



Connectivity of channelized reservoirs: a modelling approach

David K. Larue¹ and Joseph Hovadik²

¹*ChevronTexaco, Energy Technology Company, Bakersfield, CA, USA*

²*ChevronTexaco, Energy Technology Company, San Ramon, CA, USA*

ABSTRACT: Connectivity represents one of the fundamental properties of a reservoir that directly affects recovery. If a portion of the reservoir is not connected to a well, it cannot be drained. Geobody or sandbody connectivity is defined as the percentage of the reservoir that is connected, and reservoir connectivity is defined as the percentage of the reservoir that is connected to wells.

Previous studies have mostly considered mathematical, physical and engineering aspects of connectivity. In the current study, the stratigraphy of connectivity is characterized using simple, 3D geostatistical models. Based on these modelling studies, stratigraphic connectivity is good, usually greater than 90%, if the net: gross ratio, or sand fraction, is greater than about 30%. At net: gross values less than 30%, there is a rapid diminishment of connectivity as a function of net: gross. This behaviour between net: gross and connectivity defines a characteristic 'S-curve', in which the connectivity is high for net: gross values above 30%, then diminishes rapidly and approaches 0.

Well configuration factors that can influence reservoir connectivity are well density, well orientation (vertical or horizontal; horizontal parallel to channels or perpendicular) and length of completion zones. Reservoir connectivity as a function of net: gross can be improved by several factors: presence of overbank sandy facies, deposition of channels in a channel belt, deposition of channels with high width/thickness ratios, and deposition of channels during variable floodplain aggradation rates. Connectivity can be reduced substantially in two-dimensional reservoirs, in map view or in cross-section, by volume support effects and by stratigraphic heterogeneities. It is well known that in two dimensions, the cascade zone for the 'S-curve' of net: gross plotted against connectivity occurs at about 60% net: gross. Generalizing this knowledge, any time that a reservoir can be regarded as 'two-dimensional', connectivity should follow the 2D 'S-curve'. For channelized reservoirs in map view, this occurs with straight, parallel channels. This 2D effect can also occur in layered reservoirs, where thin channelized sheets are separated vertically by sealing mudstone horizons. Evidence of transitional 2D to 3D behaviour is presented in this study. As the gross rock volume of a reservoir is reduced (for example, by fault compartmentalization) relative to the size of the depositional element (for example, the channel body), there are fewer potential connecting pathways. Lack of support volume creates additional uncertainty in connectivity and may substantially reduce connectivity. Connectivity can also be reduced by continuous mudstone drapes along the base of channel surfaces, by mudstone beds that are continuous within channel deposits, or muddy inclined heterolithic stratification. Finally, connectivity can be reduced by 'compensational' stacking of channel deposits, in which channels avoid amalgamating with other channel deposits. Other factors have been studied to address impact on connectivity, including modelling program type, presence of shale-filled channels and nested hierarchical modelling.

Most of the stratigraphic factors that affect reservoir connectivity can be addressed by careful geological studies of available core, well log and seismic data. Remaining uncertainty can be addressed by constructing 3D geological models.

KEYWORDS: *reservoir, sequence stratigraphy, connectivity, deep-water channel deposits, turbidites*

INTRODUCTION

Reservoir connectivity represents one of the primary controls on recovery from a petroleum reservoir. Reservoir connectivity issues are especially significant in sparse well environments, such as deep water, in which economic limits to drilling wells exist but questions regarding connectivity pertain. This study reviews definitions of different types of reservoir connectivity and shows how stratigraphic architecture affects connectivity. Different types of stratigraphic architectures in 3D geostatistical models were created and analysed for connectivity. This approach, while allowing analysis of thousands of different stratigraphic characterizations, is limited mainly by our ability to create realistic reservoir stratigraphy, as well as scaling issues associated with using gridded models. Based on the results of this study, lists of stratigraphic characteristics that influence reservoir connectivity and techniques for their recognition are presented.

Vertical compartmentalization of a reservoir can occur whenever a laterally continuous impermeable unit separates a lower from an upper permeable unit. That is, because of the impermeable unit, pressures in the upper and lower reservoirs prior to, and/or during production may be different. If only one of the units is completed in a well, only that reservoir interval will be drained, and the other reservoir interval will maintain original pressure and fluid saturation distributions. Based on sequence stratigraphic studies (Van Wagoner *et al.* 1990; Van Wagoner 1995; Larue & Legarre 2004), reservoirs

may become vertically compartmentalized associated with changes in sea-level, tectonic activity and accompanying changes in depositional systems (Fig. 1A).

Lateral compartmentalization of reservoirs, or the areal separation of reservoir compartments, is the focus of this study. Lateral compartmentalization can occur in several situations. It is clear that impermeable fault zones (Fig. 1B, 'sealing fault') or faults that emplace impermeable intervals next to permeable intervals (Fig. 1B, 'non-sealing fault') cause lateral reservoir compartmentalization. Fault compartmentalization will not be discussed further here (see Fulljames *et al.* 1997; Knipe 1997). Lateral compartmentalization of channelized deposits occurs when individual channel bodies fail to intersect (Fig. 1C) and there are no permeable conduits connecting channels (for example, crevasse-splay deposits or overbank sandstones). Factors influencing lateral connectivity of channelized and other reservoirs will be presented, stressing the cases in which permeable sandstones are confined to channel deposits, and overbank deposits are non-permeable mudstones.

Many of the concepts accepted today about connectivity are derived from field-based studies of waterflooding in West Texas and other fields in the USA (Stiles 1976; George & Stiles 1978; Barber *et al.* 1983; Gould & Sarem 1989; Stiles & Magruder 1992). These studies stressed that unless there was continuity between the injecting and producing wells during a waterflood, the reservoir would be incompletely swept. If the reservoir is incompletely swept, infill drilling provides an

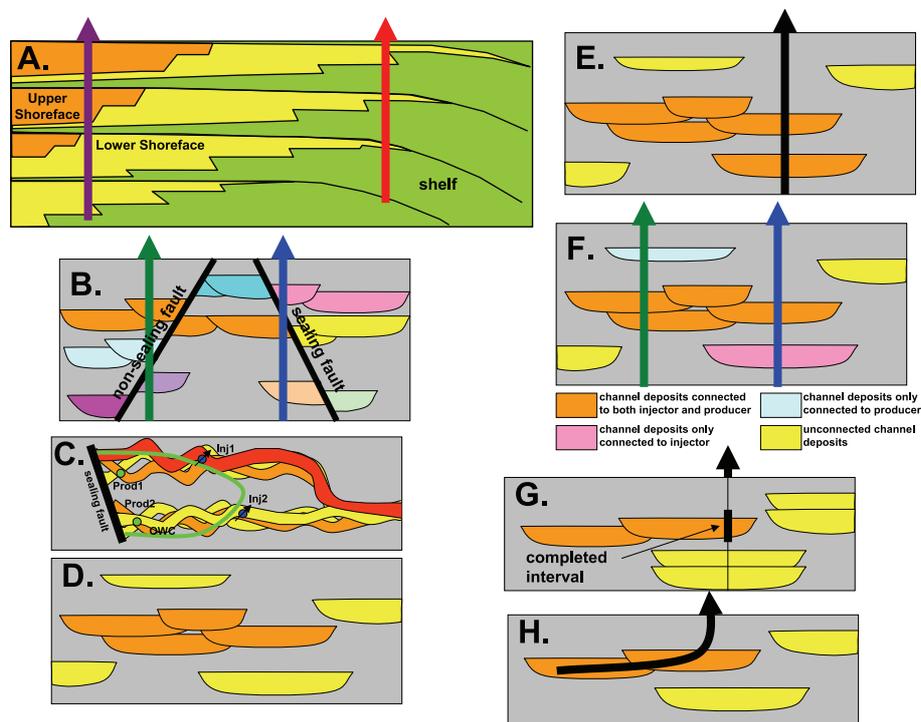


Fig. 1. (A) Formation of vertical compartments in a shoreface reservoir associated with progradational cycles and relative changes in sea-level. Wells intersecting four separate vertical compartments are shown. Modified from a figure in Van Wagoner *et al.* (1990). (B) Lateral compartmentalization can be accomplished through sealing and non-sealing faults. Connected channel deposits shown in the same colour. Sandstone bodies in contact across the fault are connected in the non-sealing case and unconnected in the sealing case. Two wells are shown. (C) Map view, showing formation of lateral compartments in a channelized reservoir by avulsion. 'OWC' is the oil-water contact. Injecting and producing wells ('Inj' and 'Prod') are shown for each channel complex. (D) Example of reservoir geobodies, representing individual channel deposits (yellow), or amalgamated channel deposits (orange). (E) Reservoir connectivity is defined as the proportion of reservoir connected to one or more wells. Here, the orange geobodies are connected elements, while the yellow bodies are unconnected. (F) If producing and injecting wells are present, connectivity can be defined as the percentage of the reservoir geobodies intersected by both injecting and producing wells (the orange channel deposits). Note that other types of connectivity are also defined in this situation, including geobodies in contact only with injecting or producing wells (pink or blue, respectively) and geobodies unconnected to the wells (yellow). (G) Connectivity can be defined as a function of the completed interval in the well. Colours as in (E). (H) Connectivity can be defined for non-vertical wells. Colours as in (E).

opportunity to both increase the rate of production in the field and also to add to reserves (Abbots & van Kuijk 1997).

RECOGNITION OF RESERVOIR COMPARTMENTS

Reservoir compartments are non-connected parts of the reservoir. They are recognized in fields undergoing development based on interpretation of seismic data, and measurements from wells, including different pressures, pressure gradients, or different fluid contacts (for example, Smalley & Hale 1995; Hardage *et al.* 1997). Differences in oil geochemistry from different wells or zones in the well can also lead to interpretations of reservoir compartments (Beeunas *et al.* 1999; Edman & Burk 1999). In older fields, differences in pressures or changes with pressure over time may be associated with production, or may be associated with reservoir compartments. Penetration of a zone with original pre-production field pressures could indicate a new compartment unless the field has been undergoing pressure maintenance, or has a strong aquifer. In a field produced with a water drive or by waterflooding, original field water saturation values cannot be used as an indicator of compartmentalization, because water motions can be complex. Interpretation of 4D seismic data can lead to definition of new reservoir compartments (Anderson *et al.* 1995). In general, definition of subtle reservoir compartments may not be simple or straightforward.

SEDIMENTOLOGY AND STRATIGRAPHY OF CONNECTIVITY

Concepts about origins and causes of lateral connectivity of reservoirs are based on sequence stratigraphic, sedimentological and geomorphological studies (for example, Martinsen 1994). During deposition, all channel types, whether fluvial, estuarine or deep water, undergo some degree of migration or shifting which tends to produce channel deposits that are wider and thicker than original channel dimensions (Leeder 1978; Bridge & Leeder 1979; Bridge 1993; Mack & Leeder 1998; Posamentier *et al.* 2000). Gradual migration and shifting of channels with accompanying local events, such as chute and neck cut-off, tends to make channel belt deposits, also referred to as channel family or channel complex deposits (Bridge 1993; Bratvold *et al.* 1994). The relative sudden movement of the channel belt to another position in the depositional system is termed avulsion (Smith *et al.* 1989; Jones & Schumm 1999; Mohrig *et al.* 2000). Channel deposits that are laterally disconnected were clearly subjected to either or both gradual migration and avulsive events. An example of channels disconnected by an avulsion event is shown in Figure 1C. Here, an updip avulsion resulted in the bifurcation of two channel belts. Within the oil zone, shown by the oil–water contact, the two channel complexes are not in communication, such that there will be minimal communication between the two well pairs shown (there could be some pressure communication due to a common water leg, however). There are aggradational and sequence stratigraphic components to channel connectivity that will be addressed herein, in that channel base-level changes are tied to changes in relative sea-level, climate and tectonics (Shanley & McCabe 1994; Bryant *et al.* 1995; Van Wagoner 1995; Posamentier *et al.* 2000). Much of the understanding of channel migration and avulsion is derived from studies of fluvial systems. Although deep-water channel deposits are also known to migrate and aggrade, and avulsions have been documented, depositional processes and origins are less well understood (Posamentier *et al.* 2000; Kolla *et al.* 2001; Abreu *et al.* 2003).

TYPES OF CONNECTIVITY

Several types of connectivity between channels or other depositional elements can be defined. **Geobody or sandbody connectivity** refers to the connectivity of individual elements in a reservoir, such as amalgamated channel deposits (Fig. 1D). Connected and unconnected channel deposits define channel-sized or larger potential flow units referred to as geobodies. Geobody connectivity has been studied by a number of workers (Allen 1978, 1979; Allard & HERESIM Group 1993; Pardo-Iguzquiza & Dowd 2003).

Reservoir-to-well connectivity, or simply reservoir connectivity, is defined as the proportion of the reservoir connected to wells (Fig. 1E). Because reservoir connectivity requires information about the wells, and is unique to their location, reservoir connectivity is both a well property and a reservoir property. It is a well property because, given one or more wells, the proportion of the reservoir connected to the wells can be defined and this number is uniquely defined for that well group. Reservoir-to-well connectivity is also a reservoir property in that it defines which reservoir elements are connected to a given well or group of wells.

In a field with both producing and injecting wells, reservoir connectivity can be defined as the proportion of the reservoir connected to both producing and injecting wells, or to only the producing or injecting wells (Fig. 1F). Note that reservoir connectivity is dependent on where the well was perforated or completed (Fig. 1G). A technique for searching for connectivity from completions is presented by Lo & Chu (1998). In our studies, a simpler and faster technique based on intersections of geobodies is used. Connectivity can also be defined for horizontal or deviated wells (Fig. 1H).

CALCULATING CONNECTIVITY IN RESERVOIR CHARACTERIZATIONS

To define connectivity, one or more parameters are defined that differentiate ability for fluid to flow in the reservoir. For example, a permeability, facies, porosity or V_{shale} cut-off (or combination of cut-offs) may be applied that differentiates rocks in which fluids could flow at some geologically reasonable rates from rocks that are essentially impermeable. Time-scale is, of course, important and the cut-offs considered in the oil industry usually involve time-scales that are compatible with producing a field, typically 20 years or so. Examples of permeability cut-offs might be 0.1 mD or 1 mD for a relatively light oil, or 10 mD or >100 mD for a heavier oil. In the present study, a facies cut-off is used to define potential flow units.

Once potential flow units are defined based on the user specified cut-off, a computer program is used to find the connected cells in the reservoir (Allen 1978; King 1990; Allard & HERESIM Group 1993; Deutsch 1998; Lo & Chu 1998; Pardo-Iguzquiza & Dowd 2003). Groups of connected cells are defined as geobodies, and geobody connectivity is defined as the ratio of the volume of the largest geobody to the sum of all the reservoir geobodies. Then, to define reservoir connectivity, the volume of geobodies intersected by wells is divided by the total volume of geobodies.

IMPLICATIONS OF CONNECTIVITY

A tacit implication of these definitions of connectivity is that if the reservoir is connected to the well, then the reservoir is producible. This is a binary or categorical classification of the reservoir and clearly cannot always be the case. In Figure 2A, a well is shown that penetrates a channel deposit. This channel deposit continues on for a kilometre. It is questionable whether

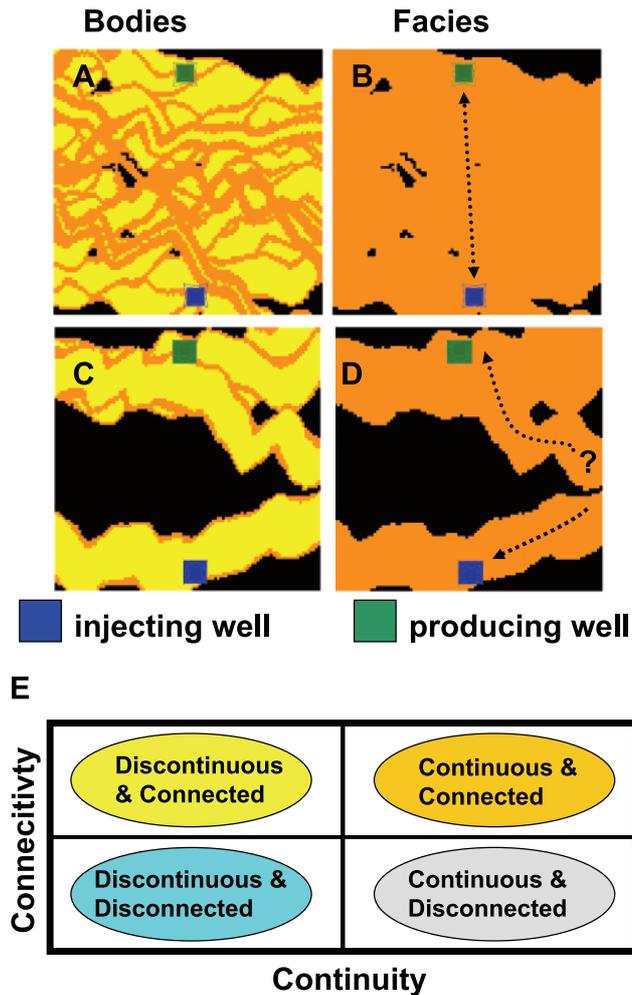


Fig. 3. Examples of continuity, with relationship to connectivity: (A) formation of a continuous sheet through amalgamation of channel deposits; (B) facies equivalent of (A) – note the potential straight pathway between the injecting and producing well; (C) formation of a discontinuous interval consisting of two channel complexes; (D) facies equivalent of (C) – note that there is no simple pathway between the injecting and producing well at this stratigraphic level. (E) Types of relationships between reservoir continuity and connectivity, defining continuity and connectivity fields. The most easily produced reservoirs are continuous and connected. Discontinuous and connected and discontinuous and disconnected reservoirs will tend to leave greater amounts of by-passed pay. An example of a continuous disconnected reservoir is a 2D reservoir consisting of sheets. Continuous laterally disconnected reservoirs do not exist (unless faulting is involved).

complexes and there is no simple continuous path between the producer and injector pair, hence the sandy facies is more discontinuous. In Figures 3C, D, the sandstones are connected in three dimensions, but the facies are more discontinuous. Figure 3E summarizes continuity and connectivity relationships. The most easily produced reservoirs typically have excellent continuity and connectivity, such as that shown in Figures 3A, B. Other reservoirs can be characterized by discontinuity, such as that shown in Figures 3C, D, with connected or disconnected reservoir elements. These reservoirs may provide opportunities for infill drilling or, in a sparse-well environment, represent non-attainable net. Finally, in Figure 3E, sheeted reservoirs (thin reservoir intervals separated by impermeable units) or reservoirs consisting of strongly

parallel channel deposits (with unidirectional continuity) might represent examples of continuous and unconnected reservoirs.

MODEL CONSTRUCTION

In the studies presented here, the grid dimensions are 2 km × 2 km × 33 m, in which cells are 25 m × 25 m × 0.7 m. To construct the conceptual 3D geological models, many of the examples of geological models herein use a Boolean or object-based approach, in which the fundamental unit of modelling is the bar or individual channel deposit. Channel deposits were assigned a range in characteristics, such as variable sinuosity, width and thickness, using data from literature studies. In most of the studies, connectivity was assessed based on facies type: all channel sandstones were considered porous and permeable. Other models described here were created using more classical variogram-based geostatistical techniques, and the newer Multi-Point Statistics (MPS) technique (Strebelle 2002). The stratigraphic character of variogram-based models is not as visually recognizable as their Boolean counterparts, whereas MPS models tend to look reasonably geological.

Modelling meandering channel deposits and channel belt deposits

Bridge (2004) has noted that geostatistical models of meandering channels do not capture their true geometry adequately. More complex models of meandering channels and their point bar deposits have been defined by Howard (1996) and Sun *et al.* (2001), but Bridge (2004) dismissed these geometries as well. Bridge (2004) has further argued that the fundamental building block of a fluvial reservoir is a channel belt (also referred to by others as a channel family or channel complex (Bratvold *et al.* 1994) because individual channels migrate so quickly within the limits of the belt that individual channels are rarely preserved (Mackey & Bridge 1995). If aggradation occurs during channel belt formation, a multi-storey sandstone body can result. Ironically, Van Wagoner (1995) argued that component bars may be the fundamental building blocks of fluvial reservoirs (see also, Patterson *et al.* 2002). Bridge's (2004) concerns are valid, and improving the ability to model depositional systems may lead to breakthroughs in understanding of such derivative reservoir properties as connectivity. Until 3D geostatistical reservoir characterizations can be created to the satisfaction of sedimentologists and stratigraphers, those who construct models must exercise more caution and creativity to ensure that limitations in programming do not hamper the ability to understand the implications of stratigraphic architecture. It is comforting to realize that most of the conclusions about 2D connectivity presented by Allen (1978, 1979), using the crudest of modelling techniques, are still embraced today.

HOW STATIC CONNECTIVITY INFLUENCES FLOW IN A RESERVOIR

Reservoir connectivity is an important concept because it is a stratigraphic variable that has clear and demonstrable impact on recovery. Figure 4A shows an example of a relatively straight channel connected to both producer and injector wells. Figure 4B is the identical channel to that shown in Figure 4A, connected to identical wells, except that there is a large unconnected sandstone body included in Figure 4B. The results of the waterflood flow simulation (Fig. 4C) for the channel configurations shown in Figures 4A, B are identical if recovery is plotted against time in days for either model. However, in Figure 4D, where recovery efficiency is plotted against time

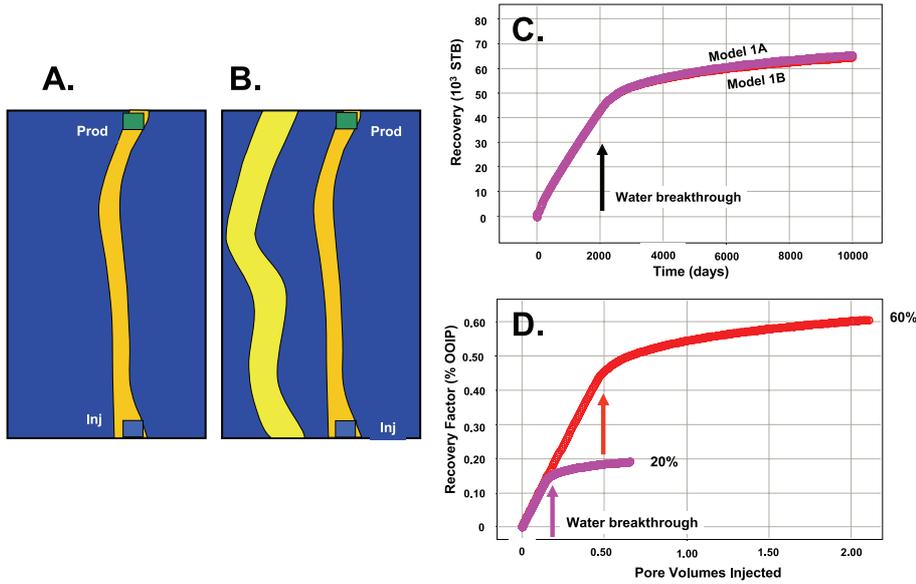


Fig. 4. (A) A single channel deposit penetrated by a producing and injecting well. (B) The same channel deposit as (A), but here an unconnected channel has been added. (C) Results of a waterflood simulation for the geological models shown in (A) and (B). Volume recovered is plotted as a function of time in days. Note the overlap of results from the two models. (D) Results of the same waterflood simulation in (C), but here percent recovery (oil produced divided by original oil in place) is plotted as a function of dimensionless time (Pore Volumes Injected, or PVI). Note that in (C) the effect of the unconnected volume is not accounted for, as it is in this figure. The effect of the unconnected volume is observed in the reduction of the recovery factor and the reduction in the PVI value (i.e. there is more reservoir volume to inject water into).

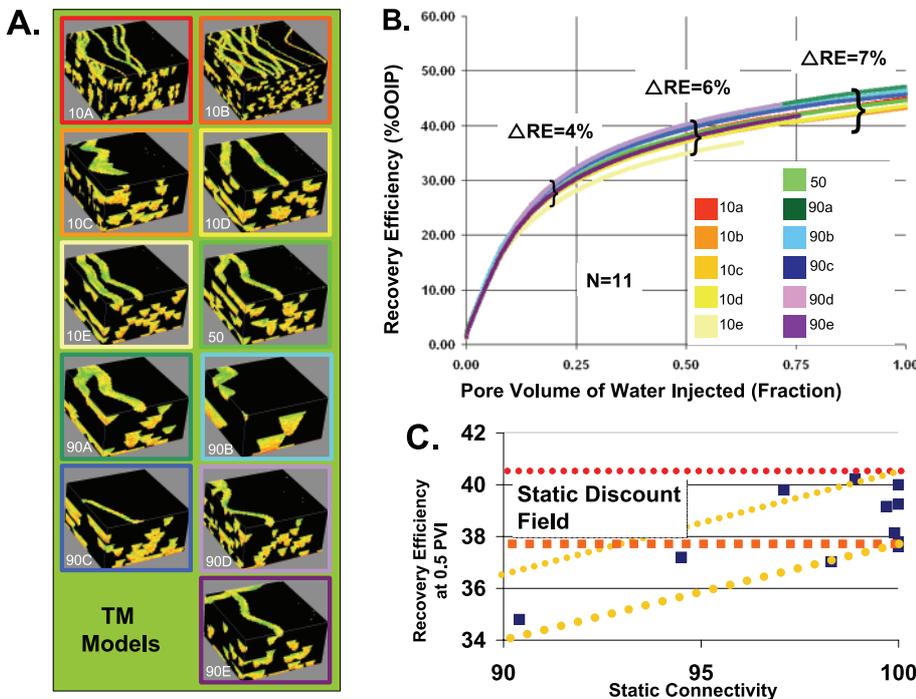


Fig. 5. (A) Examples of the 11 models constructed to exemplify subtle relationships between reservoir architecture, connectivity and waterflood recovery. The 11 models were constructed by varying characteristics described in Table 1. See text for discussion. (B) Results of waterflood simulation performed on the 11 models (see Larue & Friedmann 2005). Time is expressed as PVI, and recovery factor is relative to original oil in place (OOIP). (C) Recovery efficiency at 0.5 PVI is plotted as a function of reservoir connectivity. The red line shows the highest overall recovery efficiency, the orange line the lowest recovery efficiency at 100% connectivity. The yellow lines show the predicted reduction in recovery efficiency by removing connected volumes. See text for discussion.

expressed as pore volume of water injected (PVI), there are significantly different results. Figure 4D appears different from Figure 4C because the effects of the unconnected sandstone body are shown in Figure 4D (because percentage of oil recovered is plotted), but not in Figure 4C. Note that the total recovery from the model shown in Figure 4A after 2 PVI was 60%, and the total recovery from the model shown in Figure 4B after 0.7 PVI was 20%. The connectivity of the model shown in Figure 4A is 100% and in Figure 4B is 35%. Because only 35% of the reservoir is connected (that means 65% cannot be swept), the product of 35% and 60% is approximately 20%. That is, by knowing the recovery efficiency at a given time at 100% connectivity, one can approximate the recovery efficiency at 35% connectivity to a high degree of accuracy at a similar time step.

Figure 5A shows a suite of 11 conceptual channelized models that were constructed with identical geological characteristics at

35% net: gross, but ones in which reservoir architecture was varied systematically (Larue & Friedmann 2000, 2005). A set of five geological characteristics were defined with P10, P50 and P90 values (Table 1). The P50 case is a model constructed with

Table 1. Characteristics of channels used in model suite studies.

Characteristic	P10 value	P50 value	P90 value
Net: gross (%)		35	
A. Width/thickness	20	50	80
B. Channel thickness (m)	2	5	15
C. Stacking pattern	Bars ^a	Random	Clustered at base
D. Sinuosity	1.1	1.5	2.3
E. Deviation of channel (°)	±3	±30	±60

^aFeatures resembling point bars were formed when the channel width at meander inflection points was set to zero.

only P50 values. Then ten additional models were constructed using P50 values and one P10 or P90 value. The model name refers to which parameter was varied. A waterflood pore-voidage replacement simulation was performed on each model using a 110-acre well spacing. Results are shown in Figure 5B and the range in recovery efficiency at a given PVI is on the order of 5–7%. Given that the models are identical in all respects except reservoir architecture, what caused this variation in flow performance? Was it due to changes in reservoir architecture? Was it simply some random effect? In Figure 5C, the static connectivity of the models is plotted against the recovery after 0.5 PVI. There seems to be a weak linear trend, such that recovery efficiency appears to be related to connectivity. The red line in the figure shows the highest recovery efficiency of any model (approximately 40.5%) and the orange line shows the lowest recovery efficiency for any 100% connected model. The 2% spread in recovery efficiency between the orange and red lines is probably due to slight differences in permeability heterogeneity between the models. The yellow lines show how the recovery efficiency should degrade if reducing connectivity effectively removes ‘sweepable’ volumes from the reservoir. The slope of the upper yellow line predicts that if the recovery efficiency is 40.5% at 100% connectivity, then at 90% connectivity, the recovery efficiency should be about 36.5%. For the lower yellow line, the recovery efficiency should be about 34% at 90% connectivity. Note that the points, representing different flow simulation results, fall mostly between these lines. If a point falls above the band defined by the yellow lines, this means that sweep efficiency is enhanced with reduction of sweepable reservoir volume. If the points fall within the band, it means that reduction in connectivity effectively predicts reduction in recovery efficiency. Finally, if the points fall below the band, it means that other factors beyond static connectivity reduction may be reducing recovery efficiency.

Based on these two examples, a clear relationship between reservoir connectivity and flow performance can be expected.

CONNECTIVITY AS A FUNCTION OF NET: GROSS

Two dimensions: the ‘S-curve’

Four classic geological papers on two-dimensional aspects of channel connectivity were written by Allen (1978, 1979), King (1990) and Allard & HERESIM Group (1993). In these four studies, the 2D plane was vertical, so connectivity of channel deposits in cross-section was considered. The studies used simulations of channel geometry to address connectivity. King (1990) and Allard & HERESIM Group (1993) analysed connectivity using percolation theory and defined a percolation threshold in 2D at 66%. Percolation theory predicts that connectivity is very low until a percolation threshold is reached, after which connectivity approaches 100%. All studies concluded that there is a clear relationship between net: gross and connectivity, and there is significant decay in connectivity when net: gross values are less than about 60–70%. Figure 6 shows an example of a 2D plot of connectivity as a function of net: gross. To create Figure 6, 270 different Boolean models of channels were generated using a wide variety of channel characteristics. Connectivity of the reservoir to both a single injector and a producer well was measured and the results were plotted. The different coloured points in Figure 6 refer to different reservoir characteristics of the models (sinuosity and so on) which turned out to be non-distinctive in this case. Note the characteristic ‘S’ geometry of the plot: at net: gross values greater than 75%, connectivity is >95%. If net: gross values are from 50% to 75%, connectivity can be anything from 0% to 100%. This

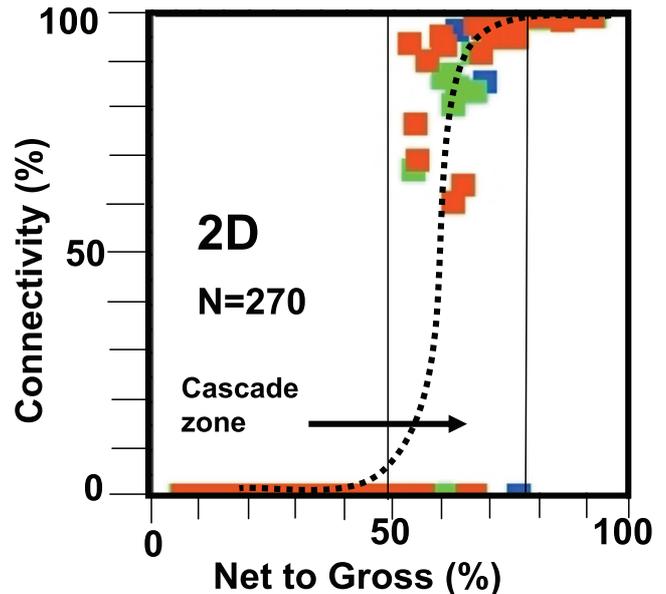


Fig. 6. Connectivity between a single producing and injecting well in a vertical 2D slice 2000 m long and 33 m thick plotted as a function of reservoir net: gross. Individual points represent results of connectivity measurement of different geological characterizations of different channel geometry types (shown in colours). A hand-drawn best-fit ‘S-curve’ is shown. The ‘cascade zone’ is defined as the zone of maximum uncertainty in connectivity as a function of net: gross.

zone is referred to here as the ‘cascade zone’, in which connectivity is predicted poorly. Below 50% net: gross, the connectivity is essentially 0% in this study.

Three dimensions: the ‘S-curve’

In King’s (1990) geobody connectivity study, only brief mention was made of the relationship between connectivity and net: gross in 3D; however, a 3D percolation threshold of 25% was defined. Other studies have shown that the percolation threshold in 3D for a variety of shapes is less than 20% (referenced in Korvin 1992). Figure 7 represents the same data as in Figure 6, but shows for the same grid and stratigraphic models the results of connectivity in 3D as a function of net: gross. In fact, to create the 2D data shown in Figure 6, a single plane cutting the 3D models and including the two wells was used. The shape of the ‘S-curve’ shown in Figure 7 is very similar to that shown in Figure 6, except the cascade zone extends from net: gross values of about 10% to 30% (see also Handyside *et al.* 1992). The tail of the ‘S-curve’, where net: gross is less than 10%, is defined poorly.

This ‘S-curve’ has considerable significance. It appears to show that if the net: gross of a reservoir is >30% the reservoir is highly connected. It appears to show that if the net: gross of a reservoir is <30% it may be poorly connected.

IMPACT OF WELL CONFIGURATION ON CONNECTIVITY

The main focus of the current study is stratigraphic factors that lead to reservoir connectivity. However, there are several non-stratigraphic factors that affect reservoir connectivity and there is a clear interplay between these factors and stratigraphic factors. First, as mentioned previously, faulting and folding can lead to structural compartmentalization (Fig. 1B). Because this study considers the relationship between wells and geobody connectivity, characteristics of the wells are significant.

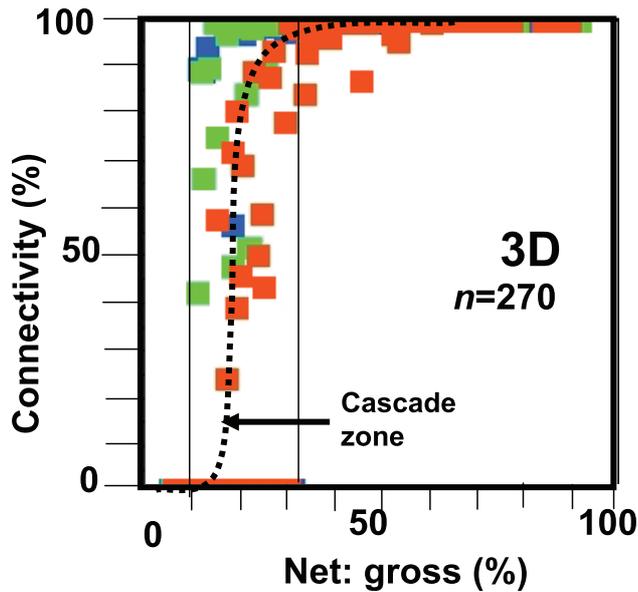


Fig. 7. Same data as Figure 6, but here the connectivity is measured in 3D in a volume $2000\text{ m} \times 2000\text{ m} \times 33\text{ m}$. Note the shifting of the ‘S-curve’ and the cascade zone to the left.

Figure 8A compares geobody connectivity, single injector or producer connectivity (that is, only two wells within the 2 km^2 area) and injector to producer connectivity for 200 conceptual reservoir characterizations. Note that the most rigorous of connectivity definitions – injector to producer connectivity (for example, Fig. 1F) – results in a slight shifting of the ‘S-curve’ to the right, toward worse connectivity. In Figure 8B, the influence of well count on connectivity is shown (see also Budding & Paardekam 1992). Note that for a 12-fold increase in well density, the cascade zone shifts to the left by about 10% in net: gross. To examine this effect more quantitatively, a suite of 200 geological models was built at 20%, 30% and 40% net: gross, and analysed for the two well groups (Fig. 8C). At 20% net: gross, the connectivity dropped 41%, whereas at 30% the connectivity dropped 10%, while at 40% the connectivity dropped only 3%. Differences in connectivity are largely associated with wells with zero connectivity or those that do not intersect the reservoir. In Figure 8D, the effects of completions are considered (for example, Fig. 1G). Only portions of wellbores are completed to minimize costs, or to prevent water influx. In one group of models, the entire 33 m wellbore is completed, whereas, in the second, only the top 3 m of the model is completed. In all cases, and as summarized in the embedded table, the average connectivity drops significantly (mostly due to 0% connectivity values). This large drop in connectivity is, in part, due to how the completions were defined: the top 3 m of the model was completed whether or not sandbodies were present, so these results represent an unrealistically pessimistic case. The impact of completions on connectivity is minimized with a higher well count (Fig. 8E). Orientation of the producer–injector pair, whether vertical or horizontal, and parallel or perpendicular to the channel direction, can also affect connectivity (Figs 8F, G) and is probably best considered on a case-by-case basis.

INCREASED VARIANCE OF GEOLOGICAL CHARACTERISTICS: STRATIGRAPHIC FACTORS

The eleven geological models shown in Figure 5 were created by changing geological characteristics one by one at a fixed net: gross value of 35% (Table 1). Additional models were built

using parameters described in Table 1 at net: gross values between 0% and 100%. Three hundred realizations were created for each model type. Producer–injector reservoir connectivity for a single well pair (again, two wells in a 2 km^2 area) was calculated for each model realization and results are plotted as a function of net: gross in Figure 9. The resulting ‘S-curve’ shows much greater variability than that shown in Figure 7. Figure 9L summarizes each model type (Figs 9A–K) and shows reservoir connectivity for net: gross values greater than 35%: in this way, stratigraphic factors that lead to worse connectivity can be analysed quickly. Geological factors that promote greater variance in connectivity are straighter (Fig. 9D), more parallel (Fig. 9E), wider (Fig. 9G) and thicker (Fig. 9H) channels, relative to the average channel values shown in Table 1. Geological factors that promote less variance in connectivity relative to the average values are thinner (Fig. 9B), narrower (Fig. 9A), more sinuous (Fig. 9J), non-parallel (Fig. 9K) channel deposits. In addition, channel deposits composed of bars also tend to show better connectivity than the average values (Fig. 9C). Clearly, there is a relationship between reservoir architecture and reservoir connectivity. The origins of this relationship and, more generally, factors that tend to increase or decrease connectivity, will be the subject of continued investigation in this study.

FACTORS THAT IMPROVE CONNECTIVITY: SHIFTING THE ‘S-CURVE’ TO THE LEFT

Although the shapes of the ‘S-curves’ shown in Figures 7 and 9 would appear to represent relatively optimistic reservoir conditions, they can be made even more optimistic under certain stratigraphic conditions. To make the ‘S-curve’ more optimistic, higher connectivities would be observed in lower net: gross rocks. How can this occur? In a mud-rich setting, why would connectivity be high?

Overbank sandy facies

Clearly, the occurrence of overbank sandy facies, such as sandy levees, crevasse-splay or sheet-flood deposits could serve to connect unconnected channel deposits at any net: gross (Fig. 10A). Sandy overbank facies may be characterized by different permeability distributions and by variable and uncertain continuity. However, clearly they could serve as important lateral conduits in channelized successions.

Width to thickness ratios of channel deposits

If the width to thickness ratio of channel deposits was extremely high, or if sheet-like deposits were present, then connectivity could be achieved at very low net: gross values (Fig. 10B). Channel complexes represent the lateral and vertical amalgamation of smaller channel bodies, such that the channel complex has a larger width/thickness ratio (Fig. 10C). This enhanced width/thickness ratio should increase connectivity at low net: gross values. For the models described in Figure 9, better connectivity was shown to be associated with narrower channel deposits than wider channel deposits (compare Figs 9A and G). This apparent refutation of the proposed relationship between channel width and enhanced connectivity is a function of the grid volume and the modelling process. At low net: gross values, it is more likely that edges of channels are inserted into the grid (that is, the channel centre is located outside of the grid volume) and connectivity is limited by channel edges. However, this effect is really a function of the size of the object to the volume of the study area (a volume effect) and is described in greater detail later.

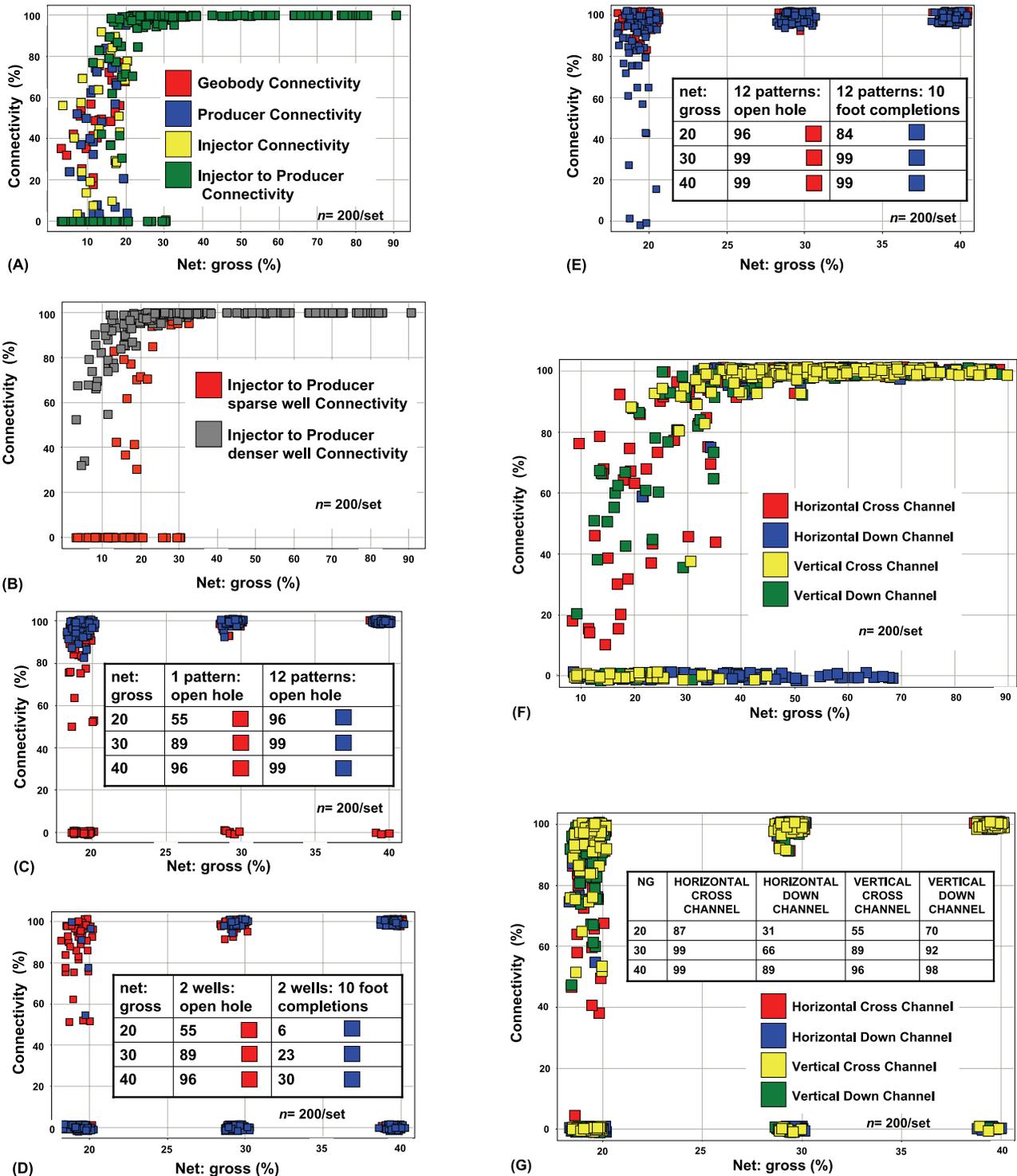


Fig. 8. (A) Three-dimensional connectivity for 200 conceptual Boolean models. Four types of connectivity were measured: geobody connectivity, connectivity to the producer well, connectivity to the injector well, and connectivity from the injector to the producer well. Note that the connectivity from injector to producer is slightly more pessimistic than the other types of connectivity (that is, the ‘S-curve’ is shifted to the right), which largely overlap. (B) Influence of well density on connectivity. Here, 3D injector to producer connectivity is compared for one well pair versus 12 well pairs in the 4 km² area. (C) Six hundred additional geological realizations were created at net: gross values of 20%, 30% and 40%, and connectivities were compared for one injector–producer pair and 12 pairs (patterns). Average results are summarized in the table, and show that the importance of well density for reservoir connectivity diminishes at higher net: gross values. Note that the most significance impact on average connectivity for the 30% and 40% net: gross examples are wells that do not intersect reservoir (i.e. wells in which connectivity is 0%). (D) The importance of the completion interval is shown for the same dataset as in (C). The connectivity of two wells with open-hole completions is compared with two wells with 10 ft (3 m) completions. The effect of the limited completions was made worse because no requirement for sand presence was made (although no requirement for sand presence was made for the open hole either). Average results shown in table. (E) The importance of the completion interval is shown for the same dataset as in (C). The connectivity of 12 well pairs (or patterns) with open-hole completions is compared with 12 well pairs with 10 ft completions. The effect of the limited completions was made worse because no requirement for sand presence was made (although no requirement for sand presence was made for the open hole either). Average results shown in table. (F) Effect of well orientation with respect to stratigraphic trend is shown for the same model dataset. Connectivity of vertical well pairs in cross-channel and down-channel directions is compared. Connectivity of horizontal well pairs oriented cross channel and down channel is compared. (G) Using the dataset of (C), well orientation connectivity effects are studied at 20%, 30% and 40% net: gross.

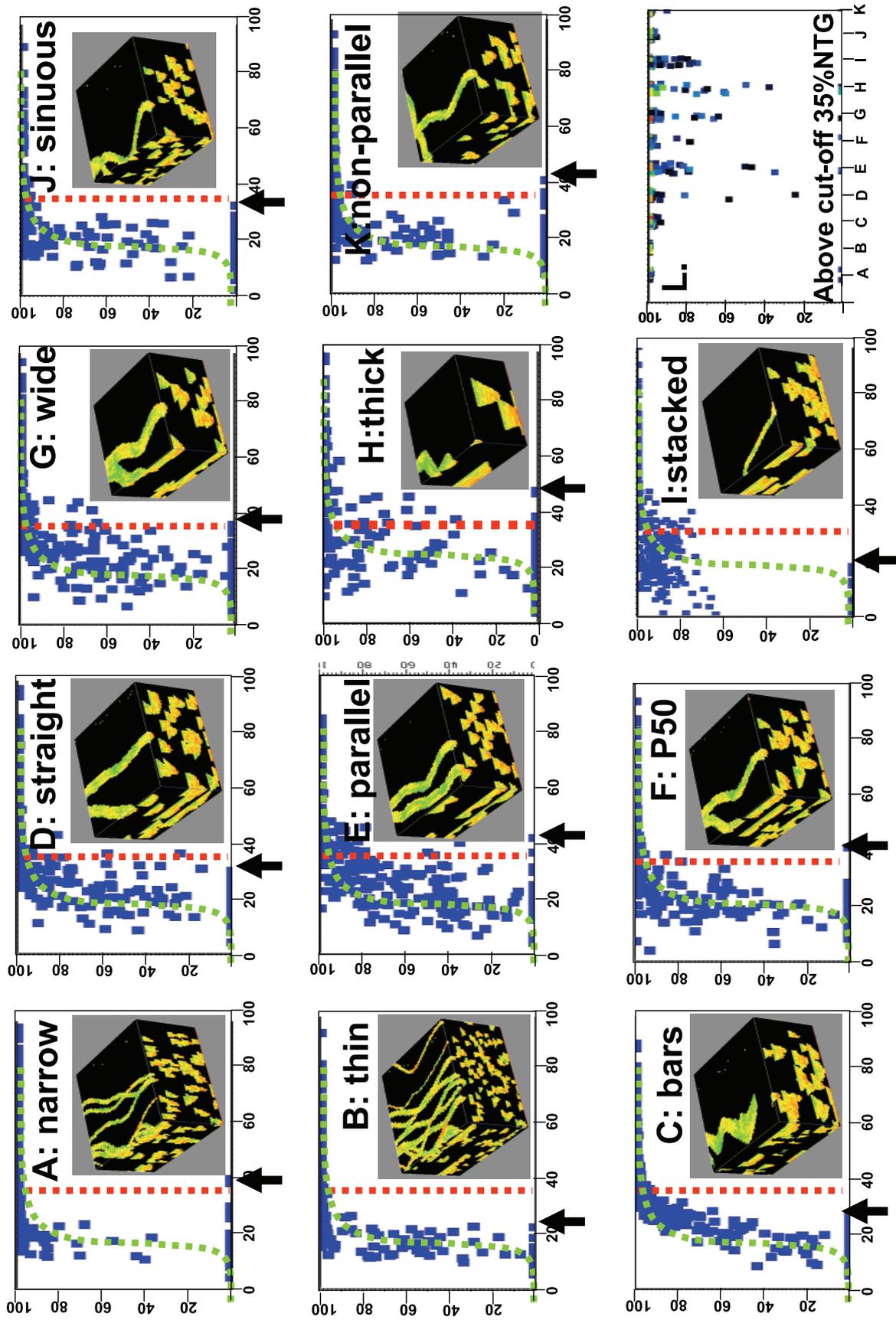


Fig. 9. Results of thousands of geological simulations of channels and reservoir elements of different geometries. Each point represents measurement of injector to producer connectivity on a separate geological characterization. Each geological model is $2000\text{ m} \times 2000\text{ m} \times 33\text{ m}$. Basic geological parameters for creating the models are shown in Table 1, only net: gross values are allowed to vary between 0% and 100%. The arrow at the bottom of each graph shows the highest net: gross with 0% connectivity and ranges from 20–40% net: gross. The red line shows the 35% demarcation point used in Figure 9L. (A) Narrow channels; channel width/thickness ratio is 20. All other values are shown as P50 values in Table 1. (B) Thin channels, 2 m thick. (C) Channel bars represent the dominant fluvial element. (D) Straight channels. (E) Parallel channels. (F) P50 case in Table 1. (G) Wide channels, in which width/thickness is 80. (H) Thick channels, 15 m thick. (I) Stacked channels, in which more channels occur near the base of the model. (J) Sinuous channels, with sinuosity of about 2.3. (K) Non-parallel channels, showing large deviation in orientation. (L) Summary plot: connectivity for models with net: gross greater than 35% plotted against run number. See text for discussion.

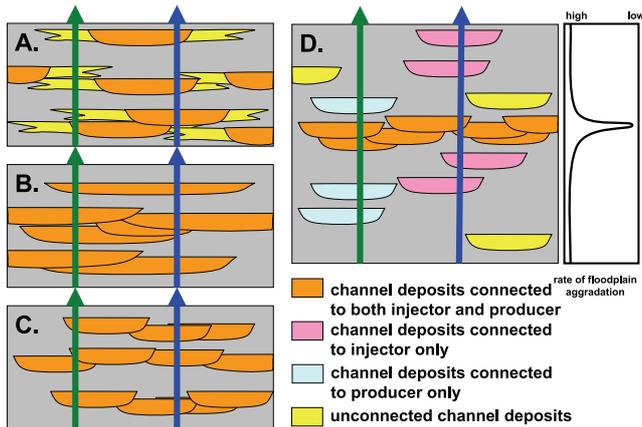


Fig. 10. Stratigraphic factors that cause shifting of the 'S-curve' to the left, toward better connectivity. (A) Channel width can be augmented by lateral sandy facies such as crevasse splays and levees. (B) Channels with high width/thickness ratio will tend to shift the 'S-curve' to the left, although a volume support effect can complicate interpretations (see text for discussion). (C) Genetic clusters of channels, also known as channel belts, channel families or channel complexes result in reservoir units with greater width/thickness ratio. (D) Due to periods of minimal floodplain aggradation, lateral channel shifting results in lateral channel amalgamation and formation of complexes that have greater width/thickness ratios.

By making the channel deposits even wider, relative to thickness, connectivity will increase at a given net: gross. In the limiting case of sheet deposits that extend over the entire reservoir area, 100% connectivity could be achieved even if the net: gross value was exceedingly low.

Variable floodplain aggradation rates

If the rate of floodplain aggradation was punctuated, such that periods of rapid aggradation alternated with periods of slow aggradation, channelized sheets could be formed amidst disconnected channel deposits (Fig. 10D). That is, during periods of rapid floodplain aggradation, abundant muddy overbank deposits would be preserved. During periods of slow floodplain aggradation, mostly erosive channel deposits would be preserved, and abundant lateral amalgamation would occur, forming channelized sheets. The formation of these channelized sheets is compatible with interpretations based on sequence stratigraphic concepts (Shanley & McCabe 1994). Of course, net: gross is actually changing in the vertical sense, such that periods of low aggradation rates are associated with preservation of higher net: gross intervals. However, vertical variations in net: gross are commonly missed in stratigraphic studies that do not emphasize sequence stratigraphic concepts.

FACTORS THAT REDUCE CONNECTIVITY: SHIFTING THE 'S-CURVE' TO THE RIGHT

How can the 'S-curve' in Figure 7 be made to be less optimistic? How can lower connectivities occur at higher net: gross ratios? If reservoirs were two dimensional, then their connectivity would be greatly reduced, but how can a reservoir be 2D? In outcrops of cliff faces or in cross-section (such as those shown in Fig. 1), channel deposits that do not intersect in 2D may intersect in 3D. Quasi-two-dimensional reservoirs do exist in nature and there are essentially two types.

Two-dimensional reservoirs with parallel channel deposits

If channels are relatively straight and parallel, and therefore do not intersect in a given stratigraphic layer, the reservoir will

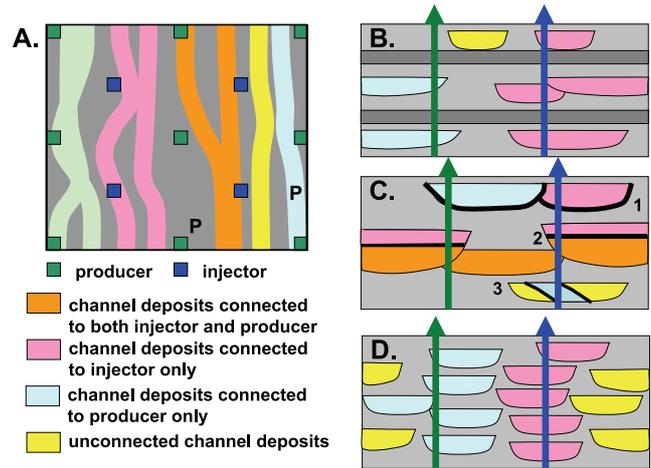


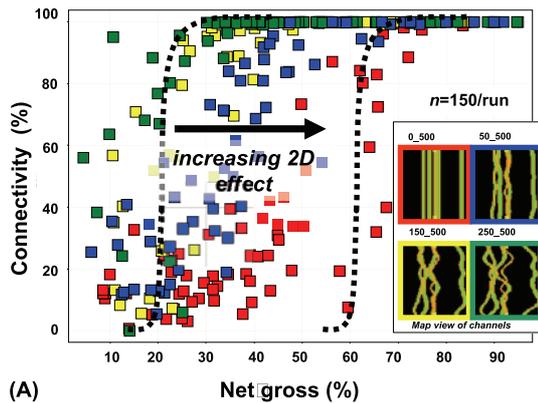
Fig. 11. Stratigraphic factors that cause shifting of the 'S-curve' to the right, toward worse connectivity. (A) Strongly parallel channel paths tend not to intersect in map-view, causing 2D connectivity in that plane. Note the complex relationships between injector and producer wells. (B) Continuous mudstone units between thin channelized units stratify the reservoir such that it behaves as a series of 2D volumes. (C) Local heterogeneous impermeable units compartmentalize the reservoir. In the top (1), a mudstone drape coats the base of the channel, causing compartmentalization between otherwise amalgamated channels. In the centre (2), continuous horizontal mudstone beds within a channel can also effectively compartmentalize the reservoir. Finally, near the bottom (3), inclined heterolithic units can cause reservoir compartmentalization. (D) Compensational stacking of channels could in theory result in a poorly connected sand-rich reservoir. See text for discussion.

behave as a quasi-2D model (obviously, what happens above and below the given time slice can affect the true two dimensionality of the model). Figure 11A shows a conceptual example of parallel channels in a waterflood situation. Because of parallelism of the channels, there is relatively poor connectivity at least in the plane of this figure. Results of modelling channels that range in character from perfectly straight and parallel to parallel and sinuous are shown in Figure 12A. Perfectly parallel straight channel deposits in three dimensions should behave as quasi-2D objects and this is observed in Figure 12A. As the straight parallel channel deposits become progressively more sinuous, the connectivity shifts from 2D to 3D. In Figure 12B, results of modelling channel deposits that range in character from perfectly straight and parallel to straight and deviated in orientation are shown. In a similar way to the example of sinuous channel deposits, as the straight and parallel channel deposits become progressively more varied in orientation, the connectivity shifts from 2D to 3D.

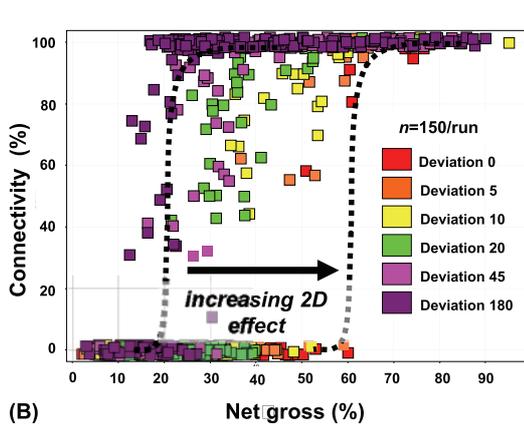
The poorer connectivity noted previously of models shown in Figure 9E relative to Figure 9K is apparently associated with a weak 2D component to the models.

Two-dimensional sheeted reservoirs

Quasi-2D reservoirs may result from laterally continuous heterogeneities (Fig. 11B). If a reservoir is vertically stratified into separate reservoir compartments, and the stratification thickness is approximately the same as the channel thickness, then the reservoir will behave as a quasi-2D reservoir. Mudstones deposited on top of flooding surfaces or abandonment surfaces in fluvial strata, or associated with condensed intervals could cause vertical stratification. Vertical reservoir stratification could also be produced by continuous muddy debris flow units, continuous hemipelagic intervals, or continuous muddy turbidite deposits. Essentially any impermeable mudstone unit



(A)



(B)

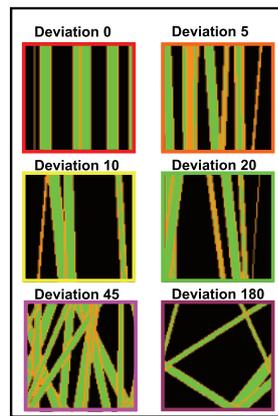


Fig. 12. Plots of connectivity, as a function of net: gross, for: (A) models containing straight and parallel to sinuous and parallel channels; (B) models containing straight and parallel to straight and deviated channels. Results are colour coded to match box perimeter colour: parallel channel data points shown in red, and so on. Note the transitional behaviour between 2D and 3D connectivity.

that is continuous across the entire reservoir and forms reservoir compartments on the order of the thickness of the channel deposits can cause two-dimensional connectivity (Fig. 11B). The effects of reservoir stratification based on analysis of connectivity in conceptual models are shown in Figure 13. As the thickness of the reservoir interval increases relative to the thickness of the reservoir element, the connectivity behaves in a progressively more 3D fashion. 2D or transitional 2D connectivity exists in these models at up to two times channel thickness, beyond which, connectivity as a function of net: gross is essentially 3D.

Local mudstone beds

A third way in which connectivity can be reduced is through compartmentalization by local mudstone beds. There are three types of local mudstone beds shown in Figure 11C that can affect reservoir connectivity. The uppermost channels in Figure 11C are affected by mudstone drapes that cover the entire erosional surface. The interpreted origin of the mudstone and siltstone drapes (Beauboeuf *et al.* 1999) is that the erosional event that cut the channel transported sediment in a downslope direction, bypassing deposition in the channel at the location of the outcrop. A dilute turbidite drape of siltstone and/or mudstone subsequently covered the erosional scar. The topographic depression of the channel was filled later with sandstones that erode the basal siltstone drape only partly. For compartmentalization to occur, the mudstone or siltstone drapes must be relatively continuous (Barton *et al.* 2004; Larue 2004). Such highly continuous drapes have not been described in outcrop examples to date, so the continuity shown in Figure 11C is speculative, although possible. Mud-clast conglomerates could conceivably form permeability barriers at channel bases if mud-clast density is high enough (for example, North & Taylor 1996). A second way in which local mudstone beds can reduce

connectivity (Fig. 11C) is where the mudstone beds are continuous across local channel deposits (Larue 2004). Because of the combination of a continuous mudstone bed within a

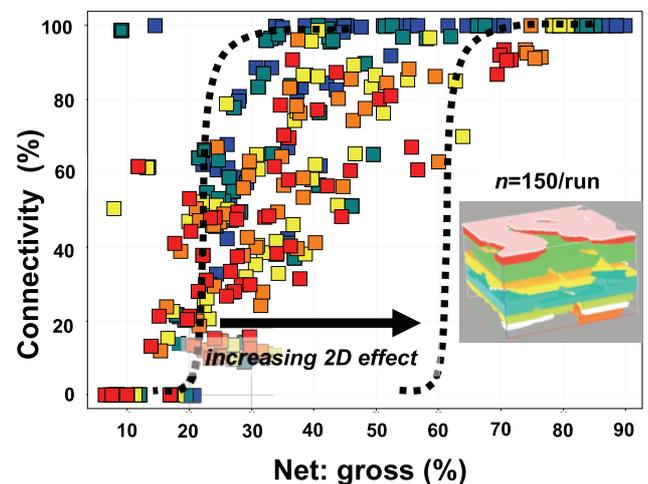


Fig. 13. Plot of connectivity as a function of net: gross for vertically compartmentalized stratified units. The coloured points show differing degrees of stratification. Layering was added by progressively splitting the grid using impermeable mudstones. An approximate scale is shown relative to channel thickness. Note the transitional behaviour between 2D and 3D connectivity.

channelized body, a disconnected sandstone body can result. The third way in which local mudstone beds can reduce connectivity (Fig. 11C, bottom) is where mud-draped clinoforms compartmentalize the reservoir. Mud-draped clinoforms within a channel can be associated with lateral accretion surfaces and inclined heterolithic stratification (Thomas *et al.* 1987).

Compensational stacking of channels

There are several ways in which channel deposits can be modelled. Channel deposits can be modelled such that there is equal probability that a channel can occur anywhere in the simulation volume. Channel deposits can also be modelled such that there are vertical and/or lateral trends, and channels are more likely to occur in some places than others. Channel clustering can also be accomplished by modelling channel families, which are groups of spatially related channel deposits (Bratvold *et al.* 1994; Tyler *et al.* 1995). More generally, attraction or repulsion properties may be assigned such that channels tend to cluster or avoid one another spatially. All of these approaches are stochastic representations of natural processes. In general, when a given channel is simulated using standard geostatistical techniques, it does not know about channels that have been deposited previously in the same area.

In the case of compensational stacking, the position of an underlying deposit strongly impacts the position of subsequent deposits (for examples, Mutti & Sonnino 1981; King & Browne 2001). For example, if a submarine channel is filled with sandstone, and the adjacent mudstones compact around this sandstone, then the channel deposit will form a topographic ridge that subsequent channel deposits could avoid (Fig. 11D). Such compensational stacking could lead to relatively high net: gross reservoirs (60%?) with poor connectivity. However, it is important to stress that most compensational stacking patterns have been defined for depositional lobes (Mutti & Sonnino 1981), channel complexes and larger-scale submarine fan features (King & Browne 2001). What is not known is how fine a scale such compensational stacking patterns can be, how to model them or what the connectivity might be. A modelling program for submarine channel deposition that addressed compensational stacking patterns was created by Jones & Larue (1997).

FACTORS THAT AFFECT CONNECTIVITY: SHIFTING THE 'S-CURVE' IN EITHER DIRECTION

Volume support

Volume support addresses the issue of whether there is sufficient reservoir volume for connectivity to be achieved (King 1990). Referring again to Figure 9, models with more varied connectivity are those in which the ratio of the volume of the channel object to the volume of the containing box is highest (Figs 9G, H). Conversely, models with channel deposits of lesser volume relative to the volume of the container have less variance in connectivity (Figs 9A, B, C).

An example of the importance of support volume is shown in Figure 14. In this example, five identical channel models were built, where channel width/thickness and net: gross were the only variables. As the channel deposits become bigger relative to the volume of the gridded volume, the resulting connectivity becomes more variable. King (1990) showed that in 2D, volume support effects tend to flatten the 'S-curve' such that above the percolation threshold, connectivity is reduced,

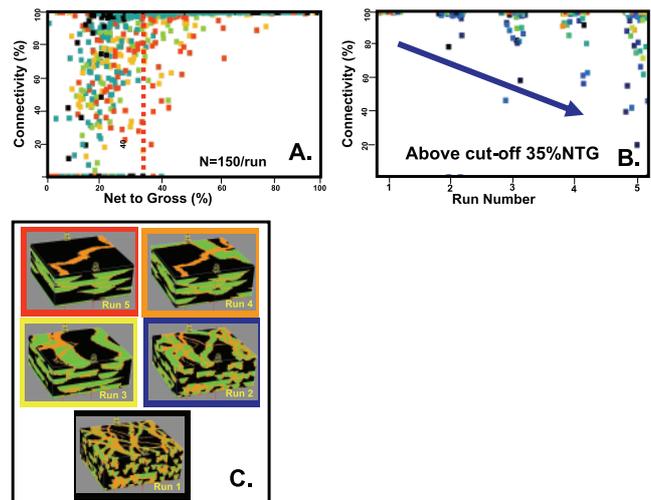


Fig. 14. (A) Example of volume support issue. A series of identical models were constructed at a range of net: gross values, but the width of the channel was increased in each model. (B) Plot of connectivity as a function of model run, for model runs in which the net: gross was greater than 35%. With increasing model run, the connectivity becomes progressively worse, which is a function of volume support. (C) Examples of the models used to study volume support.

while below the percolation threshold, connectivity tends to be increased.

EXAMPLES OF OTHER STRATIGRAPHIC FACTORS THAT MAY AFFECT RESERVOIR CONNECTIVITY

In the search for other factors that may affect reservoir connectivity, several other stratigraphic situations and processes were studied.

Connectivity of cell-based geological models

Boolean modelling techniques were used in this study to characterize channel deposits in 3D. Another modelling technique commonly employed in the petroleum industry uses a cell-based or pixel-based approach (Deutsch & Journel 1997). Cell-based models rely on variograms to distribute rock properties throughout the model. Key characteristics of variograms are their type and range. Common types of variograms are spherical, Gaussian and exponential, characterized by difference rates of change in variance with distance. Variogram range is a measure of continuity in 3D. In this experiment, horizontal variogram range was varied for exponential variograms. Connectivity is plotted as a function of net: gross in Figures 15A–G. For shorter ranges relative to the volume of the grid, the typical 'S-curve' is produced from the simulation results, in which connectivity rapidly diminishes at net: gross values less than about 35% (Figs 15A–C). In Figures 15D–G, there is progressively greater scatter in the 'S-curve' for a given net: gross. This increase in scatter is due to two effects – increasing width/thickness of the facies continuity and volume support effects. Increasing the continuity range has a similar effect to increasing the width/thickness of the facies bodies. This allows higher connectivity at lower net: gross values. However, as the continuity range is increased, there are also increasing examples of lower connectivity at higher net: gross values. This volume support effect is due to the fact that the volume of the box is limited relative to the size of the modelled continuity. In

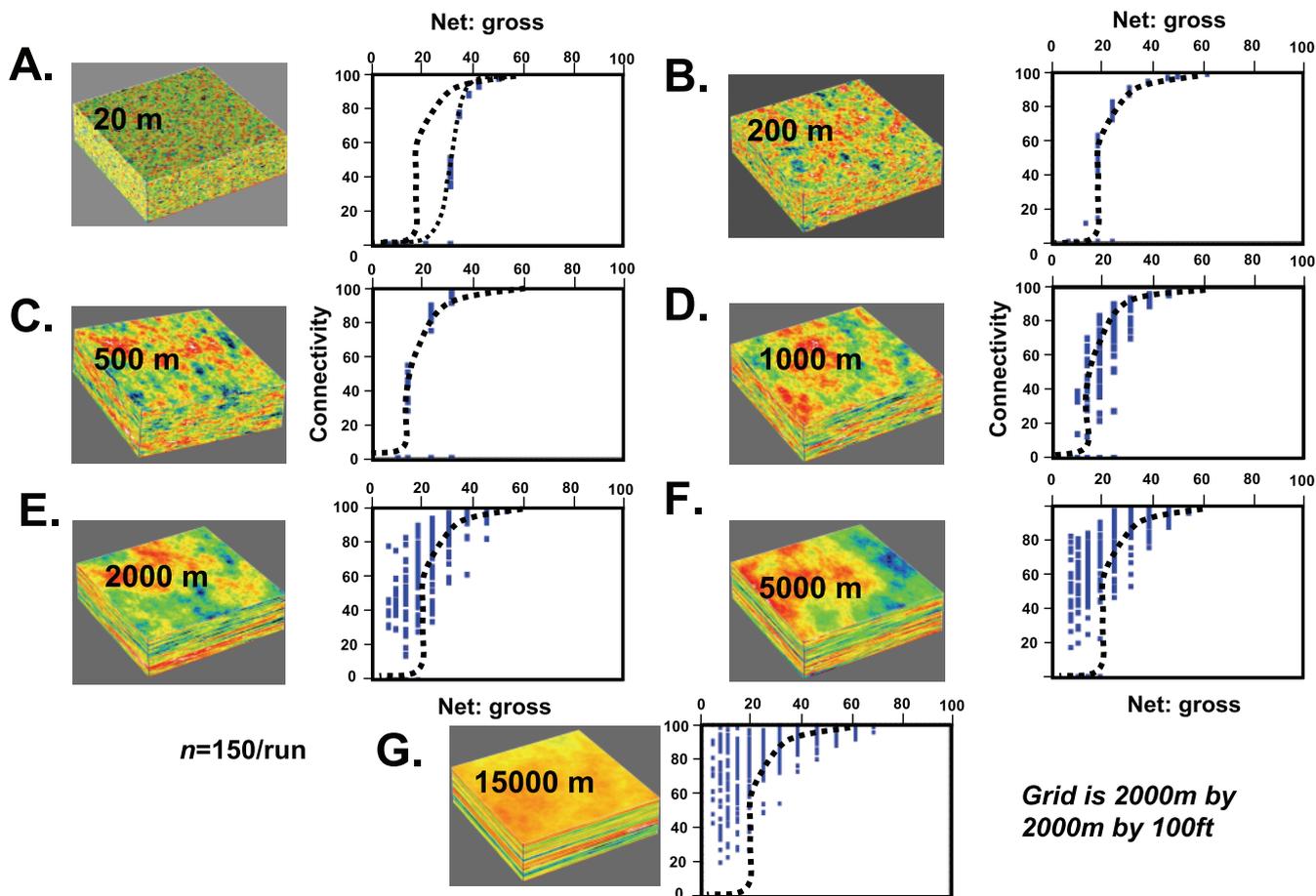


Fig. 15. Example of connectivity as a function of net: gross for cell-based models. Variogram horizontal range, a measure of continuity, has been increased from 20 m to 15 km. An ‘S-curve’ was hand-drawn in (A) and (B), and the ‘S-curve’ for (B) was applied to all graphs for comparison. The increase in point scatter from (D) to (G) is a function of volume support (finite size of the grid relative to the correlation length). Grid and cell dimensions as in Figure 9.

general, the results of the cell-based modelling exercise are compatible with the previous simulation results for Boolean models. Additional models were created using a MPS technique (for example, Strebelle 2002) and results were similar to those of the cell-based and Boolean modelling approaches.

Shale-filled channels

In the previous Boolean models that were constructed, it was assumed that channels consisted entirely of pay (i.e. were sandstones) and that overbank deposits contained no pay (i.e. were mudstones). Channels filled with siltstones and mudstones are present in deep-water reservoirs and may affect the continuity or connectivity of reservoirs (Clark & Pickering 1996). In this experiment (Fig. 16), mudstone-filled channels were randomly inserted into the Boolean model. This was to test the hypothesis that connectivity as a function of net: gross might be affected by architecture of the channelized mudstone facies. However, there was no significant or obvious change in the resulting ‘S-curve’ in which connectivity is plotted against net: gross of the reservoir.

Nested modelling

It has been long established that stratigraphic objects have hierarchical size distributions (Jackson 1975). For example, in channelized reservoirs, hierarchical distributions are observed from beds to bedsets or facies, to bar deposits, to channel

deposits to valleys. Could this hierarchical arrangement of depositional characteristics influence connectivity? To test this hypothesis, a suite of models was constructed in which complex distributions of sandstone occurred within channel deposits (Fig. 17). Injector to producer connectivity was studied in each model realization. Within a given channel architecture, the net: gross was varied using cell-based modelling and variable variogram continuity lengths. However, there was no strong effect on the resulting ‘S-curve’.

ADDITIONAL COMMENTS ON FACTORS INFLUENCING CONNECTIVITY

Correctly defining net: gross

In this study, the ‘S-curve’ was defined as the relationship between net: gross and connectivity. Net: gross was always assumed to be a primary predictor of connectivity. However, net: gross may be difficult to define. In Figure 10C, variable net: gross with vertical thickness was exemplified. There are three different realms of net: gross shown in Figure 10C: a lower and upper low net: gross interval, and a medial high net: gross interval. Uncertainty in the vertical distribution of net: gross is also possible or expected in a lateral sense. In Figure 11B, five different net: gross intervals are shown, two in which the net: gross is zero. These examples serve to show that the definition of net: gross can have considerable impact on the predictions of static connectivity for a given well distribution.

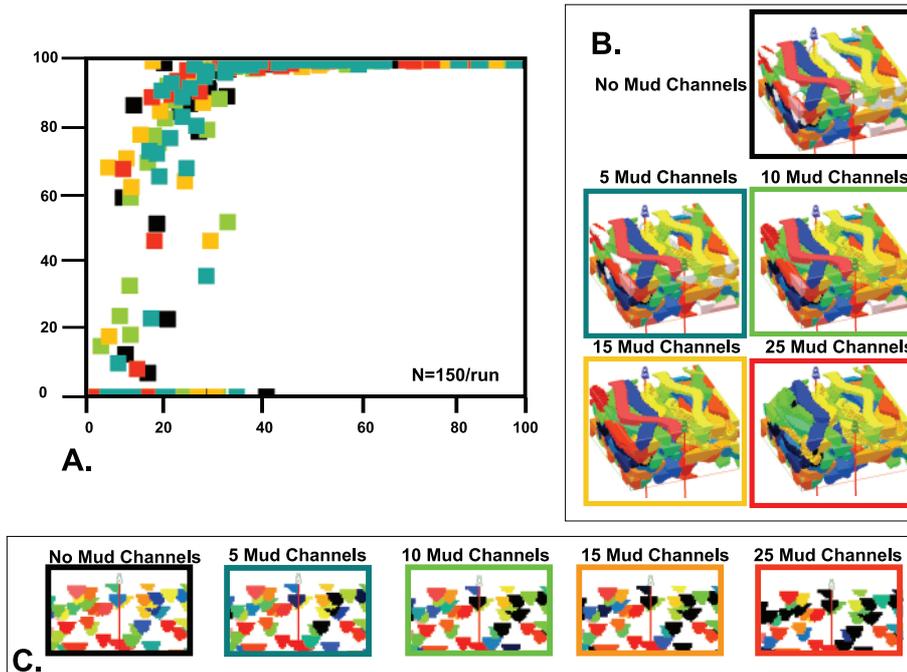


Fig. 16. Connectivity degradation by shale-filled channels. Different quantities of shale-filled channels were added to model simulations to test the effect of connectivity degradation by shale-filled channels. See text for discussion. (A) Plot of connectivity as a function of net: gross for models with different amounts of shale-filled channels. (B) Example of oblique view of sand-filled and shale-filled channels. Shale-filled channels have been removed for the model. (C) Cross-section view of sand-filled and shale-filled (black) channels..

Interplay of fault compartmentalization and reservoir connectivity

Although faulting is clearly one of the major causes for aerial compartmentalization of reservoirs (Fig. 1B), the present study has concentrated on stratigraphic origins of reservoir compartments. There is an interesting potential interplay between fault compartmentalization and reservoir connectivity. Previous

studies have noted that reservoirs tend to become more structurally compartmentalized with production history due to the increase in the amount of data with time, primarily well-based and production (for example, Bentley & Barry 1991; Demyttenaere *et al.* 1993). As it becomes apparent that a reservoir is more structurally compartmentalized than previously believed, this reduction in support volume should lead to reassessment of the potential for additional stratigraphic compartmentalization as well. That is, it was shown previously that reducing the support volume of a reservoir typically impacts the static connectivity of the reservoir negatively.

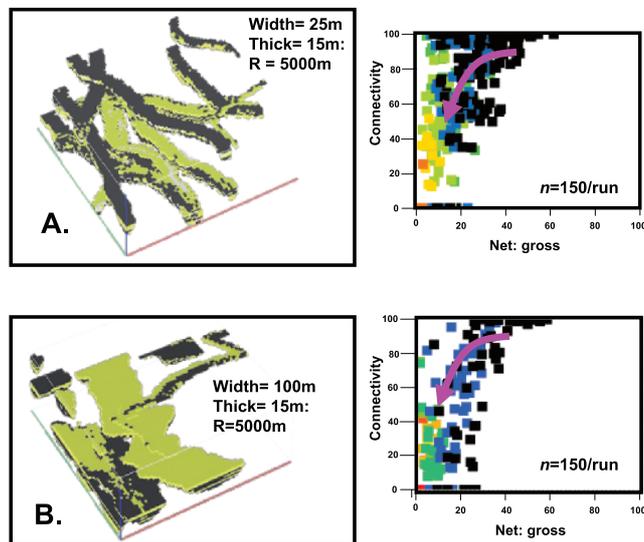


Fig. 17. The effect of nested architecture on reservoir connectivity. Two examples of channel architecture are shown with variable channel fill of sandstone and shale. In these models, mudstone can occur both as overbank deposits and as shales deposited within the channels. The set of models was characterized by channel width/thickness ratios of (A) 25 and (B) of 100, both with variable quantities of shale infilling the channel deposits. Range of the variogram for modelling shale was 5000 m to ensure that the layering was continuous. As the amount of shale increased within the channel fill, the connectivity tended to follow the direction shown by the purple arrow, toward better connectivity at lower net: gross values. This is probably because the ordering of the channels enhances connectivity.

Connectivity as a function of distance: dynamic interpretations of connectivity

As has been demonstrated herein, calculation of reservoir connectivity in 3D models tends to give optimistic results. For net: gross values greater than about 30% – and barring other complications or situations described above – connectivity tends to be >90% and therefore does not impact recovery efficiency significantly. As a result, there have been attempts to redefine connectivity such that it is more sensitive to geological situations. One such attempt is to define connectivity as a function of distance (for example, Hird & Dubrule 1998). Connectivity as a function of distance addresses the fact that infinite time is not available to drain tortuously connected reservoirs, such as those portrayed in Figures 2A–C. By defining some characteristic length away from the well, a more conservative definition of connectivity can be made. Connectivity as a function of distance represents an important direction in connectivity studies.

CONCLUSIONS

A fundamental ‘S-curve’ relationship between net: gross and reservoir connectivity has been described, as well as means in which the ‘S-curve’ can be translated to enhance or degrade reservoir connectivity as a function of net: gross. Although results are based on geostatistical models, general conclusions are believed applicable to reservoir characterization studies. Any use of conclusions presented herein must be made in

Table 2. *Enhancing and degrading connectivity at a given net: gross.*

Effect	Effect on connectivity	Recognition in reservoir
Reservoir element aspect ratio (w/th)	Greater width/thickness enhances connectivity	Continuity of reservoir element in well logs; depositional interpretation, statistical techniques, outcrop analogues, seismic stratal slice
Variable aggradation rates of overbank	Local zones of greater width/thickness in reservoir enhanced connectivity	Sequence stratigraphic analysis, analysis of clustering of channels as a function of stratigraphic position, continuity of reservoir element in well logs
Parallel channels	Parallel channel deposits make reservoir behave as 2D and degrade connectivity	Recognition in seismic stratal slice, or based on depositional interpretation (Barton <i>et al.</i> 2004)
Sheeted reservoir intervals	Thin sheets of reservoir intervals separated by continuous mudstone or non-reservoir make reservoir behave as 2D and degrade connectivity	Recognition of continuous mudstone units separating sandstone units that are essentially one element thick (for example, one channel deposit thick)
Compensation channel stacking	Channels are deposited such that they avoid intersecting, degrading connectivity	No criteria for recognition established yet, no strong proof that true compensational stacking occurs at the channel scale, although observations of compensational channel complexes have been made (see text)
Continuous mudstone layers	Mudstone layers draping channel bases and/or continuous mudstone beds within channel deposits form separate reservoir compartments, degrading connectivity	Check core, image logs or wireline logs for evidence of mudstones along erosional bases, or thick potentially continuous mudstone beds within channel deposits. Mudstone beds within channels that could compartmentalize the reservoir include impermeable debris flow units and hemipelagic or pelagic units.
Volume support	Reservoir connectivity is a function of the size of the container. As reservoir element approaches container size, connectivity is more uncertain and may be degraded.	Volume support effect typically occurs when the length scale of the reservoir element approaches that of the total reservoir volume. Given the container size was 2000 m, in the current study, volume effects were noted when reservoir element width or continuity was 200 m or greater for Boolean models and 1000 m or greater for cell-based models.

light of non-stationarity issues, sequence stratigraphic origins and non-random stacking patterns, as described in the text previously.

Table 2 discusses some of the factors found to enhance or degrade reservoir connectivity and how to recognize these effects in a given field. For example, large reservoir element width/thickness ratios clearly enhance connectivity in absence of volume support effects (Figs 10A, B). Reservoir element width/thickness can be determined using well-log correlation studies, charts of width/thickness, statistical techniques or based on sequence stratigraphic studies. Variable aggradation rates of a floodplain (Fig. 10D) can result in enhanced or degraded reservoir connectivity and can be established through sequence stratigraphic studies. Two-dimensional effects, such as parallel channel deposits and thin sheets of reservoir, can result in poorly connected reservoirs. Recognition of parallel channel deposits (Fig. 2C) can be made through reservoir architecture studies (Barton *et al.* 2004), seismic analysis and possibly through production studies. Recognition of sheeted reservoir intervals can be made through well-log correlation studies tied to core studies. A two-dimensional sheeted reservoir is defined as one whose reservoir element thickness (for example channel thickness) is approximately the same as the reservoir interval thickness (Fig. 11B). Certain types of continuous mudstone beds, including basal mudstone beds and continuous mudstones within channel fills, can compartmentalize reservoirs with respect to wells (Fig. 11C). Recognition of continuous mudstone beds can be made through core and well-log study. Key features are thick mudstone beds along channel bottoms, and thick mudstone or debris flow units within channel deposits. Compensational stacking can occur when channels are deposited while avoiding the position of underlying channels (Fig. 11D). Recognition of compensational stacking patterns has only been made in depositional lobes and channel complexes, and not at the channel deposit scale,

though this could occur. Finally, the size of the gross container can affect reservoir connectivity (Figs 14A–C). If the size of the reservoir element is a sizeable fraction of the length of the container, then volume support effects may occur. In these studies, the container was 2000 m long and volume support effects were noted in Boolean objects with widths greater than 200 m and in cell-based models with ranges greater than 1000 m.

It is those factors that shift the 'S-curve' to the right that are the most important for addressing potential downside scenarios for sparse-well development studies, in which only a few wells are used to drain the reservoir, and for considerations of later infill drilling. The potential impact of these factors can be addressed using careful geological analysis.

The authors thank the Chevron Corporation for allowing publication of this paper. The Chevron Corporation is also acknowledged and thanked for supporting research on this topic for a number of years. Discussions with Ron Behrens, Connie Terricola, Andrew Latham, June Gidman, Frank Harris, Tim McHargue, John Toldi *et al.* were very important in the evolution of thoughts in this paper. Finally, the first author would like to thank Danny Horowitz, formerly of Swanson Consulting, who helped him appreciate how connectivity could be modelled and analysed.

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Received 5 January 2006; revised typescript accepted 2 June 2006.