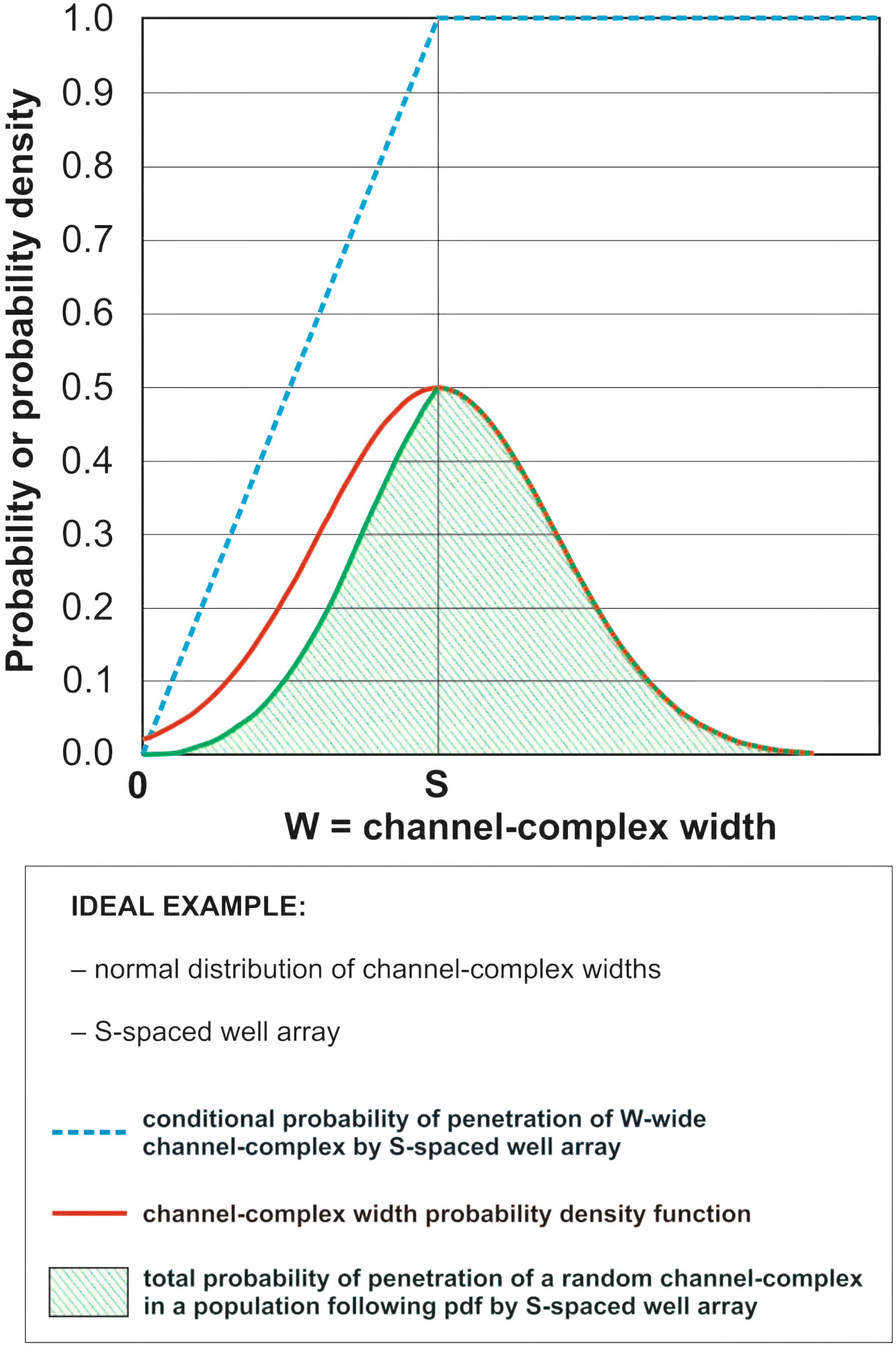

1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Probability or probability density
0
S
W = channel-complex width
IDEAL EXAMPLE:
– normal distribution of channel-complex widths
– S-spaced well array
conditional probability of penetration of W-wide channel-complex by S-spaced well array
channel-complex width probability density function
total probability of penetration of a random channel-complex in a population following pdf by S-spaced well array

FIGURE 6

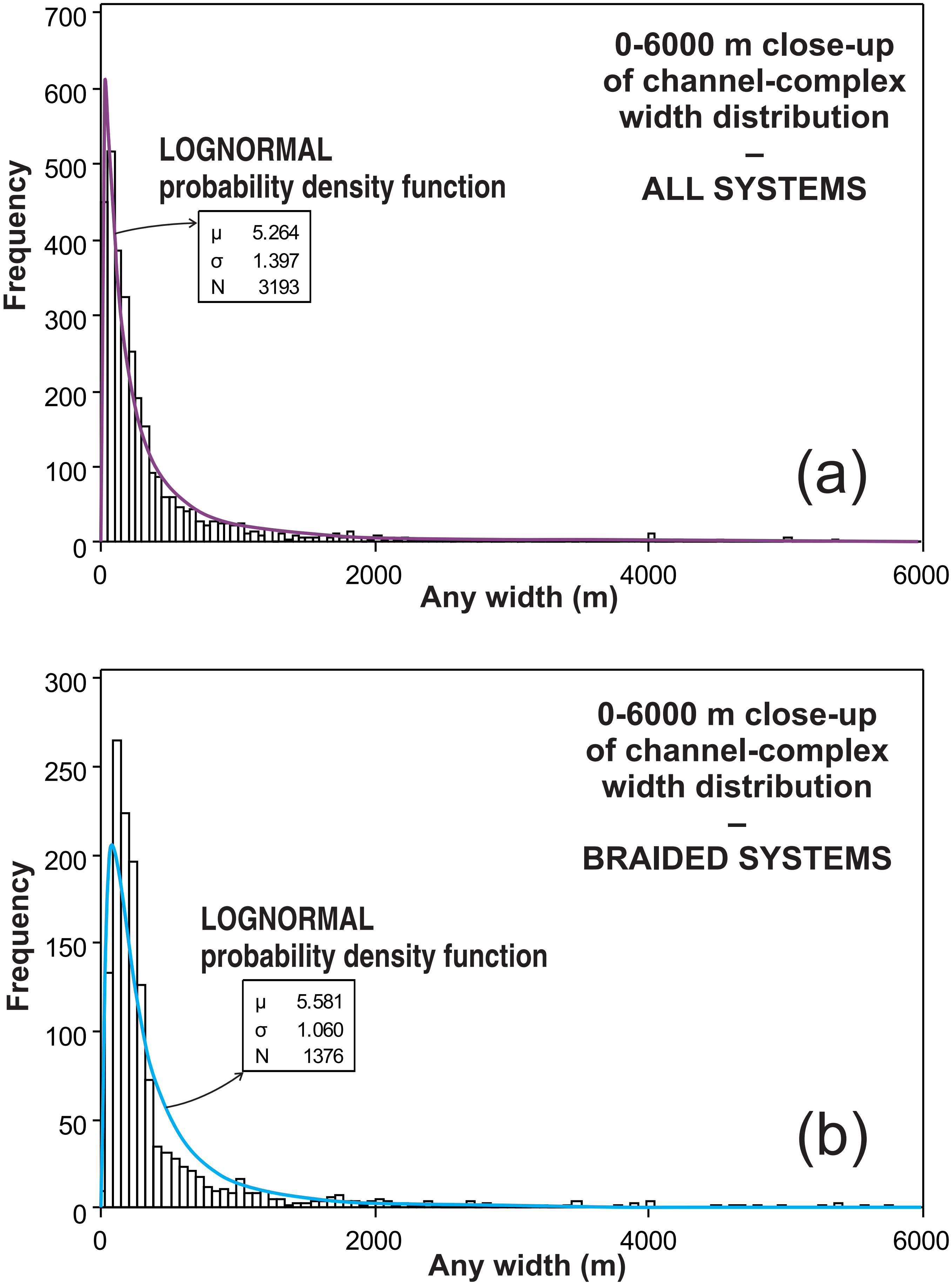

0-6000 m close-up
of channel-complex
width distribution
–
ALL SYSTEMS
LOGNORMAL
probability density function
μ 5.264
σ 1.397
N 3193
(a)
Frequency
0
100
200
300
400
500
600
700
0
2000
4000
6000
Any width (m)
0-6000 m close-up
of channel-complex
width distribution
–
BRAIDED SYSTEMS
LOGNORMAL
probability density function
μ 5.581
σ 1.060
N 1376
(b)
Frequency
0
50
100
150
200
250
300
0
2000
4000
6000
Any width (m)

FIGURE 7

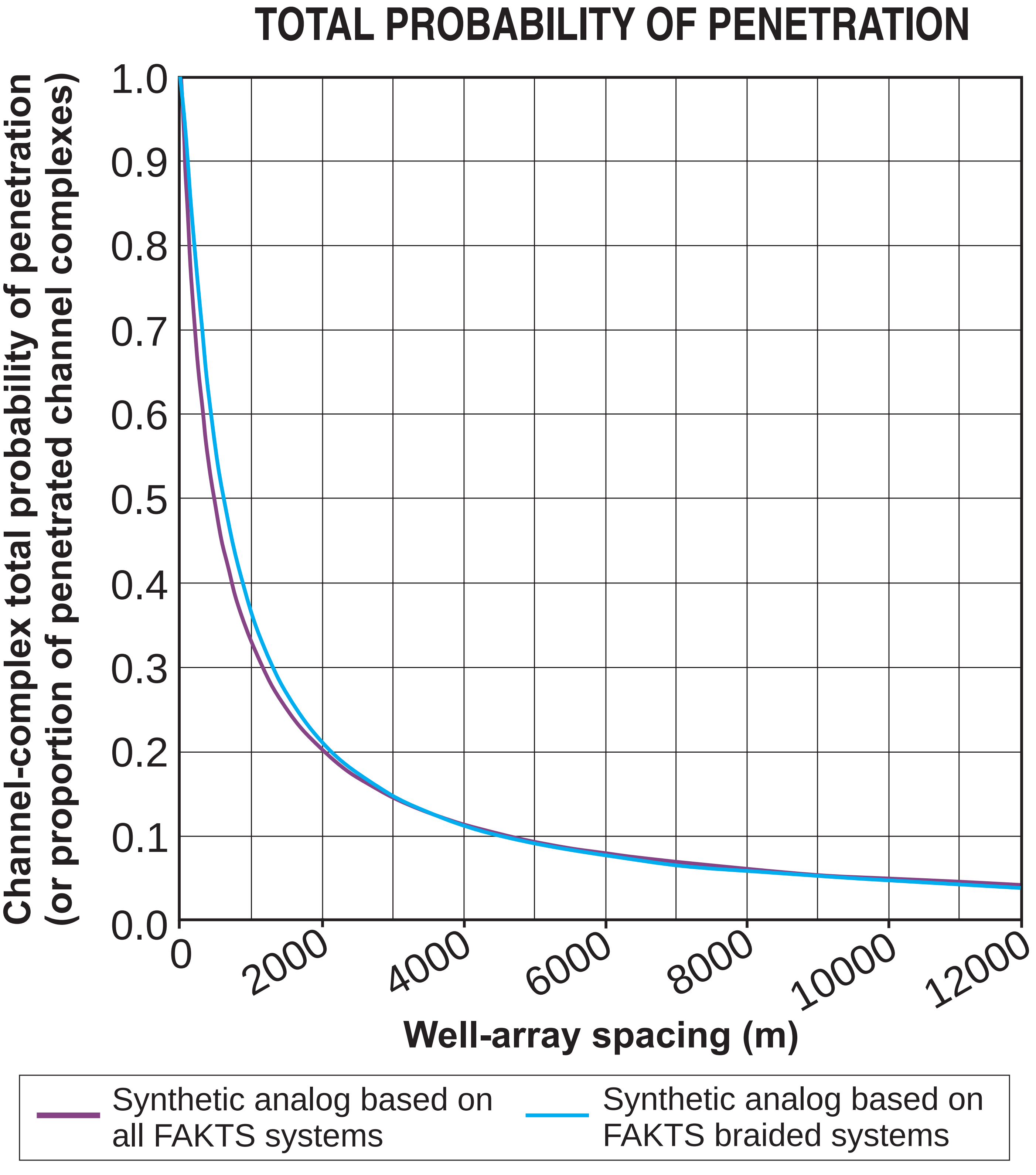

TOTAL PROBABILITY OF PENETRATION
Channel-complex total probability of penetration
(or proportion of penetrated channel complexes)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
2000
4000
6000
8000
10000
12000
Well-array spacing (m)
Synthetic analog based on all FAKTS systems
Synthetic analog based on FAKTS braided systems

FIGURE 8

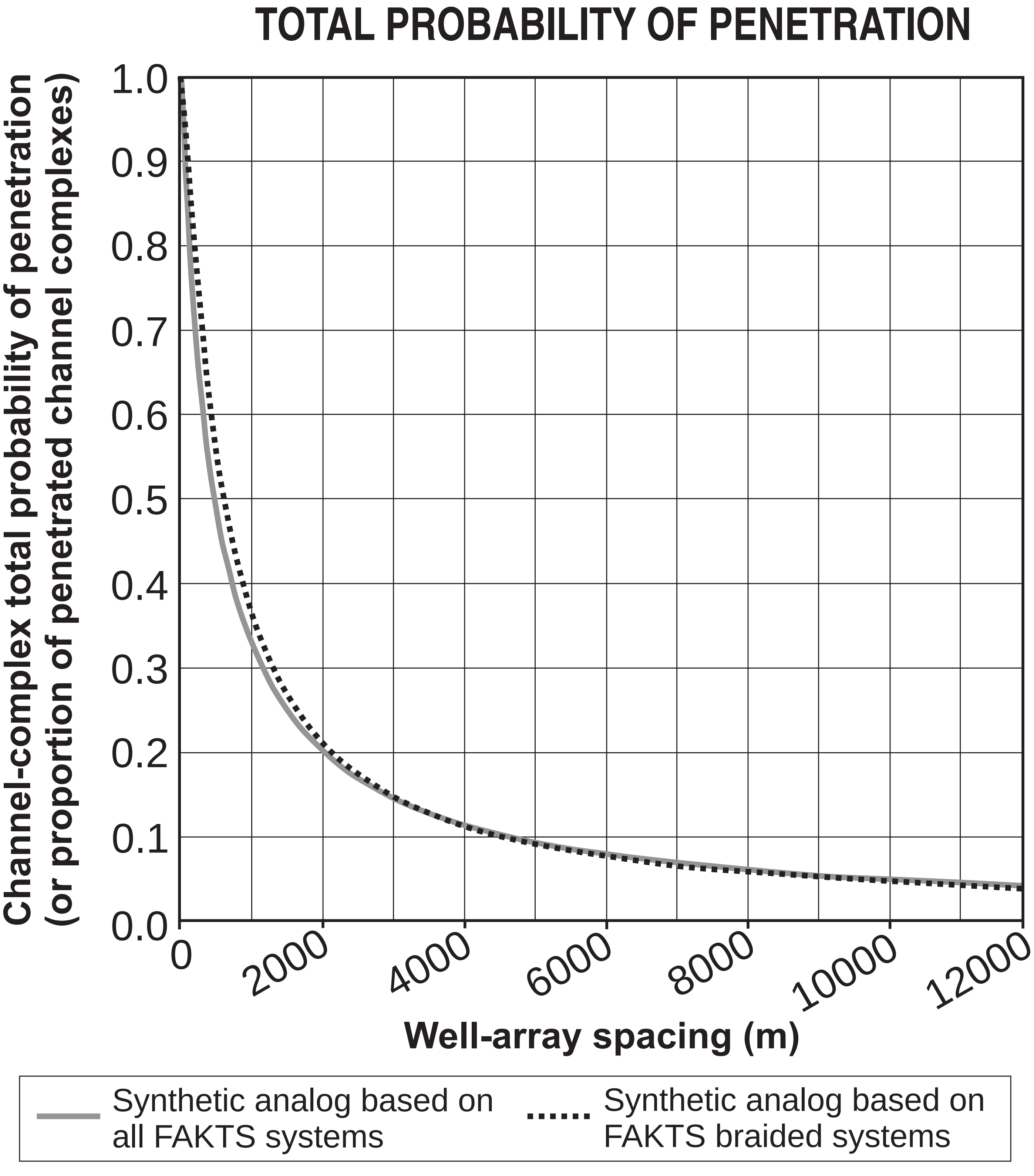

TOTAL PROBABILITY OF PENETRATION
Channel-complex total probability of penetration (or proportion of penetrated channel complexes)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
2000
4000
6000
8000
10000
12000
Well-array spacing (m)
Synthetic analog based on all FAKTS systems
Synthetic analog based on FAKTS braided systems

FIGURE 8 (b/w)

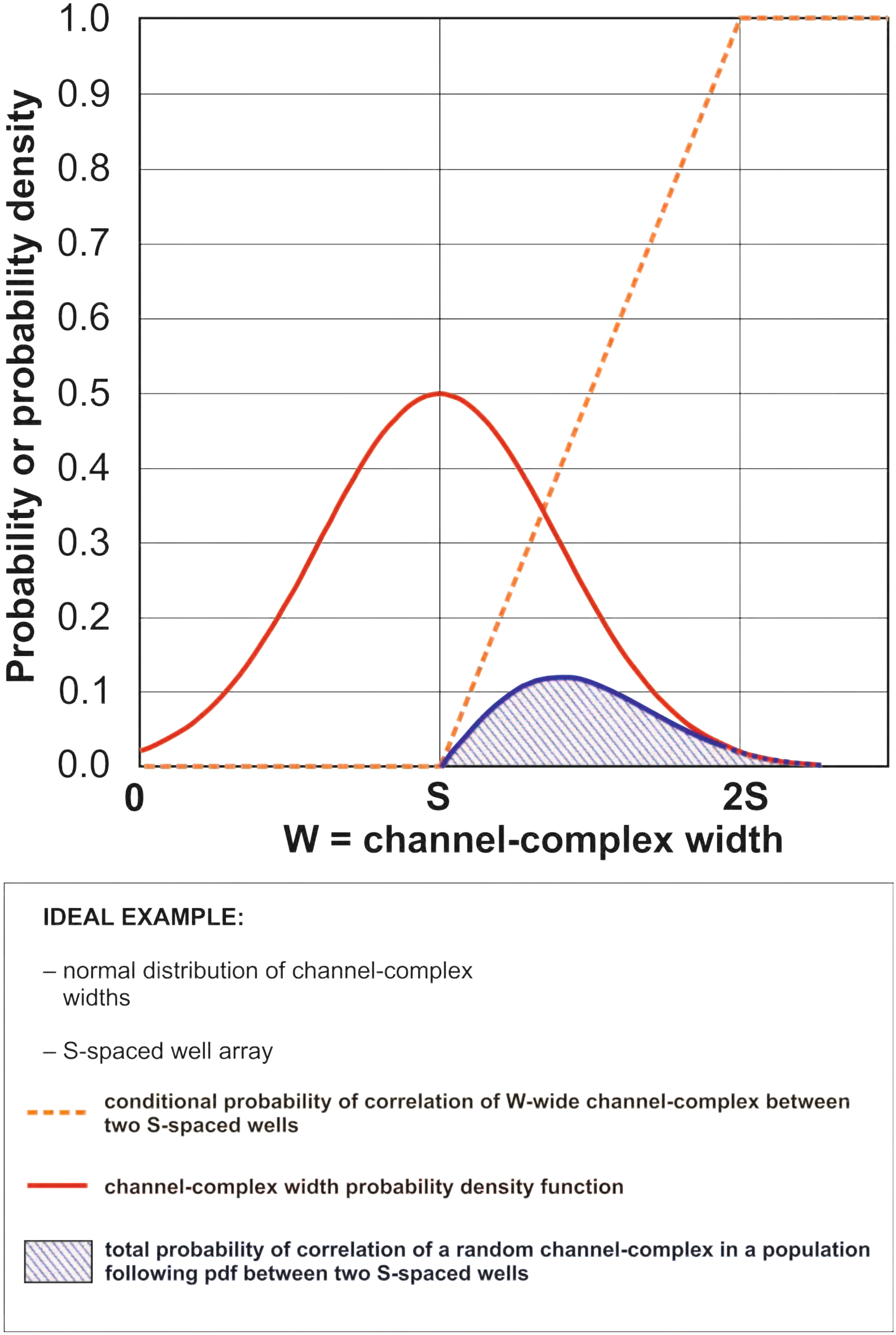

1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Probability or probability density
0
S
2S
W = channel-complex width
IDEAL EXAMPLE:
– normal distribution of channel-complex widths
– S-spaced well array
conditional probability of correlation of W-wide channel-complex between two S-spaced wells
channel-complex width probability density function
total probability of correlation of a random channel-complex in a population following pdf between two S-spaced wells

FIGURE 9

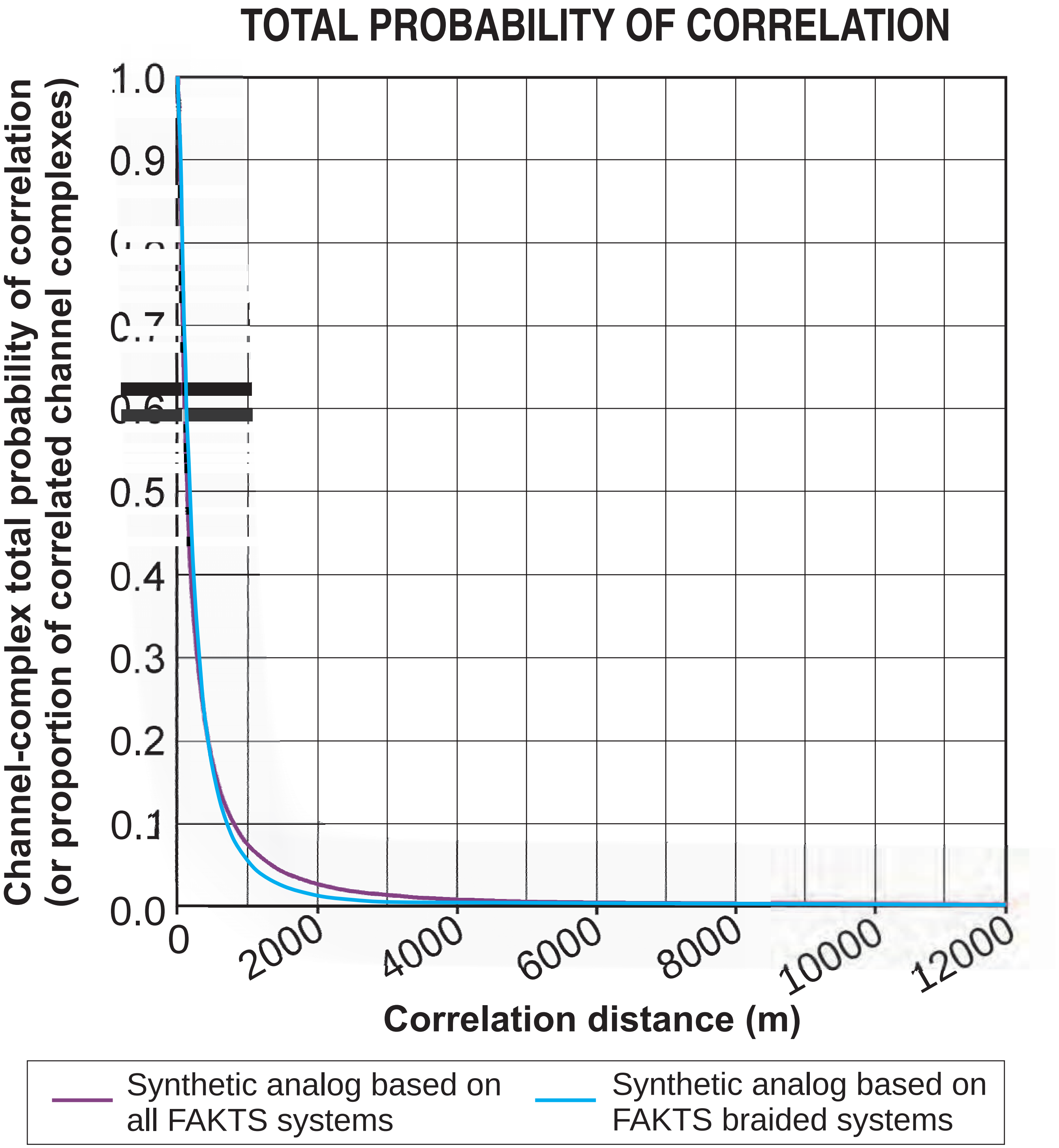

TOTAL PROBABILITY OF CORRELATION
Channel-complex total probability of correlation
(or proportion of correlated channel complexes)
1.0
0.9
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
2000
4000
6000
8000
10000
12000
Correlation distance (m)
Synthetic analog based on all FAKTS systems
Synthetic analog based on FAKTS braided systems

FIGURE 10

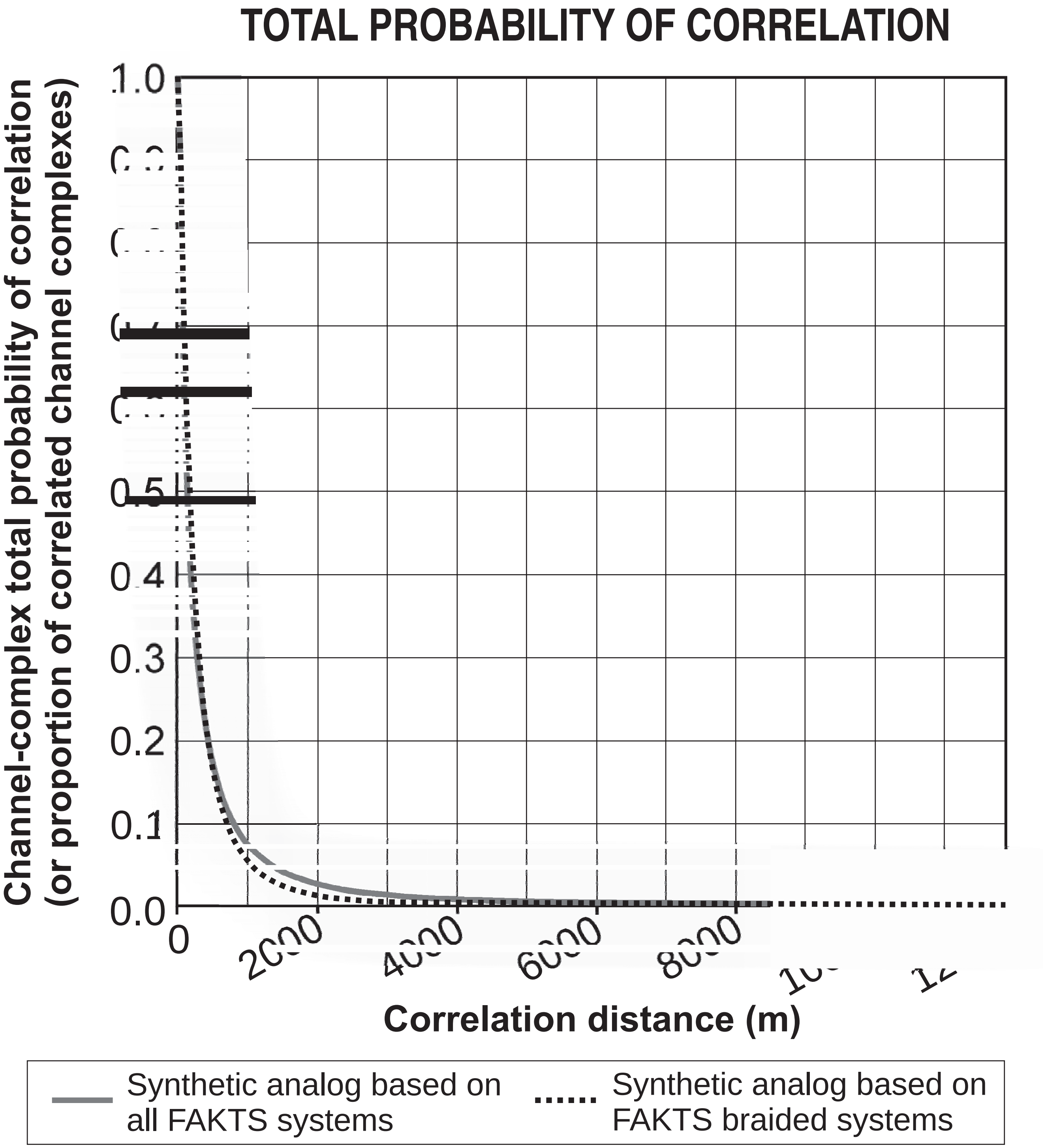
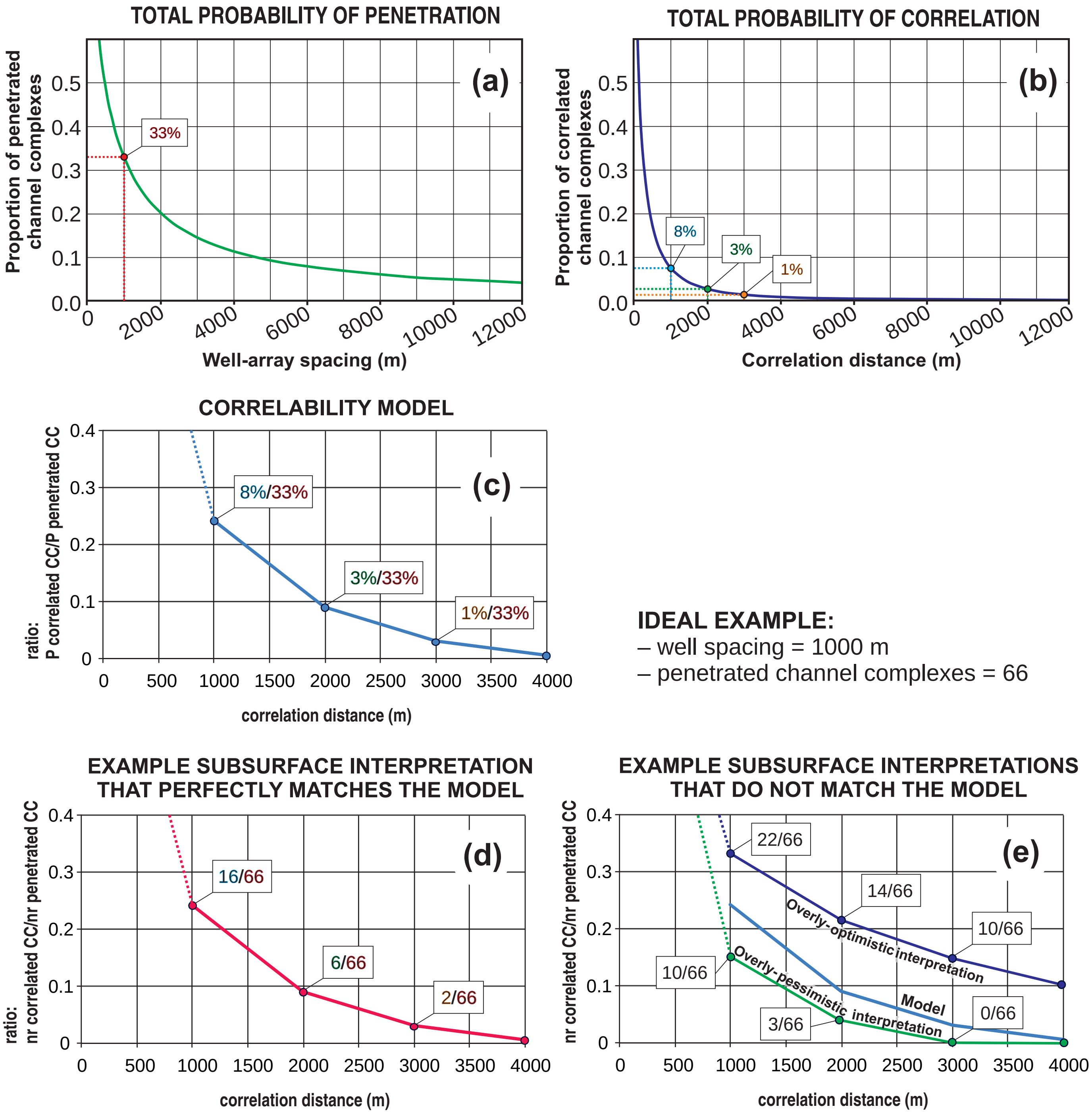

TOTAL PROBABILITY OF CORRELATION
Channel-complex total probability of correlation
(or proportion of correlated channel complexes)
1.0
0.5
0.4
0.3
0.2
0.1
0.0
0
2000
4000
6000
8000
Correlation distance (m)
Synthetic analog based on all FAKTS systems
Synthetic analog based on FAKTS braided systems

FIGURE 10 (b/w)



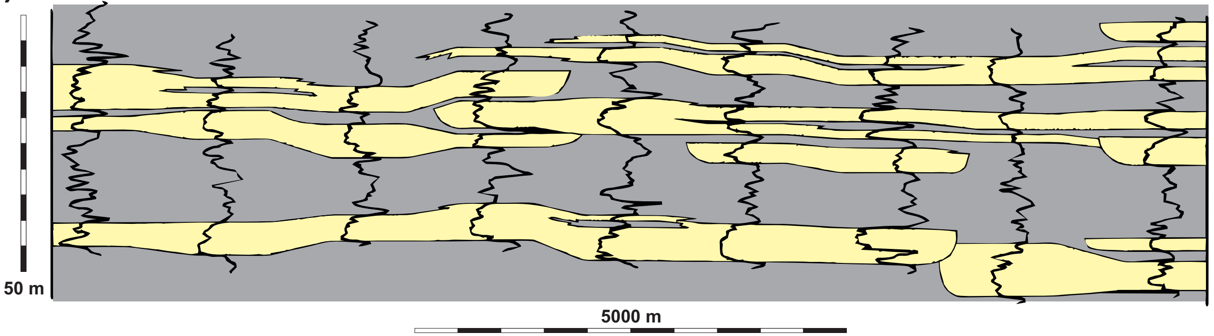
IDEAL EXAMPLE:

– well spacing = 1000 m

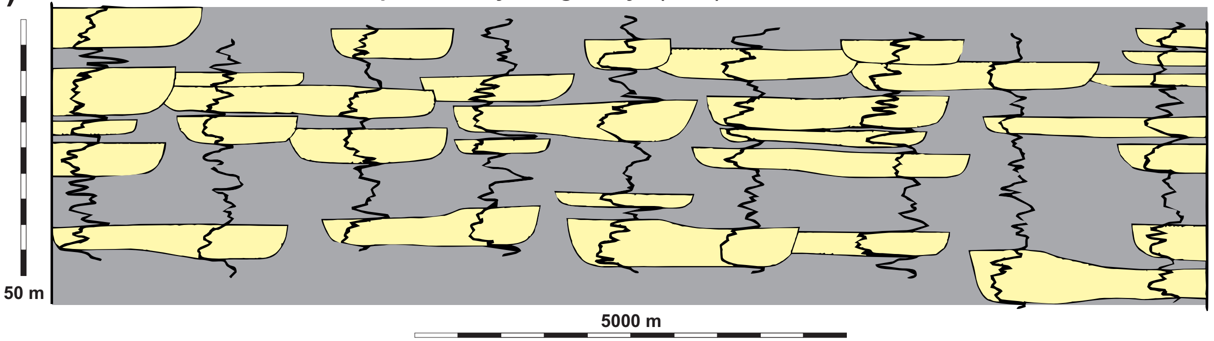
– penetrated channel complexes = 66

FIGURE 11

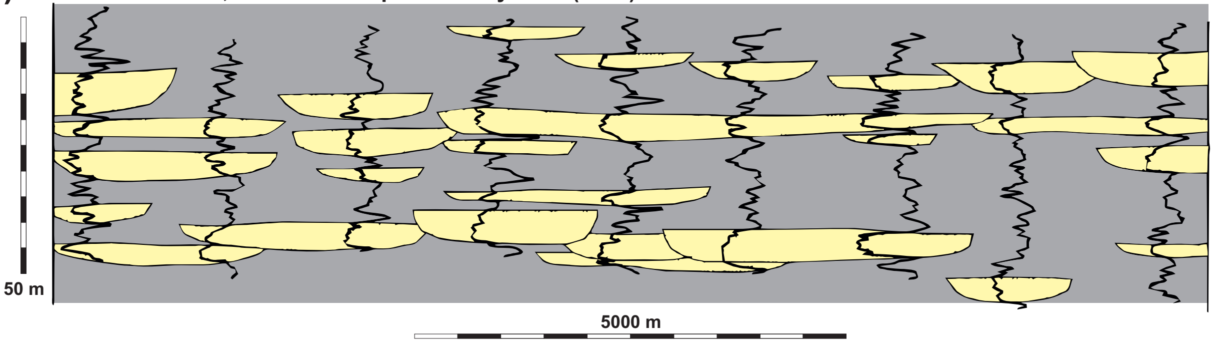
(a) Travis Peak Fm., Zone 1 – Interpretation by Tye (1991)



(b) Travis Peak Fm., Zone 1 – Interpretation by Bridge & Tye (2000)

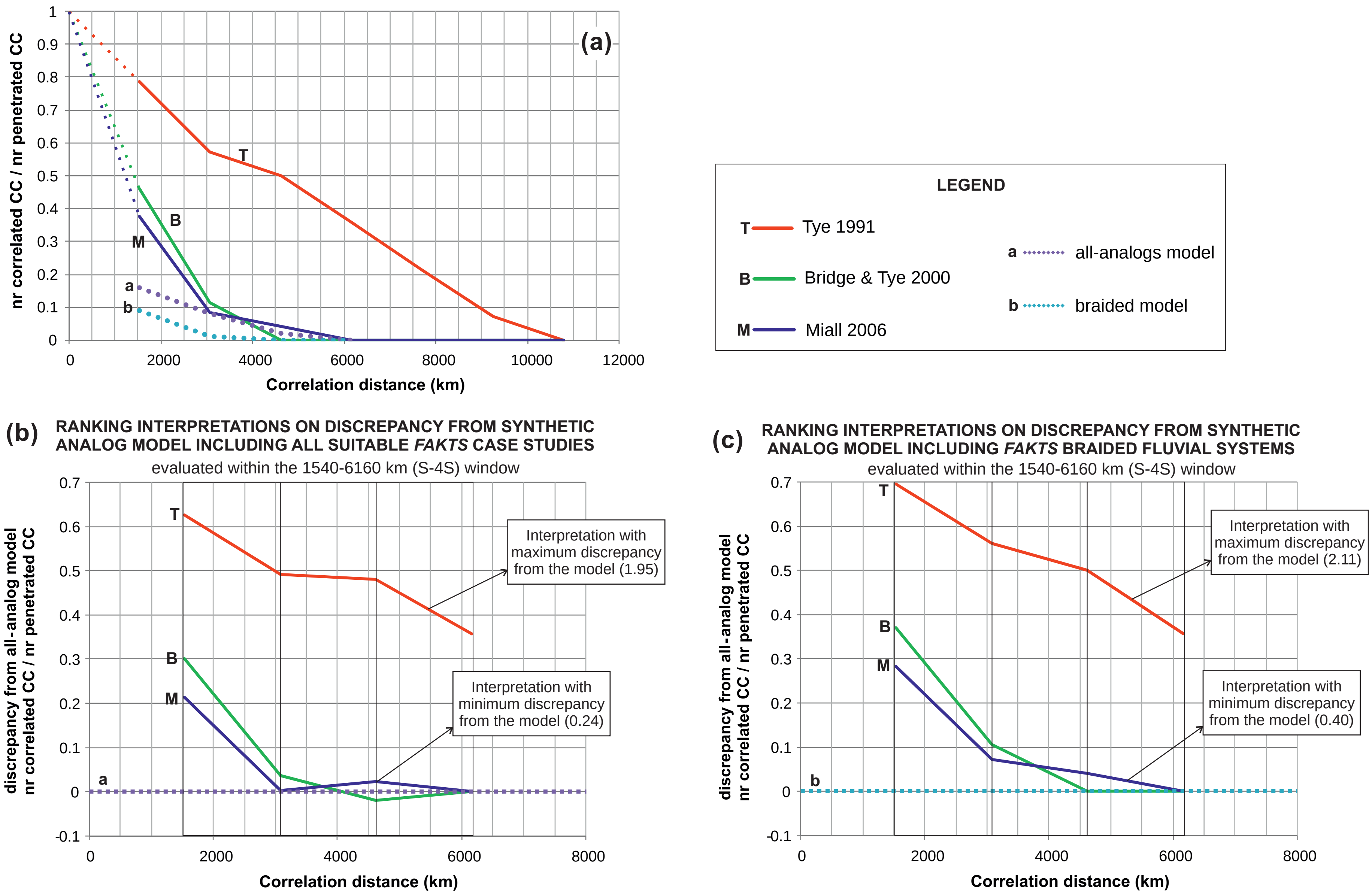


(c) Travis Peak Fm., Zone 1 – Interpretation by Miall (2006)



modified after Miall (2006)

FIGURE 12



(b) RANKING INTERPRETATIONS ON DISCREPANCY FROM SYNTHETIC ANALOG MODEL INCLUDING ALL SUITABLE *FAKTS* CASE STUDIES

evaluated within the 1540-6160 km (S-4S) window

(c) RANKING INTERPRETATIONS ON DISCREPANCY FROM SYNTHETIC ANALOG MODEL INCLUDING *FAKTS* BRAIDED FLUVIAL SYSTEMS

evaluated within the 1540-6160 km (S-4S) window

FIGURE 13

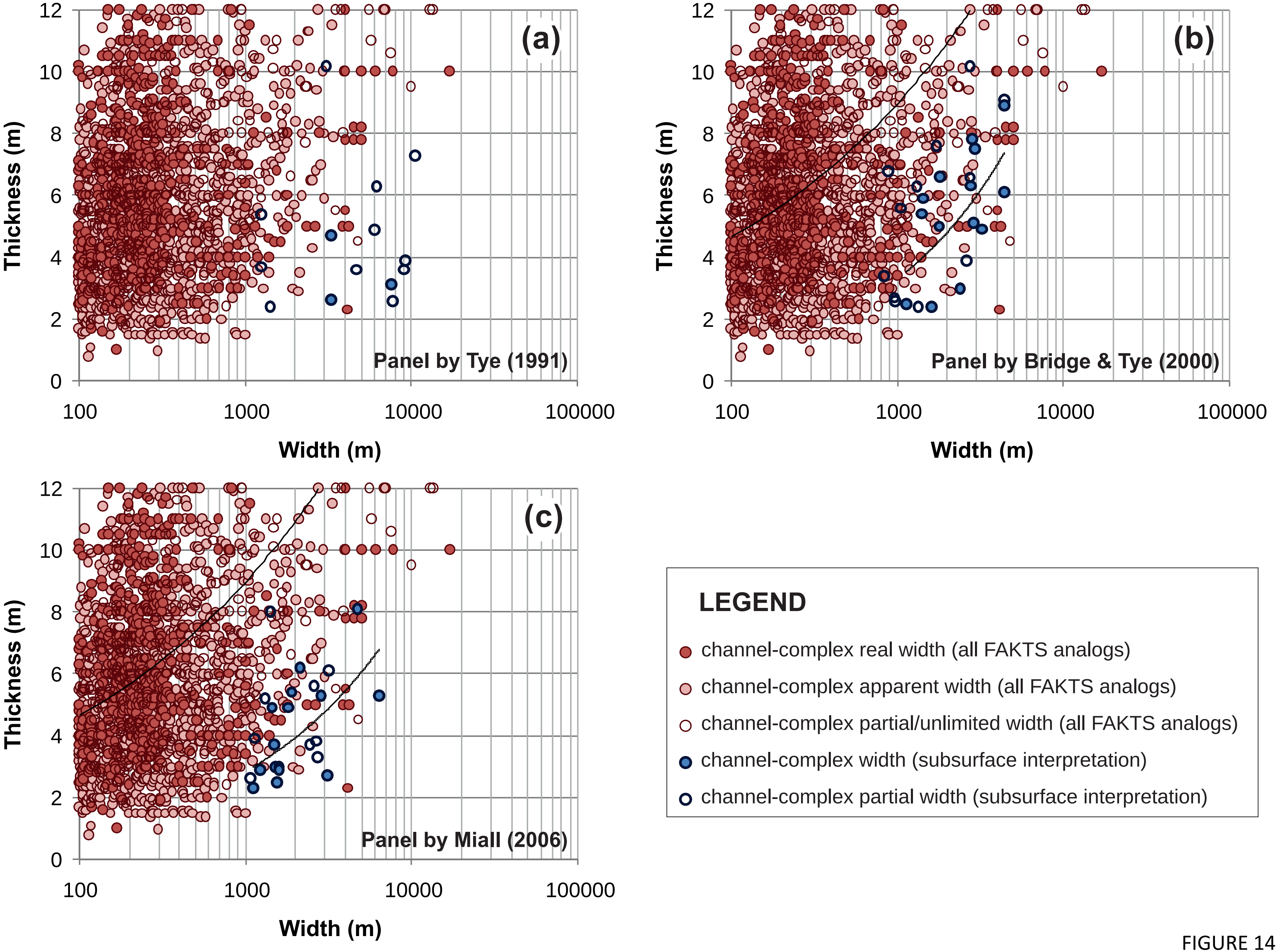

(a)
Panel by Tye (1991)
(b)
Panel by Bridge & Tye (2000)
(c)
Panel by Miall (2006)
Thickness (m)
Width (m)
0
2
4
6
8
10
12
100
1000
10000
100000
LEGEND
● channel-complex real width (all FAKTS analogs)
● channel-complex apparent width (all FAKTS analogs)
○ channel-complex partial/unlimited width (all FAKTS analogs)
● channel-complex width (subsurface interpretation)
○ channel-complex partial width (subsurface interpretation)

FIGURE 14

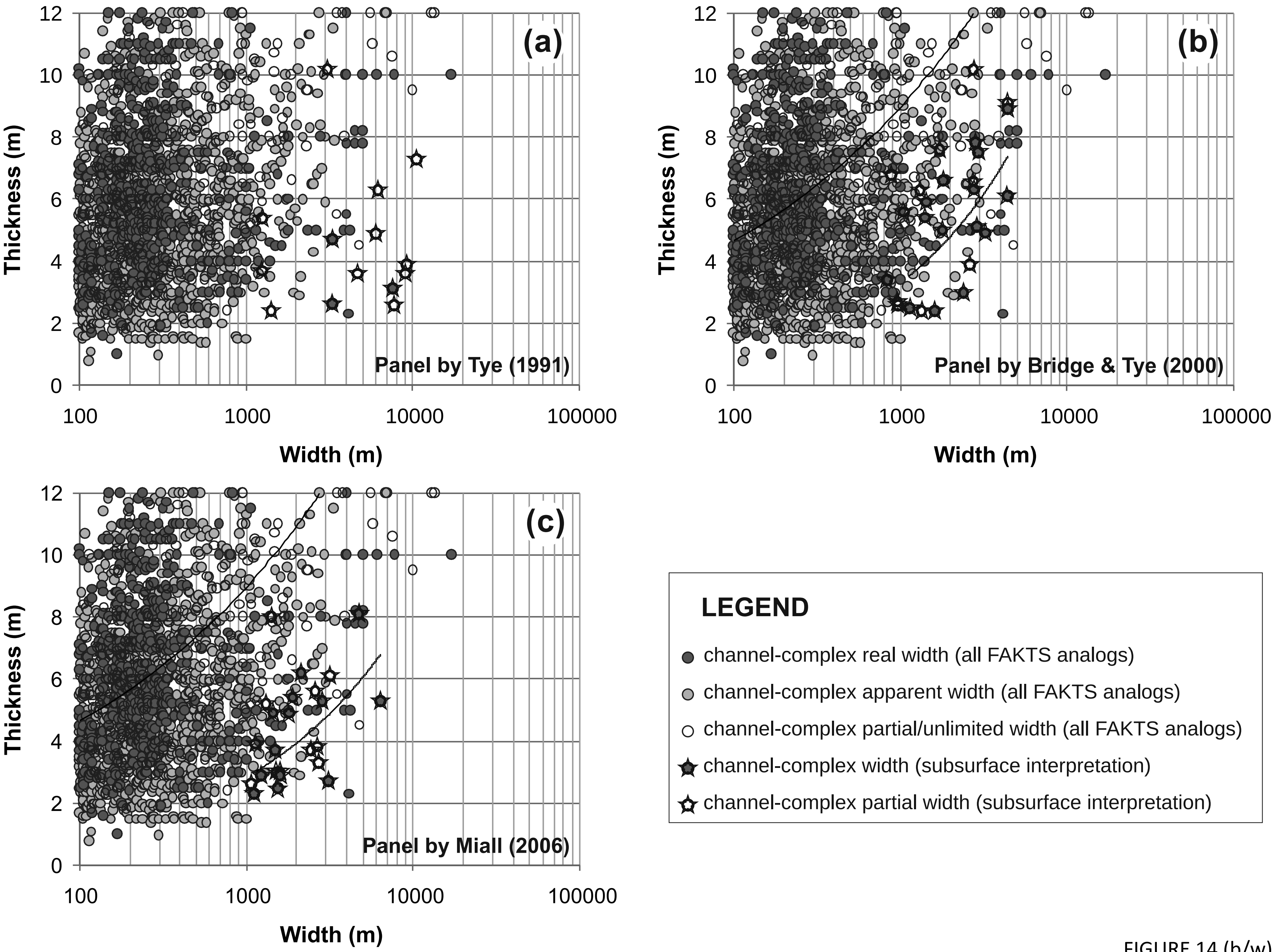

(a)
Panel by Tye (1991)
(b)
Panel by Bridge & Tye (2000)
(c)
Panel by Miall (2006)
Thickness (m)
0
2
4
6
8
10
12
Width (m)
100
1000
10000
100000
LEGEND
● channel-complex real width (all FAKTS analogs)
● channel-complex apparent width (all FAKTS analogs)
○ channel-complex partial/unlimited width (all FAKTS analogs)
★ channel-complex width (subsurface interpretation)
☆ channel-complex partial width (subsurface interpretation)

FIGURE 14 (b/w)

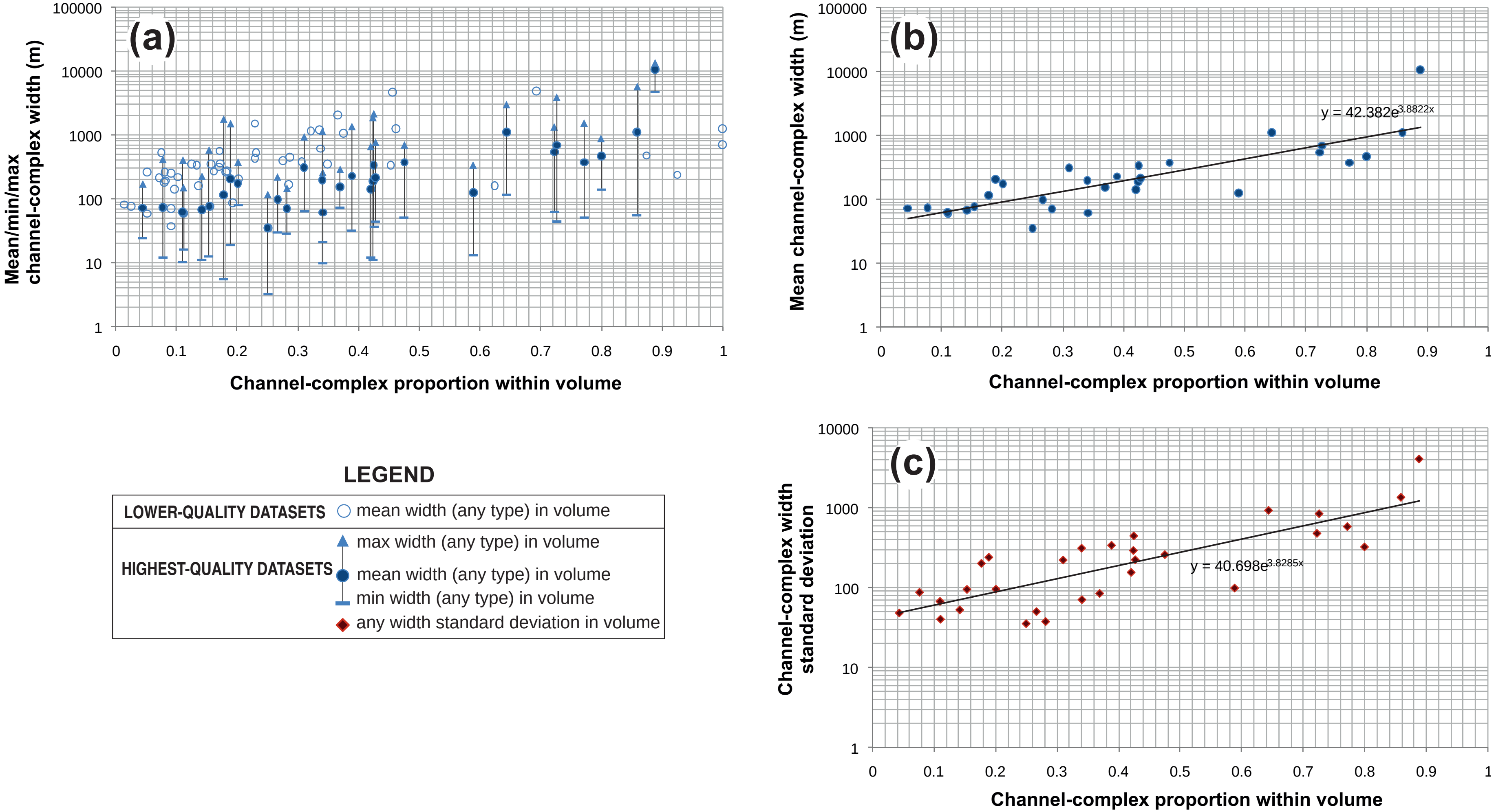

(a)
Mean/min/max channel-complex width (m)
100000
10000
1000
100
10
1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Channel-complex proportion within volume
(b)
Mean channel-complex width (m)
100000
10000
1000
100
10
1
y = 42.382e^3.8822x
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Channel-complex proportion within volume
LEGEND
LOWER-QUALITY DATASETS
○ mean width (any type) in volume
HIGHEST-QUALITY DATASETS
▲ max width (any type) in volume
● mean width (any type) in volume
min width (any type) in volume
◆ any width standard deviation in volume
(c)
Channel-complex width standard deviation
10000
1000
100
10
1
y = 40.698e^3.8285x
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Channel-complex proportion within volume

FIGURE 15

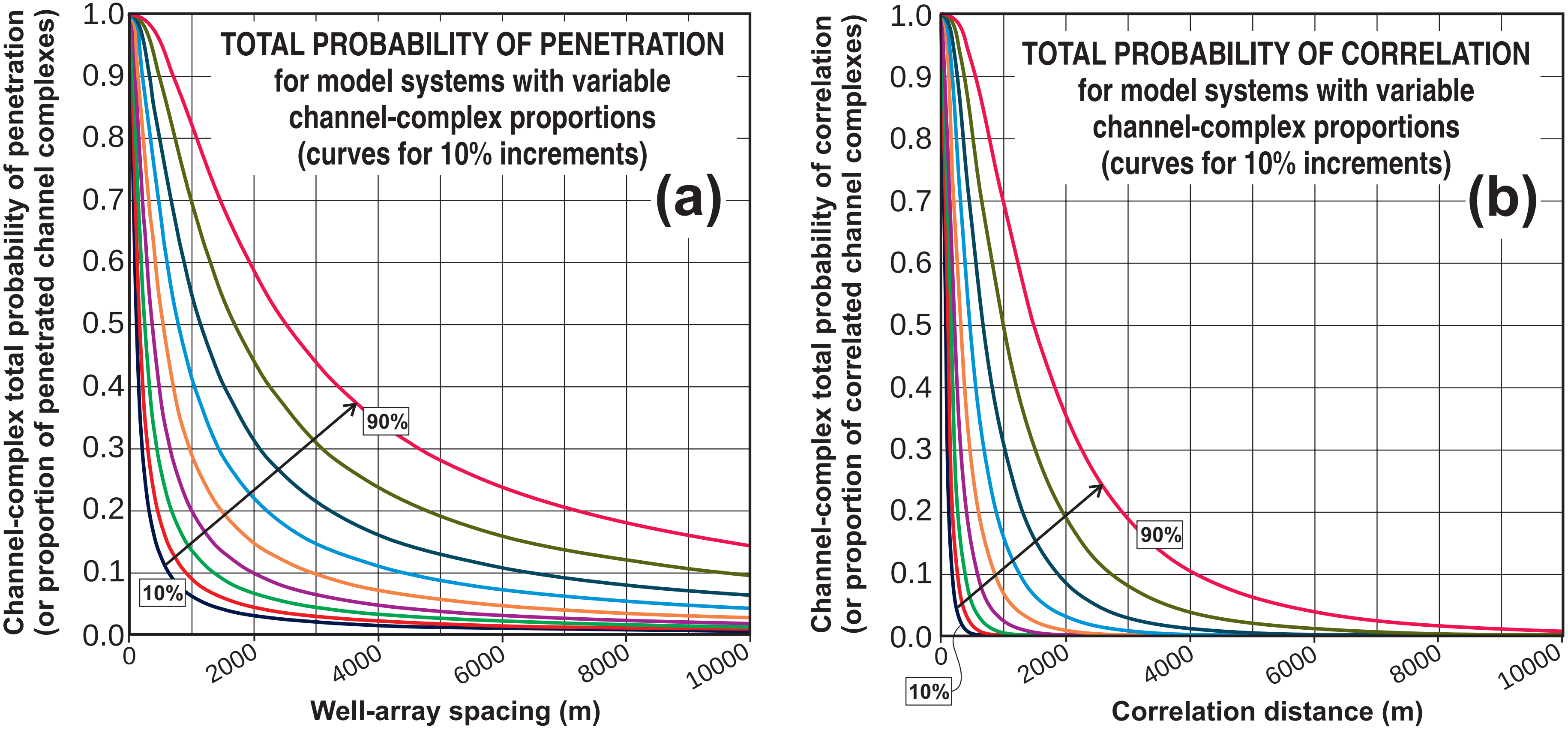

Channel-complex total probability of penetration (or proportion of penetrated channel complexes)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
TOTAL PROBABILITY OF PENETRATION
for model systems with variable
channel-complex proportions
(curves for 10% increments)
(a)
90%
10%
0
2000
4000
6000
8000
10000
Well-array spacing (m)
Channel-complex total probability of correlation (or proportion of correlated channel complexes)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
TOTAL PROBABILITY OF CORRELATION
for model systems with variable
channel-complex proportions
(curves for 10% increments)
(b)
90%
10%
0
2000
4000
6000
8000
10000
Correlation distance (m)

FIGURE 16