Development of the Slumped Crestal Area of the Brent Reservoir, Brent / Field An Integrated Approach

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Abstract

The Brent Field consists of a major, westerly dipping fault block, with a crestal area broken up into a series of slumped fault blocks*. The primary phase of development has concentrated on water-flooding the West Flank, but effort is now being applied to recover the oil in the slumped blocks. This paper describes the various studies undertaken to formulate a development plan for the ±13 million m³ (80 MMstb) of oil reserves in the slumps of the Brent Reservoir and presents initial well results.

A valid geological interpretation was crucial to successful development planning for the slumps. Structural interpretation is difficult due to limited seismic resolution, but the geological model has been supported by a review of structural analogues and by the limited well performance data. The slump faults are interpreted as running predominantly north-south. As such, they provide a significant barrier to west-east flow, whilst allowing better communication in the north-south direction.

Development options have been evaluated by reservoir simulation based on this geological interpretation. East-west communication will be too poor to enable the slumps to be developed at reasonable rates by relying solely on pressure support from West Flank water injection. In addition the use of horizontal wells, as compared with conventional deviated wells, has been shown to give significant benefits by providing offtake points in several slump blocks with one well, thereby improving the sweep efficiency and increasing the recovery whilst optimising rig usage.

A development plan has been formulated on this basis with a series of roughly parallel east-west horizontal oil producers, interspersed with horizontal water injectors. This plan is now being implemented and results from the first wells will be presented.

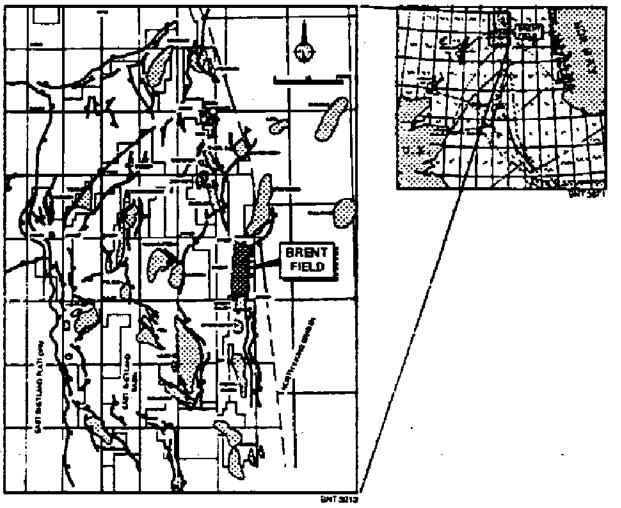

Fig.1 Location of the Brent Field

1 Introduction

The Brent Field, located in 140 m of water 150 km north-east of the Shetland Islands (**Fig. 1**), is one of the largest hydrocarbon accumulations in the U.K. sector of the North Sea. It consists of a north-south oriented, westerly dipping fault block, truncated in the east by an erosional surface and bounded by the major Eastern Boundary Fault[1]. Tectonic movements associated with this fault have created a series of crestal slumped fault

* Throughout this paper the crestal collapse features are referred to as slumps, or slumped blocks. Technically speaking these features are rotational slides, not slumps, but they were originally thought to be slumps and use of this terminology has persisted.

blocks or slides in both the Brent and Statfjord reservoirs, making the eastern flank structurally complex (**Fig. 2**).

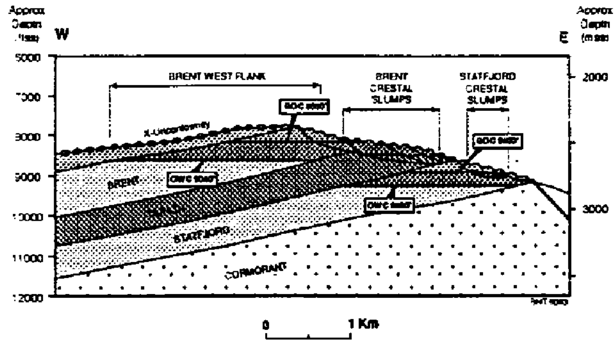

Fig.2 Brent Field East - West Cross Section

Development of the field to date has been mainly concentrated on the structurally simple West Flank, with an edge water drive being used to flood the reservoirs, sweeping oil up-dip towards the crest. This development is now well advanced. and is leading to oil recoveries estimated at around 55% of STOIIP. Production from the slumped fault blocks has been extremely limited, due to the greater perceived rewards of West Flank activities. However, as the West Flank waterflood matures, greater emphasis has been placed on the remaining areas of the field and this has driven efforts to define the optimum development for the slumped fault blocks, taking into account the planned depressurisation of the field from 1997[2-3] and the limited rig time available on the full platform drilling sequence.

Initial work has concentrated on the slumps in the Brent Reservoir, since these contain more oil than the Statfjord slumps. In addition, the structural picture at the Brent level is clearer, since the slumps have been penetrated by a number of wells drilled to develop the West Flank of the underlying Statfjord Reservoir. By contrast, the Statfjord slumps have fewer well penetrations and further appraisal is required before an acceptable geological model can be defined upon which a development plan can be based.

A notional development strategy for the Brent slumps was defined already in 1990, and this recommended the drilling of four wells to obtain performance data prior to finalising the development plan. Although only two of these producers (BA26S2 and BC15) were actually drilled, due to conflicting pressures on the drilling sequence, enough new information was available by the end of 1992, including a major seismic reinterpretation of the fault pattern, to provide the basis for a complete revision of the development plans.

2 Geological Description

2.1 Interpretation History

The geological model of the slumps has been revised several times since 1975 (**Fig. 3**), but the earlier interpretations were never called upon to support drilling. The possibility of gravity-driven mass movement of rocks as a mechanism for the evolution of the crestal area of the Brent Field was first proposed in 1975, but this model implied large-scale listric faults, producing single slump features encompassing the Brent Group, Dunlin shale and Statfjord Formation and implied total erosion of the Brent slumps. In 1982, large slumped fault blocks were mapped at Brent level (Fig. 3A), interpreted and extrapolated from well data. Later examination of the evidence of crestal collapse concluded that the features were most likely due to tectonic movement, inducing 'scoop-shaped' listric faults that sole out in the heterogeneous Cook Formation. In 1988 the concept of separate listric slump faulting was further examined, introducing a large number of scoop-shaped faults at both the Brent and

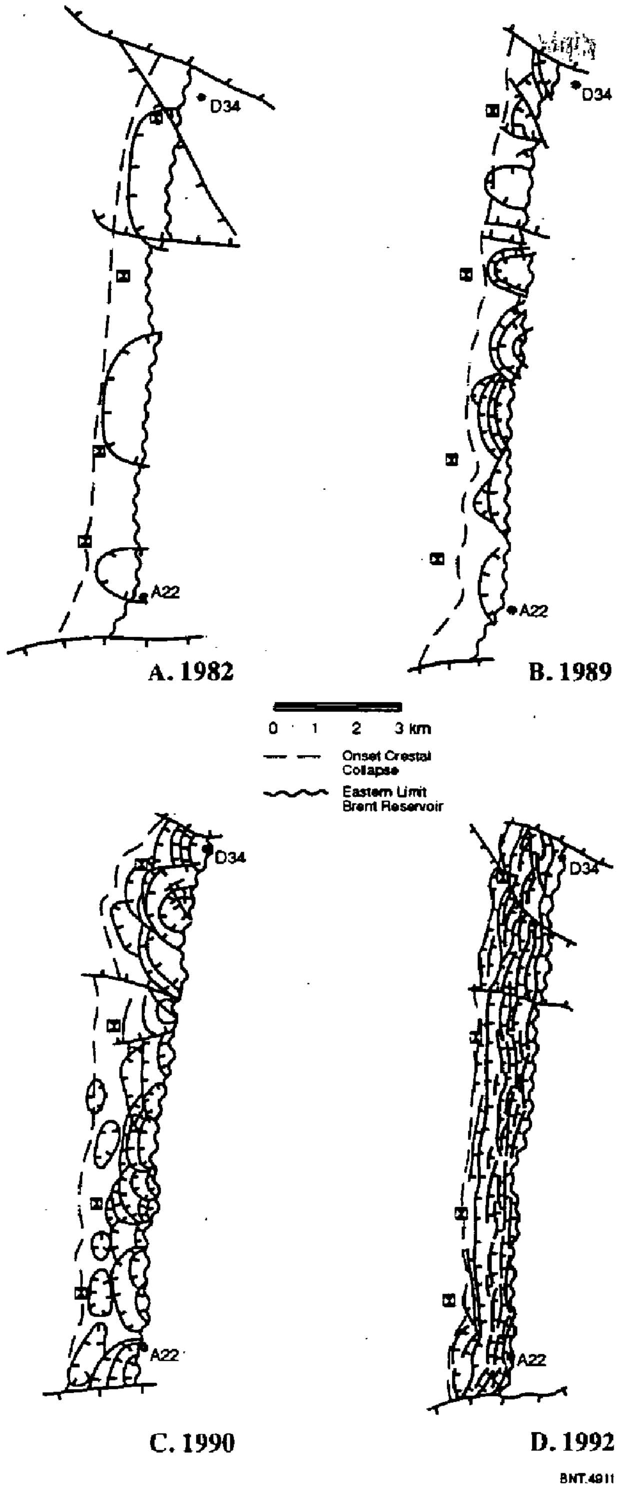

Fig.3 Brent Slumps Structural Interpretations '82-92

Statfjord reservoir levels. These faults were mainly picked from well data, but seismic time slices were also used in an attempt to define the shape and location of the slump faults, leading to an arcuate fault pattern (Fig. 3B). This pattern was refined further (Fig. 3C), using seismic dip and azimuth maps to locate the slump faults and this model formed the basis of the initial development planning.

The geological structure of the Brent slumps has now been completely revised, based largely on a seismic re-interpretation. The resulting fault pattern reflects a consistent structural model and is supported by the limited well performance data and by a complementary structural geological review of the faulting mechanisms, which has also looked at structural analogues to the Brent slumps, notably the Mars Canyon on the US Gulf Coast. All the major slump faults are now mapped as running in a north-south direction with fairly limited curvature (Fig. 3D),

2.2 Structural Evolution

The crestal slumps developed as a result of the Kimmerian rifting event in late Jurassic time, which led to the formation of the North Viking Graben. On the western side of the Graben a system of westerly rotated fault blocks developed. These fault blocks were initially eroded on the crest, but as the Eastern Boundary Fault defining the Viking Graben developed, the crest became gravitationally unstable and collapse occurred. This resulted at the Brent level in a large number of listric, curvilinear faults, soling out in the low shear zones of the underlying Dunlin shales, creating separate crestal 'slump' blocks. Similar crestal collapse features can be seen in several other fields in the East Shetland Basin, notably Statfjord, Strathspey and Ninian. The sequence of events leading to the formation of the slump blocks is outlined in **Fig. 4**.

The structural models previously presented (Figs. 3A-C), all invoked arcuate fault patterns, partly based on seismic (one arcuate event was observed on a seismic time slice) and partly on crestal collapse features reported from present day outcrops. During the course of this work, it became clear however that a more curvilinear, north-south trending fault pattern is more likely, since it fits both the seismic and the geological model.

It is envisaged that the slumping started in the east and progressively moved westwards as the crestal edge became unstable due to the slumping process. A system of 'phases' has therefore been developed, where the easternmost slumps represent the earliest phases of the slump development, and more westerly slump phases occurred later in time. This 'phase' scheme also subdivides the slumps into areas with distinct differences in pressure communication with the west flank, i.e. the easternmost slumps are the most isolated ones, and communication improves as one goes west.

Four distinct slump 'phases' have been distinguished, of which the Distal slumps and Phase I and II represent slumps sensu-stricto, i.e. slumps that are distinctively different from the West Flank in terms of structural position (seismically defined) and show significantly different production and pressure behaviour compared

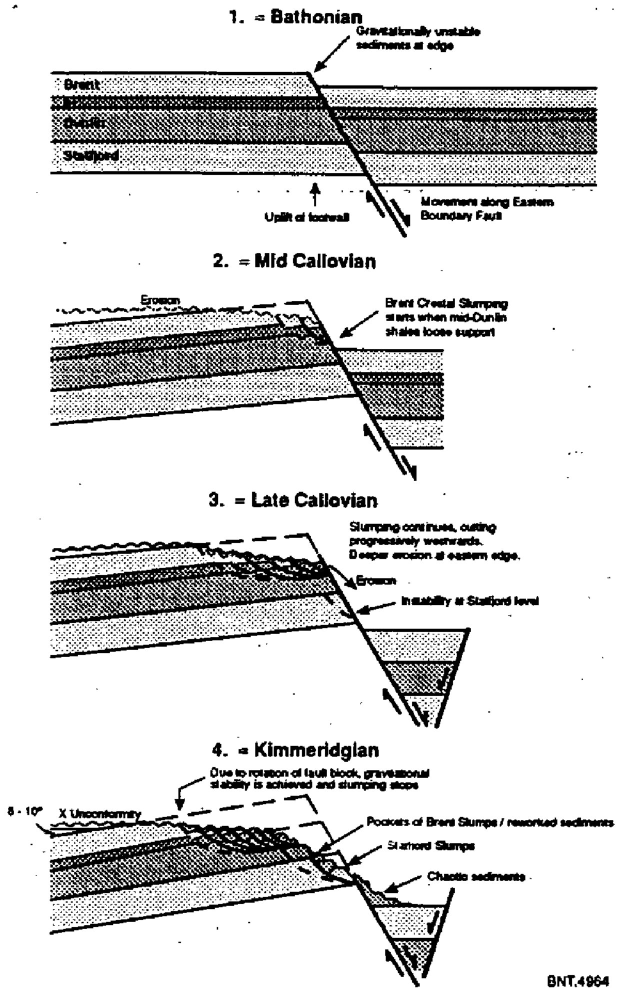

Fig. 4 Evolution of Crestal Collapse

to West Flank wells. The last phase (III) is here recognised as a slump development, but to all intents and purposes it can be treated as West Flank, since the generally small fault throws (less than 30 m) allow good communication with the west flank. In addition, the distribution of the so-called 'reworked sediments' has been clarified, and although not recognisable as a distinct 'phase', these sediments constitute a significant portion of the slump rock volume.

In addition to the listric slump faults, a number of more or less east-west trending normal faults have been recognised. These faults, which include the northern and southern boundary faults as well as the Delta Graben faults, are believed to have been reactivated after the slumping, and will consequently have affected the slumps as well. They may well act as north-south barriers with respect to communication within the slumped area.

2.3 Seismic Interpretation

The top Brent and X-unconformity merge over the crest, where they are seismically represented by a strong reflection. The base Brent is also clearly represented by a low frequency negative loop, caused by the impedance contrast between the porous, oil-bearing Brent sands and the non-porous Dunlin shales. A major feature of this reflector is a very clear break or change in dip at the crest of the West Flank which is consistent throughout the field and corresponds to a break at top Brent/X-unconformity level. This is interpreted as representing the main slump fault, separating West Flank beds (including Phase III slumps) from slumps sensu-stricto. The point where the top Brent/X-unconformity and top Dunlin merge was taken as the eastern limit of the Brent slumps and this has been reconciled with well data. These limits clearly define the slump envelope, which is also represented by a low frequency negative loop, from which no internal stratigraphy can be interpreted.

The top Brent/X-unconformity reflection over the slumps is characterised by a large number of small discontinuities, which have been interpreted as representing slump faults. These discontinuities show a remarkable consistency from line to line and they have been used to map out a coherent fault pattern which ties to corresponding breaks at the top Dunlin reflection.

2.4 Fault Pattern

Since the structural model indicates that the gravitational sliding took place when the formation was consolidated, any interpretation of the fault pattern should allow the pre-faulted structure to be reconstructed without significant deformation or loss of rock material (Fig. 5). On this basis a series of balanced sections have been constructed through the slumps. They have been built up from the stratigraphy and fault cut-outs observed in wells, adding firstly the faults interpreted on seismic and then the minimum number of additional faults needed to balance the section. The overall re-interpretation results in a picture of the slumps being divided into blocks by a series of north-south faults, having an east-west spacing of around 120 m with bed dip increasing eastwards. Typical fault throws range from 20 to 100 m, which, when coupled with the application of regionally derived length/throw relationships, leads to average fault lengths of at least 800 m.

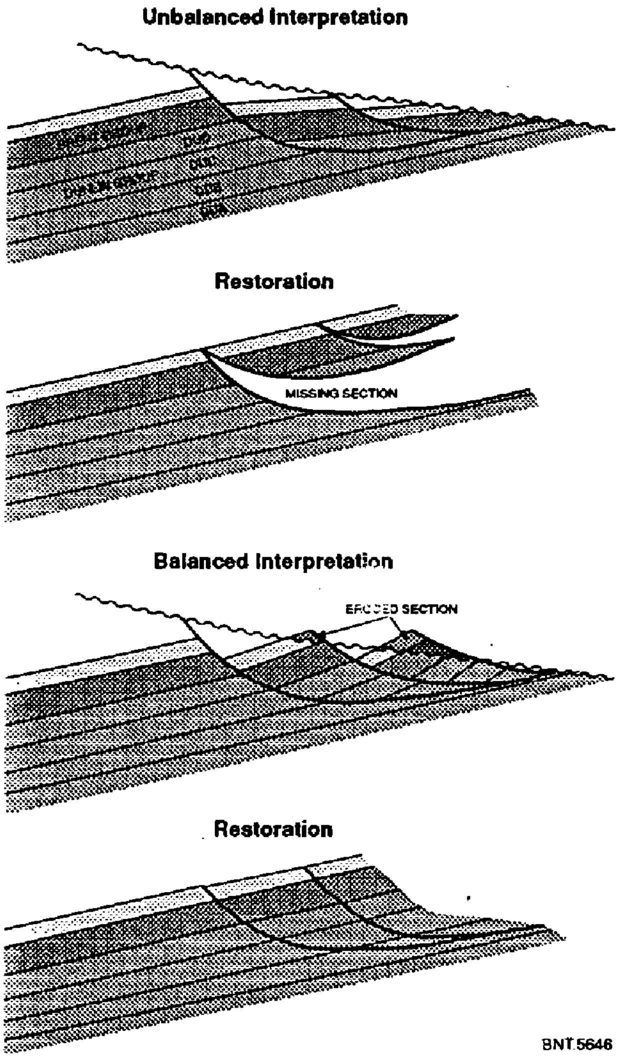

Fig. 5 Illustration of Concept of Balance Sections

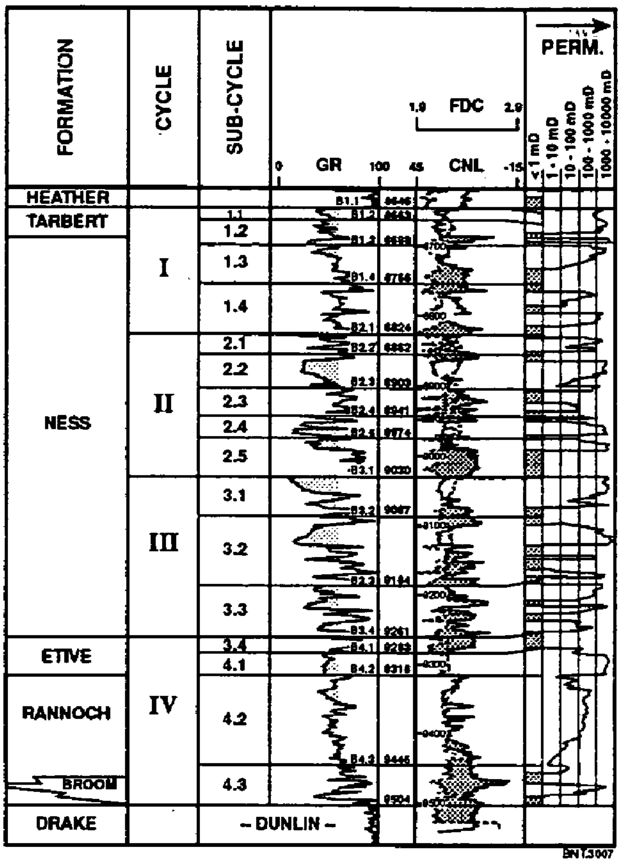

Fig. 6 Type Log of the Brent Reservoir Group

The internal stratigraphy of the slumps is built up from the underlying top Dunlin, with the assumption that the stratigraphic layer thicknesses, and reservoir properties, are similar to those of the West Flank (Fig. 6). Truncation of the top Brent leads to a reduction of the total Brent section in the slumps, which includes Cycle III and even some Cycle II in the western blocks, but is reduced to only the lower part of Cycle IV (units 4.2 and 4.3) in the east. In addition, reworked sediments eroded from the crest of the structure comprise the major part of the Distal slumps and in the other phases they have filled up depressions formed at top Brent as a result of the slump faulting.

2.5 Communication

Under this geological model, communication between blocks in the east-west direction will be restricted by the faulting, but north-south communication will be largely

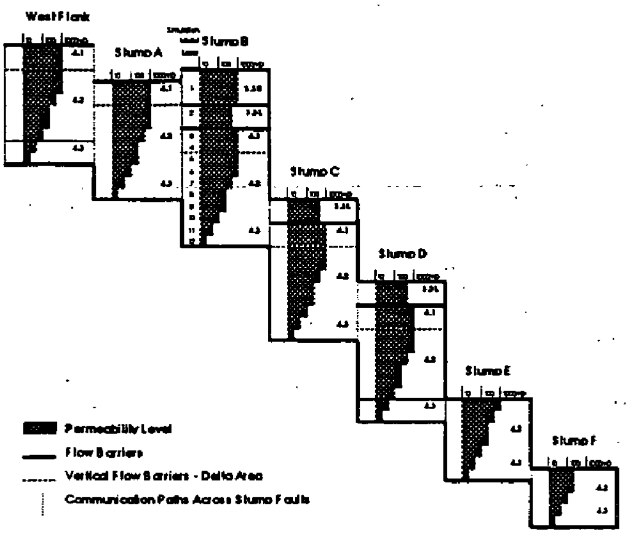

Fig. 7 Brent Slumps Cross Section - Schematic of Permeability Profile and Fault Juxtaposition

unaffected, at least within any single fault block. Communication across the fault planes can, potentially, be affected by several mechanisms, including juxtaposition, clay smear and deformation associated with the faulting.

Juxtaposition is considered to be the main factor reducing transmissibilities across the slump faults in Brent. Clay smear is likely to have little effect, given the high net/gross ratio of the Brent sands and the fact that the faulting occurred after consolidation of the sediments when the clays were no longer plastic. Some fracturing associated with individual faults has been observed, leading to intense fracture zones up to 10 m wide, mainly concentrated in the fault hanging walls. The fractures are associated with a considerable decrease in porosity, due to compaction, and thus act as zones of low permeability, as in BC15. However, this permeability reduction can not explain the observed well performance, and is of secondary importance to juxtaposition in restricting communication.

The major part of the slump blocks is in Cycle IV, where there is a consistent reduction in permeability from over 1000 mD in unit 4.1 (Etive) down to 10 mD in the lower 4.2 (Rannoch) and 4.3 (Broom) (**Fig. 7**). Thus the slump faults will continually offset the low permeability lower 4.2 and 4.3 against the high permeability 4.1 and upper 4.2 as one goes from west to east, severely restricting communication between the eastern blocks and the West Flank. The effect is worse in the Delta platform area, where the presence of a mica layer between the Etive and Rannoch, provides a barrier to vertical flow.

The geological model gives no clear indication of the degree of north-south communication. Most of the individual slump faults can only be mapped for 1 to 2 km, but where they die out, other, parallel faults are present to the east and west. This applies even to the main slump fault, which is in fact a combination of several individual faults. Thus north-south communication should be mostly relatively good, and there will also be tortuous flow paths around the ends of individual faults providing some unfaulted, but restricted, communication with the West Flank.

3 Early Production Performance

The Brent slumps have been penetrated by a number of wells drilled to the underlying Statfjord reservoir, but prior to 1993 there had been very limited actual slump production, particularly from the Phase I and II slumps. All slump wells showed initial pressures (from RFTs) in line with the current West Flank Cycle IV pressure at that time indicating some communication with the West Flank, but performance data provides a better indication of the degree of communication. The observed performance of individual wells has been explained in terms of fault juxtaposition on the basis of cross-sections through the wells in question and leads to the following conclusions.

- The properties of reservoir units in the slumps are generally in line with those of the same units in West Flank except where they are affected by fracturing associated with the faulting.

- Differences in production behaviour related to varying levels of pressure support can be explained in terms of communication with the West Flank by juxtaposition across the various slump faults.

- Most existing 'slump' producers are basically West Flank wells and only BA26S2 and BC15 are effectively draining significant slump volumes.

- The westernmost fault blocks in the Phase II slumps are generally in good communication with the West Flank, but in areas of limited vertical communication, even the pre-cursor faults can effectively isolate Phase III fault blocks.

4 Development Options

Development of the slump blocks has been studied using reservoir simulation. The main objective of this work was to quantify the benefit of various production and injection strategies, taking into account the uncertainties in communication within the slump blocks.

4.1 2-D Cross-Sectional Simulation

Model Description

The initial model used was a 1000 m wide, 2-D, east-west cross-section through the West Flank and the slumps. It was based on a typical geological cross-section, with five true slump blocks in Phase I and II, plus a pre-cursor, Phase III block.

The basic model used 10 layers each 6 m thick to model Cycle IV, with horizontal permeabilities decreasing from 1000 mD in the Etive to 25 mD in the Rannoch. Vertical permeabilities were 0.1 of the horizontal values. The grid spacing was 12.5 m over the slumps and the crest of the field, increasing downdip into the water leg of the West Flank where analytical aquifers were attached. The West Flank was modelled with a constant 7^{0} dip, and the slump blocks were constructed using depths and dips from the geological cross-section. The sloping faults could not be handled easily by the gridding package and so they were constructed by inputting vertical discontinuities and voiding out additional blocks.

Cycle III was included in the main slumps, where present, by adding one or two extra layers. In general, Cycle III in the slumps is only in communication with Cycle IV in the slumps to the west and so is generally modelled correctly. Transmissibilities across the faults were input using special connections, with the transmissibility calculated from the harmonic average for the juxtaposed layers. The situation is illustrated schematically in Fig. 7.

Cases Run

The model was initialised at initial Brent conditions and then the current state of reservoir development reproduced by flooding the West Flank to the crest. This took 3000 days, using firstly a downdip oil producer, and then, after that had watered-out, opening up an updip producer. After an initial decline, pressure support was provided by a down flank water injector.

Slump block development began after 3000 days, with conventional deviated oil producers in the base case. The downdip West Flank water injector continued to provide all pressure support. The first slump well was completed in the main Phase II slump, and after it had watered out, production was switched to a well in one of the Phase I slumps. Both wells were constrained by a maximum gross rate of 1600 m^3/d and a maximum water-cut of 90%, with rates determined by lift curves. The Phase II well produced at the maximum rate, but the Phase I well was largely constrained by lift.

Conventional Wells

Several cases were run in which the number of wells was varied leading to the following conclusions:

- Very limited oil recovery can be obtained from any slumps to the east of the easternmost producer.

- Additional wells do not significantly increase the overall recovery, but they can accelerate oil.

- When relying solely on down-dip water injection for pressure support, the transmissibility restrictions created by the slump faults will result in a significant pressure gradient between the West Flank and the more eastern slumps. This will lead to low bottom-hole flowing pressures and lift problems after water breakthrough. Reducing offtake levels to allow higher pressures to be sustained is not practical.

The above leads to the consideration of alternative development options using horizontal wells and/or dedicated pressure support within the slump blocks.

Horizontal Wells

Horizontal wells, penetrating the slumps from west to east, would allow production from the more easterly slump blocks whilst high pressures and hence lift performance could be sustained at the western end. Such a well was included in the model (**Fig. 8**) in place of the two conventional slump producers. The horizontal well was modelled according to *Dikken*[4], incorporating the friction pressure drop along the well bore.

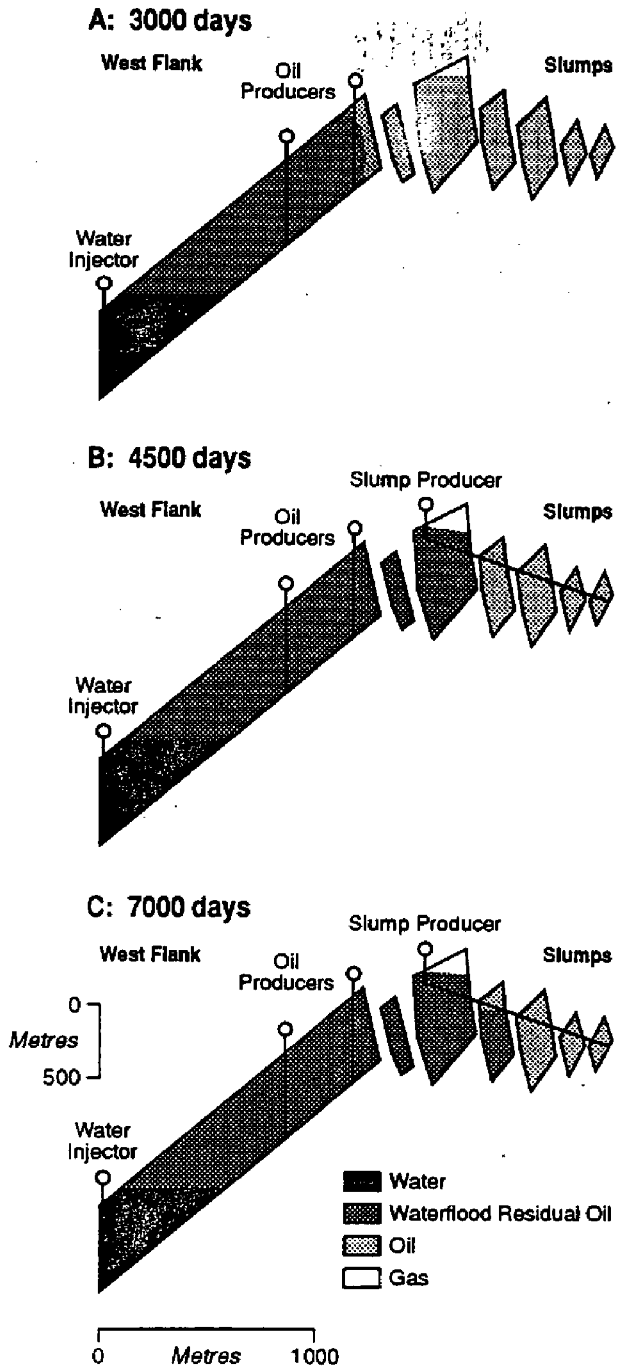

Fig. 8 Cross-Sectional Simulation - Fluid Saturation with Time for Horizontal Producer Supported by West Flank Injection

The initial runs with the horizontal well confirmed that the well would water-out from the western end, as expected (**Fig. 8**). However, when examining the inflow profile along the wellbore (**Fig. 9A**) it became apparent that the eastern slump blocks were hardly being drained because the pressure gradient in the reservoir, coupled with the friction pressure drop along the wellbore, resulted in minimal drawdown in the eastern part of the

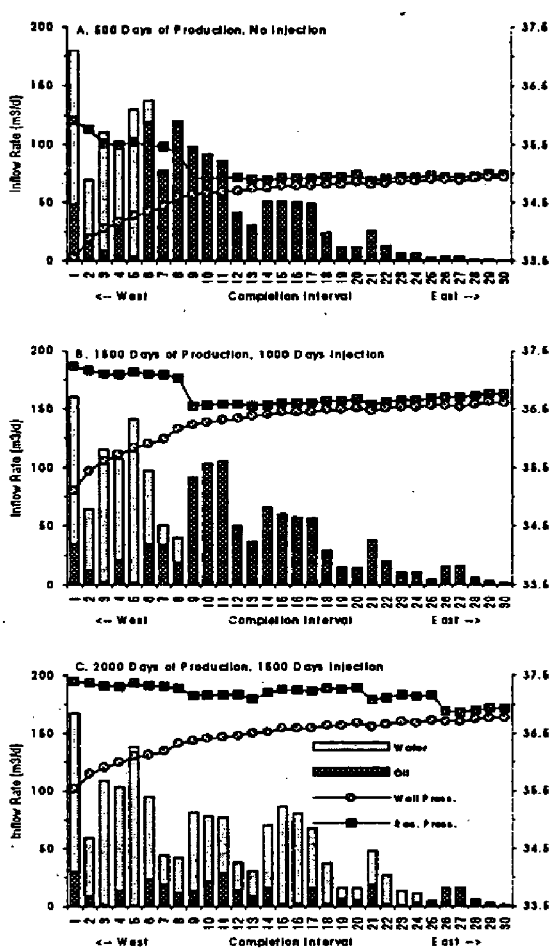

Fig. 9 Inflow Performance of Horizontal Producer

well. Performance of the horizontal well was increased by recompleting the well on only the tail end blocks after the western end had watered out. However, the recompleted well suffered from poor pressure support, resulting in unstable lift performance.

Water Injection

Water injection into an eastern slump block was modelled, using vertical wells. The overall recovery improved but a long period of high water-cut production in the crestal producer was required, since water breakthrough from the west came much before that from the east. Furthermore, there was no sweep of oil to the east of the injector or in Cycle III where it was effectively trapped in attic locations.

The overall results of the 2-D model demonstrated the need for well penetrations and pressure support in the eastern slumps, but the better communication in the north-south direction favours using water injection to sweep oil in this direction, which could only be simulated with a 3-D model.

4.2 3-D Model

The model was converted to 3-D by subdividing it into 10 grid blocks in the north-south direction. The case of a horizontal slump producer, with a recompletion, was re-run as the new base case. The results of this run are generally similar to those from the equivalent 2-D case, albeit with slight differences due to limited cusping of the flood front towards the producers and reverse cusping after the floodfront has moved updip.

The 3-D model was primarily built to investigate water flooding of the slumps in a north-south direction. The horizontal producer was replaced by two parallel horizontal wells; a producer located at the northern edge of the model and an injector at the southern end. Injection began after 3500 days, 500 days after production from the slump well, and was confined to the three easternmost slump blocks in the initial case. **Fig. 10** illustrates the sweep of oil towards the producers from a combination of West Flank injection and the

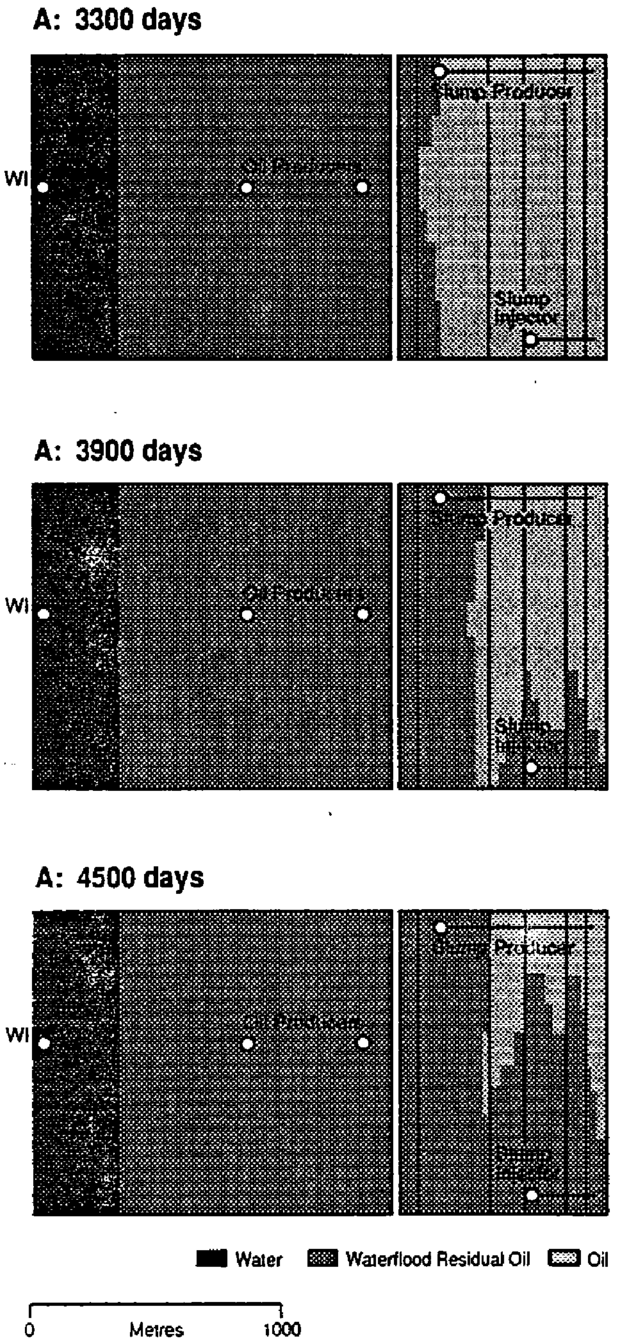

Fig. 10 3D Simulation, Area View - Fluid Saturation with Time for Injection and Production with Horizontal Wells

dedicated, slump block injection. Pressure profiles and inflow performance of the producer are shown in **Fig. 9**, illustrating the increased production from the eastern slumps after the onset of injection.

The model was used to compare various development options, with and without water injection, and to investigate the effect of the major geological uncertainties including variations in the fault transmissibility.

4.3 Conclusions from Simulation

The simulations have confirmed that the recovery mechanisms in the slump blocks will be dominated by the restricted communication across the slump faults, compared with the better communication in a north-south direction. Wells in the eastern slumps will suffer from lift problems when relying solely on pressure support from the West Flank and direct injection into these eastern slumps will be necessary to displace the oil and allow the reserves to be produced within the available time frame.

Horizontal wells have been shown to lead to improved performance by allowing completion on all slump blocks. The benefits of such wells, as compared to conventional wells, will be enhanced by an increase in complexity of the geological model. Significant recovery can not be obtained from slumps to the east of the production (and injection) completion intervals, and so, to maximise recovery, the wellpaths should extend as far east as possible.

The optimum north-south well spacing will be largely dependent upon the degree of communication in that direction, which can only be confirmed by additional well data. However, a spacing of around 1000 m will lead to recovery of the reserves within 6 years, on the basis of the homogenous north-south model used for the simulations. Under this model, a greater well spacing is possible but it will require longer production times to recover the reserves, putting tail end production at risk. A much closer well spacing is not practical given the limited rig time available to develop the slumps, but it would accelerate some production.

There remains scope for maximising recovery (and accelerating oil) by optimising the completions of the injectors and producers, particularly with regard to perforation of the more westerly slumps. However this will depend upon the timing and potential of individual wells, and must be considered on a case by case basis.

Waterflooding of the slumps is not seriously affected by the onset of depressurisation as long as injection continues and the reserves are recovered before the producers die. With gas lifted wells, the slumps can be swept by a low pressure water flood, with injection used only to displace oil, not to maintain pressure.

5 Development Plan

The simulation study justifies development of the slumps by horizontal wells, with dedicated water injection in the more easterly blocks to complement flooding from the West Flank. On this basis, a detailed development plan has been drawn up (**Fig. 11**), taking into account variations in mapped slump development and the presence of several existing slump producers.

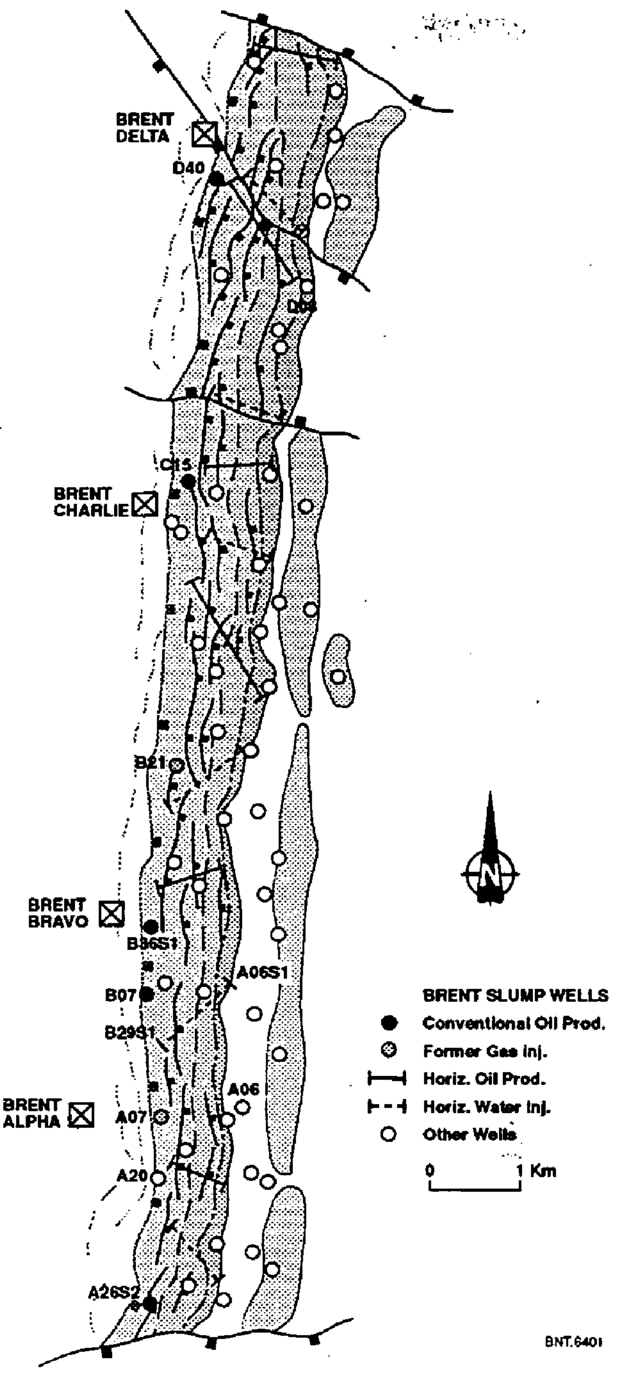

Fig. 11 Brent Slumps Development Plan

Since north-south communication is still the major source of uncertainty, the plan envisages an optimistic initial development with a fairly wide well spacing of up to 2000 m. Several potential infill targets have been identified which could be drilled, if necessary, to reduce the maximum well spacing to less than 1000 m, but further infilling is unlikely to be justified.

The main principles underlying the development plan (horizontal wells, dedicated water injection and the approximate well spacing) can be considered firm. However, within these constraints the detailed planning for individual wells will continue to be optimised, taking into account changes in operational circumstances. In particular, the proposed designation of some wells as producers and others as injectors may be modified on the basis of well results or changes to the order of drilling the wells.

This development plan is now being implemented, and two wells (BD08S2 and BA06S1) have already been drilled. Cemented liners are being run over the slumps and the wells completed with two or three zone multi-straddle assemblies using sliding side doors to isolate the more westerly slumps if these water out first.

The geological structure of the slump blocks is considerably more complicated than that of the relatively simple West Flank. Consequently, a significantly greater monitoring and surveillance effort will be required to understand how the slumps are being drained and to be able to effectively maximise recovery. This will include pressure measurements from RFTs and permanent downhole gauges, production logging for flood front monitoring and production allocation, plus the possible use of tracers to determine the source of water production.

6 Results from First Wells

6.1 BD08S2

The first Brent horizontal slump producer, BD08S2 was drilled in late 1993/early 1994, to develop Cycle IV of the northern Graben Phase II/I slumps. The well was mainly steered using LWD, although a near-bit geosteering tool was also used. A 1430 m horizontal section was achieved, containing 1270 m of oil bearing sands, of which 270 m were lower quality reworked sediments (**Fig. 12**). RFT pressure measurements showed the slumps to be partially depleted, with pressures around 37.9 MPa (5500 psia), some 0.7-1.4 MPa (100-200 psi) above current West-Flank levels but 2.1 MPa (300 psi) below initial.

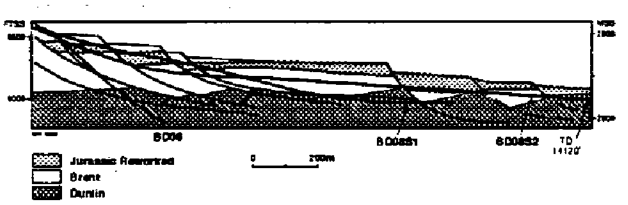

Fig. 12 BD08S2 Schematic Cross Section

Two plug-backs were required to optimise the well path; the first after a planned pilot hole and the second after penetrating the base Dunlin 25 m shallow. The well took 148 days, 23 days longer than planned, mainly due to a sub-optimum liner cement job and a casing leak. It was completed with three zones and a permanent downhole pressure gauge was installed. An initial production test was performed on the Phase I slumps to assess north-south connectivity before all zones were opened to allow flow from all slump blocks. A multi-rate PLT was run for production allocation.

BD08S2 initially produced 3900 m³/d of dry oil at solution GOR. By the end of 1994 the cumulative production was 450 000 m³ and a 10% watercut had

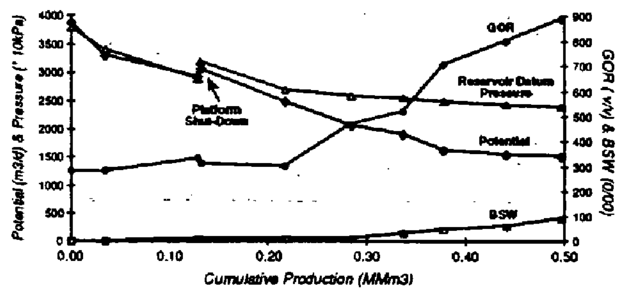

Fig. 13 BD08S2 Production Performance

developed. This off-take has lowered the reservoir pressure to 24.1 MPa (3500 psi) (some 9.0 MPa (1300 psi) below bubble point), reducing the production potential to 1500 m³/d and increasing the GOR (**Fig. 13**). Mass balance calculations showed the connected Phase I STOIP to be 1.6-2.4 million m³, corresponding to the full Graben Phase I area. Overall the connected STOIP is 5-8 million m³, representing 60-100% of Graben area, and cross-flow across the main slump fault is 3 to 5 m³/d/kPa. This is only 20% of expectation, which is attributed to severe faulting near the main slump fault, highlighted by the large pressure differences seen in the pilot hole.

The expected ultimate recovery of BD08S2 is 1.5 million m³, of which 0.5 million m³ will result from a future Graben slump water injector.

6.2 BA06S1

BA06S1 was drilled and completed in mid 1994 to develop the slumps in the southern part of the field. The well penetrated 520 m of high permeable Etive (B4.1) in the Phase II slumps. This was considerably more than anticipated due to the presence of sub-seismic faults which caused the B4.1 sands in neighbouring slump blocks to be juxtaposed against each other (**Fig. 14**). The well then penetrated 520 m of reworked sediments in the Phase I slumps, where the Brent appears to be completely eroded, with the reworked sediments directly overlying eroded Dunlin.

This well was steered from the well-site using LWD without the need for any redrilling. An open hole RFT/CIBL log was run for pressure and structural information. Pressures were 35.5-36.2 MPa (5150-5250 psia), which is in line with those in the West-Flank.

A two zone completion was run across the slumps and a multi-rate PLT showed 70% of the gross production to be coming from the Phase II Etive section. The initial well potential exceeded 4800 m³/d at 10% BSW and 400 v/v GOR. The watercut rose quickly to 50% by end 1994, after a cumulative production of 0.25 million m³

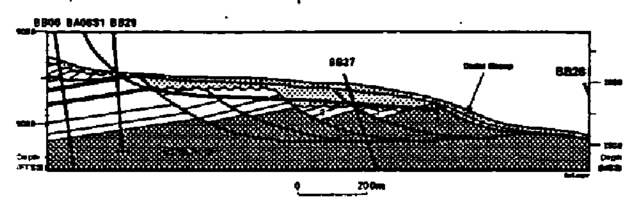

Fig. 14 BA06S1 Schematic Cross Section

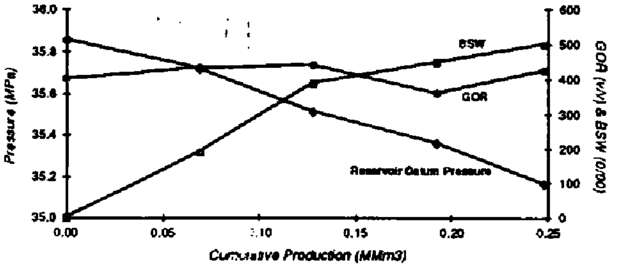

Fig. 15 BA06S1 Production Performance

(30% of the expected reserves) (**Fig. 15**). The western slump blocks will be isolated in the near future to reduce water production. The total pressure drop is less than 0.7 MPa (100 psia) and the production potential still exceeds 4800 m^3/d, due to excellent West-Flank pressure support in this area.

6.3 Implications for Further Development

The first wells have broadly confirmed the assumptions behind the development plan, whilst highlighting the geological complexity of the slumps. The geological model has improved well planning, but the resolution of the current seismic data is not sufficient for accurate well path determination, making LWD essential for well steering. The pilot hole in BD08, being close to the heel of the well, proved to be too remote from the main part of the horizontal section to provide adequate structural and stratigraphic control. Drilling the wells has indicated several areas for improvement, particularly in terms of centralising the drill string to minimise casing wear and minimising the size of the horizontal liner to achieve a successful cementation.

The initial production performance of both wells has confirmed the current slump interpretation and indicated connected STOIP volumes in line with expectation. However, the pressure support from the West Flank in BD08S2 is less than predicted and this area may require early slump water-injection. Implementation of the development plan will continue with most of the remaining wells being drilled by 1997. Water injection will then follow when most of the wells are in place.

A 3D WVSP has confirmed that increased resolution over the slumps could be obtained with the latest seismic acquisition techniques and so a new 'state of the art' full field 3D seismic survey will be shot in 1995. This should lead to improved definition of the slump faults and hence increased confidence in planning the remaining wells.

7 Conclusions and Recommendations

- A completely revised geological picture of the Brent slumps has been derived by re-interpreting the seismic and integrating the results with a consistent structural model, supported by well performance.

- The geological re-interpretation has resulted in a major change to the fault pattern, which fundamentally influences internal communication and hence the development options. The slumps faults are now interpreted as running predominantly north-south, which will allow good communication in that direction, but provide significant restrictions to east-west flow.

- Reservoir simulation, based on the new geological model, has shown the poor pressure support that can be expected in the eastern slumps when relying solely on West Flank water injection. It has highlighted the benefits of dedicated injection into the slump blocks to sweep oil north and south as a complement to the west to east drive from the West Flank. The use of horizontal producers and injectors will maximise sweep efficiency by providing completions in all slump blocks.

- A minimum first phase development plan for the slump blocks has been defined involving 12 new wells. It is based on a series of east-west oriented horizontal producers, supported by dedicated water injection through parallel horizontal injectors. The major geological uncertainty remains the degree of north-south communication, and so the plan allows for infill wells to be added, if performance data indicates that these are necessary.

- The slump blocks are considerably more complicated than the West Flank, and will thus require a much greater monitoring and surveillance effort to understand how they are being drained and hence to be able to effectively maximise recovery.

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