Integrating 3-D seismic data, field analogs, and mechanical models in the analysis of segmented normal faults in the Wytch Farm oil field, southern England, United Kingdom

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ABSTRACT

We propose a methodology for the analysis of normal fault geometries in three-dimensional (3-D) seismic data sets to provide insights into the evolution of segmented normal fault systems and to improve recovery efforts in fault-controlled oil fields. Limited seismic resolution can obscure subtle fault characteristics such as segmentation and gaps in fault continuity that are significant for oil migration and thus accurate reservoir characterization. Detailed seismic data analyses that incorporate principles of normal fault mechanics, however, can reveal evidence of fault segmentation. We integrate seismic attribute analyses, outcrop analog observations, and numerical models of fault slip and displacement fields to augment the use of 3-D seismic data for fault interpretation. We applied these techniques to the Wytch Farm oil field in southern England, resulting in the recognition of significant lateral and, to a lesser extent, vertical segmentation of reservoir-scale faults. Slip maxima on fault surfaces indicate two unambiguous segment nucleation depths, controlled by the lithological heterogeneity of the faulted section. Faults initiated preferentially in brittle sandstone and limestone units. Subsequent growth and linkage of segments, predominantly in the lateral direction, resulted in composite fault surfaces that have long lateral dimensions and multiple slip maxima. Reservoir compartmentalization is greatest at the level of prevalent segment linkages, which corresponds at Wytch Farm with the predominant hydrocarbon-producing unit, the Sherwood Sandstone. At relatively shallower depths, fault segments are younger and less evolved, resulting in a greater degree of segmentation with intact relay zones.

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INTRODUCTION

Recent work on normal fault systems has emphasized the importance of the segmented nature of fault geometries in matters of fault evolution (Peacock and Sanderson, 1994; Trudgill and Cartwright, 1994; Cartwright et al., 1995; Dawers and Anders, 1995; Childs et al., 1996; Marchal et al., 1998), sedimentary basin development (Anders and Schlische, 1994; Dawers and Underhill, 2000), geothermal fluid migration (Coussement et al., 1994; Martinez, 1998), and seismological behavior (Crone and Haller, 1991; de Polo et al., 1991; Machette et al., 1991; Wells and Coppersmith, 1994). A widely recognized impact of segmented normal fault systems, and the focus of this article, is with regard to fault-controlled hydrocarbon traps in oil fields. Well placement and recovery efforts in many oil fields have benefited significantly from highly detailed characterization of segmented normal fault systems (Bouvier et al., 1989; Morley et al., 1990; Pegrum and Spencer, 1990; Knipe et al., 1998; Ottesen Ellevset et al., 1998; Maerten, 1999). Breaks in fault continuity provide potential flow zones through which hydrocarbons can migrate across a faulted region, therefore, a thorough methodology for the analysis of segmented fault systems is needed to enhance fault interpretations and thus recognize potential water breakthroughs and hydrocarbon escape points within fault-compartmentalized reservoirs.

Although distinct fault segments may be clearly visible at the surface of the Earth, some large fault systems have evolved to a point where evidence of initial segmentation has been eradicated through fault segments linking together, allowing the accumulation of large amounts of slip over a resultant composite fault surface (Wesnousky, 1988; Peacock and Sanderson, 1991). Slip profiles along normal fault traces at the Earth’s surface commonly exhibit heterogeneities in slip distributions (Cartwright and Mansfield, 1998; Morley, 1999) that may imply a relict segmented nature. This process of initial segmentation and subsequent linkage is characteristic of normal fault system evolution (Cartwright et al., 1995; Dawers and Anders, 1995) and may be associated with geometric irregularities along fault strike at the points of linkage (Peacock and Sanderson, 1994).

Fault traces at the Earth’s surface provide limited information on the 2-D evolution of faults where they intersect a horizontal plane but cannot be used to elucidate the three-dimensional (3-D) evolution of the fault system. The 3-D characteristics of normal faults that can be determined from 3-D seismic reflection data (Childs et al., 1995; Mansfield and Cartwright, 1996; Ottesen Ellevset et al., 1998; Yielding et al., 1999; Dawers and Underhill, 2000) are crucial for accurate reservoir characterization where faults act as barriers to hydrocarbon migration and may thus potentially compartmentalize the reservoir. Insights into 3-D fault geometries are also important for formulating mechanical models that examine fault geometries, tip-line shapes, slip distributions, fault scaling laws, and mechanical interaction effects within segmented...
fault systems. Fault interpretations from 3-D seismic data, however, are limited by interpretation subjectivity, structural complexity, processing artifacts, seismic resolution, and insufficient use of principles of fracture mechanics that can aid the interpretation. This may result in erroneous fault interpretations that incorporate unrealistic fault geometries and overlook important geometrical features such as segmentation or fault linkage zones.

This article documents the use of a good-quality 3-D seismic data set from the Wytch Farm oil field in southern England to characterize normal fault styles in the reservoir. The effect of faulting on transmissibility within the reservoir is evidenced by high-pressure differentials across faults within the Wytch Farm field (Smith and Hogg, 1997). Such differences in pressure indicate fault-sealing effects, which may be related to clay smearing along the faults (R. Knipe, 1994, personal communication).

This impact on hydrocarbon flow by the faults in the Wytch Farm oil field necessitates accurate characterization of the 3-D fault geometry, including the identification of potential leakage points along faults in the reservoir. To that end, our goal is to unravel the fault geometries and fault growth histories in the oil field through the development of the following generally applicable interpretation methodology. First, emphasis is placed on the use of seismic attribute characteristics to develop an initial fault interpretation. Second, we use outcrop-scale analogs of reservoir-scale faults to describe the nature of fault geometry in cross section, linkage tendencies, and other deformation characteristics pertinent to honing the seismic interpretations. Finally, we fine tune the initial interpretation by integrating results of numerical models, which examine the relationships between fault geometries, slip distributions, and horizon displacements. The combination of these tools allows us to accurately constrain fault geometries in 3-D and to develop a hypothesis for fault evolution in the Wytch Farm field that augments previous reservoir characterizations.

**TECTONIC SETTING**

The Wessex basin in southern England is a late Paleozoic to Tertiary extensional basin approximately 80,000 km² in size (Figure 1). A prolonged period of Phanerozoic extension resulted in distinct rhomboidal depocenters confined by two sets of normal faults: east-west trending and northwest-southeast trending. The broad-scale tectonic history includes four distinct events (Hawkes et al., 1998): (1) early Atlantic rifting (Late Permian to Early Triassic), (2) Atlantic rifting and opening (Early to Late Jurassic), (3) Biscay rifting (Early Cretaceous), and (4) the Alpine orogeny (Late Cretaceous to Tertiary). Extensional events were oriented along approximately north-south axes, whereas the Alpine compression was southeast to northwest directed (Miliorizos and Ruffell, 1998). Much of the

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**Figure 1.** Map of the Wessex basin in southern England (inset) showing the location of the Wytch Farm oil field (modified after Evans and Chadwick, 1994). Solid lines represent major faults in the basin.
faulting bounding the depositional subbasins may have been inherited from reactivated basement faults associated with the Devonian to Carboniferous Variscan orogeny (Karner et al., 1987; Butler, 1998).

The Wessex basin stratigraphy encompasses a succession of Permain through Eocene sedimentary rocks overlying middle Paleozoic basement of molasse-type sediments (Underhill and Stoneley, 1998). Basin fill averages 1.5 km and has a maximum of 3.5 km (Karner et al., 1987) and consists of a variable accumulation of sandstones, shales, limestones, and evaporites (Figure 2). Depositional environments were closely linked to the tectonic history of the basin. Basin emergence in the Late Jurassic resulted in a prolonged period of Cretaceous chalk deposition during a eustatic sea level peak, contemporaneous with a change from active rifting to thermal subsidence (Hawkes et al., 1998). Wessex basin sedimentation terminated during the Alpine orogeny, which culminated in the late Oligocene (Karner et al., 1987), and resulted in internal basin deformation and inversion tectonics along normal faults south of the Wytch Farm oil field (Colter and Havard, 1981; Stoneley, 1982; Selley and Stoneley, 1987; Underhill and Paterson, 1998).

**WYTCH FARM FIELD**

The Wytch Farm field is predominantly defined by a 2.5 km–wide major horst block, internally dissected by numerous east-west–trending conjugate normal faults (Figure 3). This field is the largest onshore oil field in western Europe, having reserves in excess of 428 million bbl (Underhill and Stoneley, 1998). The field is bounded to the south by the Wytch Farm fault, which dips south, displacing down to the south, having offsets of 100–300 m. The Northern Bounding fault dips to the north, displacing down to the north by approximately 50 m. The major faults within the intervening horst block (Figure 3) are the Arne fault and the Northern fault (NF) (Smith and Hogg, 1997).

Stratigraphic offsets indicate that faulting ceased in the Early Cretaceous (Colter and Havard, 1981; Underhill and Stoneley, 1998), and postrift sedimentation

**Figure 2.** Stratigraphic column of Paleozoic and Mesozoic units in the Wessex basin. Shaded units are hydrocarbon-producing units at Wytch Farm oil field. Hachured lines represent unconformities. Horizontal bars on the right represent locations of major seismic reflector horizons.
continued into the Late Cretaceous. Stratigraphic thickness variations across Wessex basin faults indicate several episodes of synrift deposition between the Permian and Early Cretaceous (Stoneley, 1982; Chadwick et al., 1983; Selley and Stoneley, 1987; Jenkyns and Senior, 1991; Hawkes et al., 1998). In the Wytch Farm field, such syntectonic stratigraphic thickness variations are most evident in the Upper Jurassic and Lower Cretaceous strata. Inversion tectonics associated with the Alpine orogeny reactivated several formerly extensional faults south of the Wytch Farm oil field (e.g., Purbeck–Isle of Wight fault system) (Underhill and Paterson, 1998) but did not induce reverse motion on any of the normal faults at Wytch Farm (Underhill and Stoneley, 1998).

Three formations currently produce hydrocarbons at Wytch Farm (Figure 2) (Smith and Hogg, 1997; McKie et al., 1998): the Sherwood Sandstone (~1585 m depth), the Bridport Sands (~925 m depth), and the Frome Clay Limestone (~800 m depth). Source rocks for hydrocarbons are thought to be the Blue Lias Mudstone (Ebukanson and Kinghorn, 1986; Selley and Stoneley, 1987) in downdropped fault blocks south of the Purbeck–Isle of Wight fault system, where structural burial depths were sufficient for source rocks to reach thermal maturity for hydrocarbon generation by the Late Cretaceous (Colter and Havard, 1981; Bowman et al., 1993; Hawkes et al., 1998). Hydrocarbons then migrated into the highly faulted Wytch Farm region, accumulating within the main reservoir units, compartmentalized by a network of normal faults. Hydrocarbon accumulation preceded Tertiary uplift associated with the Alpine collision event, during which time inverted normal faults may have begun acting as seals (Selley and Stoneley, 1987; Underhill and Stoneley, 1998).

Hydrocarbon traps in the Wytch Farm oil field are controlled by reservoir facies and dip closures to the east and west and have sealing faults constraining the north and south extents of the reservoir (Figure 3) (Dranfield et al., 1987; Smith and Hogg, 1997); hydrocarbon traps also influence hydrocarbon migration across the oil field. Approximately 100 wells have been drilled at Wytch Farm, the trajectories of which were specifically designed to avoid fault zones so as to reduce water breakthrough and drilling losses. Detailed fault characterization is thus a major initiative at Wytch Farm to isolate potential fault-controlled traps and optimize future well trajectories.

THREE-DIMENSIONAL SEISMIC SURVEY

To facilitate accurate characterization of the oil field, an approximately 66 km² 3-D seismic data set was acquired in 1994 by the Wytch Farm partnership companies. Coverage is predominantly onshore at the entrance to Poole Harbour (Figure 1), extending into the...
harbor for a distance of about 3 km (30% of the data set width). Normal fault locations are easily discernible in the seismic data as a result of the shallow dips of sedimentary layering, which result in clear offsets of seismic reflectors (Figure 4). Most major normal faults extend deeper than the maximum depth of good seismic resolution (~1250 ms two-way traveltime, or about 1750 m depth), preventing fault characterization below the deepest resolvable unit in the field (Sherwood Sandstone). Resolution of all overlying units is excellent, with the exception of the on-land part of the data set beneath Poole Harbour, where seismic quality is greatly reduced. Seismic horizon identification and correlation to the local stratigraphy was carried out by geologists at Wytch Farm (G. Watts, 1997, personal communication), using ties to well synthetics.

Fault interpretations were made using an unconverted two-way traveltime (TWTT) data set. The depth conversion algorithm developed for the region specifies a linear relationship between depth and TWTT plus correction factors for easting and northing. An approximate TWTT conversion is 1.4 m/ms (equivalent to an average velocity of 2800 m/s).

Figure 4. Normal fault appearance in the Wytch Farm 3-D seismic data. Faults appear approximately planar and are sharply resolved. The section is shown in two-way traveltime (TWTT) with approximate depth conversions (in meters) indicated in parentheses (using 2800 m/s). Note that Upper Jurassic units are missing below the Lower Cretaceous unconformity in the main horst block north of the Wytch Farm fault.
Horizon interpretations were made on strong reflectors throughout the faulted sedimentary section, facilitated by an autopicking tool. To ensure accurate matching of horizons across faults, interpretations were confirmed using closed loops that circumscribed interpreted faults at each horizon level (i.e., tracing out an unbroken horizon from footwall to hanging wall and back to footwall without crossing the fault plane). This enabled accurate matching of horizons across faults and the determination of reliable fault slip distributions.

Faults were interpreted on every fifth inline (i.e., every 62.5 m). Inlines strike approximately perpendicular to the east-west trend of fault strikes, allowing accurate determinations of true, rather than apparent, fault offsets. In addition, random seismic traverses were used to constrain fault locations in three dimensions and to assess the occurrence of fault segmentation and linkage locations.

**FAULT INTERPRETATIONS**

Normal faults were investigated in the major horst block between the northern and southern bounding faults (Figure 3). The geometries of fault traces in map view were obtained using hanging-wall and footwall cutoffs on a succession of seismic horizon maps from the Sherwood Sandstone up through the faulted section (Figure 5). The utility of such maps is that they can be compared and contrasted with maps of fault traces documented from normal fault environments at the Earth’s surface and they demonstrate variability in depth-dependent map patterns and fault geometries in a simple and comprehensible manner. In the deepest horizons, faults appear continuous with staggered or sinuous traces oriented along an overall west-southwest–east-northeast or west-northwest–east-southeast strike trend. With decreasing depth, faults become increasingly segmented and have laterally stepping individual fault traces consistently aligned east-west.

The stratigraphy is compartmentalized into numerous horst and graben blocks (Figure 5) that interweave along fault strike. As slip decreases toward the lateral tips of graben-bounding faults, slip increases on adjacent horst-bounding faults, and the major structural style transfers along strike from graben to horst. The amount of overlap of grabens and horstes may be as much as one-third of the individual fault lengths (Figure 5).

Fault interpretation and reservoir characterization can be augmented using 3-D fault rendering (Figure 6), which illustrates 3-D variations in fault geometry and tip-line shapes. Fault surfaces at Wytch Farm exhibit flat tops and bottoms at the upper and lower extents of the fault system, respectively. The flat bottoms are an artifact of the depth limitations of good seismic resolution. The flat tops are real and result from the faults having approached or pierced the Late Jurassic to Early Cretaceous paleosurface associated with syntectonic sedimentation before subsequent burial by postrift marine deposits. Also, some degree of erosion may have removed parts of the upper tips.

One of the largest faults at Wytch Farm is the north-dipping NF/Horst East fault (HEF) system (Figures 5, 6) that strikes across the entire survey area. Above the Lower Jurassic section (Bridport Sands), the NF and HEF appear in fault maps as separate entities striking approximately east-west (Figure 5) that overlap by about 20% of the mappable lengths and have a spacing of about 10%. Mapped out in 3-D, however, these faults can be linked to a common pre-Lower Jurassic basement fault system that strikes west-southwest–east-northeast in the western part of the data set and east-west in the eastern part (Sherwood Sandstone level map in Figure 5). Both the pre- and post–Lower Jurassic parts of the fault system exhibit significant lateral segmentation and have only minor overlaps between identifiable segments, perhaps implying that the segments are hard linked by smaller scale faults.

In the western part of the survey area, where the NF/HEF basement fault begins curving toward the northeast, a south-dipping fault (North Graben fault [NGF]) to the north of NF apparently inhibited the NF from following the basement fault trend in the post–Lower Jurassic section. The NF thus continued striking east-west where the basement part steps to the north (Figures 5, 6). In response, a second post–Lower Jurassic system of faults (HEF) formed above the basement fault in the eastern area of the data set. These relationships suggest contemporaneous growth of the NGF and the NF/HEF system and indicates that conjugate fault pairs impact greatly on each other’s development. The fault styles also indicate that faults in the shallower parts of the stratigraphy are spatially controlled by the locations and orientations of deeper faults.

At the scale of seismic resolution, fault tip-line shapes are variable (Figure 6) and are highly dependent on the presence and shape of adjacent fault segments.
Figure 5. Fault trace maps for various horizons through the faulted section (Figure 4). Ball and stick symbols indicate downthrown hanging-wall blocks. Approximate depths are shown in the bottom left corner of each box. As depth decreases, there is an increasing degree of segmentation and a tendency toward east-west fault orientations. AF = Arne fault; NF = Northern fault; NFB = North fault basement; NGB = North Graben basement fault; NGF = North Graben fault; HEF = Horst East fault; HEU = Horst East Upper; EGN = East Graben North; EGN2 = East Graben North 2; FA = Fault A; FB = Fault B; FC = Fault C; FD = Fault D.
Figure 6. 3-D rendering of fault geometries using fault segments interpreted from seismic data. Fault names are as in Figure 5. Lines on fault surfaces indicate respective dip directions. Flat bottoms of faults represent the maximum depth of seismic resolution, whereas flat tops are real and indicate that the faults pierced or approached the paleosurface. (A) Oblique view from above and toward the southeast. (B) Oblique view from above and toward the northwest.

(e.g., Nicol et al., 1996). Most fault shapes can be approximated by rectangular, elliptical, or semielliptical tip lines. In general, faults have high aspect ratios (ratio of fault length to fault height) in the range of 2–4. Many faults exhibit steep tip lines along their lateral edges (Figure 6), generally at relay zones between adjacent fault segments. In addition to the flat tip lines at the upper extent of the fault system, horizontal tip lines occur at vertical steps between fault segments (Figure 6) or where the antithetic fault of a conjugate fault pair approaches the through-going fault that cuts across the entire faulted stratigraphy.

Although some faults are apparently continuous throughout the pre-Cretaceous stratigraphic section, variations occur along strike where fault surfaces bifurcate into separate segments (e.g., HEF and HEU in Figure 6). Such segments are separated from each other both vertically and perpendicular to fault strike. In this manner, faults across a wide region collectively form a systematic patchwork of faults, which is similar to a concept described by Willemse and Pollard (2000) for the development of a single fault surface through the linkage of multiple segments. The patchwork geometry is most compelling where viewed from directly
above, each fault filling a gap in the patchwork (Figure 7). Of particular significance is that the pieces of the patchwork at various levels of the stratigraphy do not necessarily consist of faults that dip in the same direction but may be conjugate to each other.

**FIELD ANALOGS**

Fault styles were examined in outcrop analogs of the Wytch Farm units to provide potential insights into seismic-scale fault architectures in the event of some degree of scale independence and to provide constraints on boundary conditions (e.g., slip vectors on faults) in numerical models (see next section). All faults in the Wytch Farm field are constrained below the Aptian–Albian unconformity below the Cretaceous Chalk and thus only occur in outcrop where the units below this unconformity intersect the Earth’s surface. Along the southern coast of England, the regional dips of the sedimentary units result in successively older units cropping out with increasing distance west of Wytch Farm. Excellent exposures of the Wytch Farm units occur along the high sea cliffs of western Dorset and eastern Devon. Outcrop-scale field analogs of Wytch Farm normal faults can be observed at least as far west as Exmouth (Figure 1), approximately 100 km west of Wytch Farm. These faults have similar orientations to those at Wytch Farm and developed during the same succession of regional tectonic events. They are thus potential analogs of the reservoir-scale faults and may demonstrate the characteristics of faulting within the various sedimentary units at Wytch Farm in terms of both broad-scale fault geometries and internal fault architectures (R. Fox, 1997, personal communication).

A Sherwood Sandstone equivalent (Otter Sandstone) at Ladram Bay, west of Sidmouth (Figure 1), provides numerous examples of conjugate fault styles on an approximately 20 m–high cliff face (about 10% of the total thickness of the Sherwood Sandstone at Wytch Farm) (Figure 8A). Fault zones are narrow (~15 m wide) and about 100 m apart, and no visible deformation exists in the regions between the fault zones.

The outcrop exhibits a conjugate fault style, which bears a strong resemblance to fault geometries at the 3-D seismic scale. A southwest-dipping normal fault cuts through the entire outcrop and offsets horizontal layering by about 5 m. Minor northeast-dipping anticlinal faults (<1 m offset), occur in both the hanging-wall and footwall blocks. The faults in Figure 8A are narrow (~2 cm wide) deformation band-style faults (Aydin and Johnson, 1978; Antonellini et al., 1994) that strike approximately northwest-southeast, have dips of about 65°, and exhibit slip surfaces indicating pure dip-slip motion. Although deformation is almost absent outside of the region of faulting, the sandstone in the footwall juncture zone between conjugate faults contains a network of conjugate deformation bands (Figure 8B). Thus, there is a hierarchy of deformation scales at the outcrop (subseismic) scale of faulting.

Along the main fault plane (Figure 8A), a thin layer of gouge has developed from either finely comminuted sandstone or entrained clay from shale horizons in the Sherwood Sandstone. East of Ladram Bay, a fault outcrop provides clear evidence of shale being smeared into the fault zone from a shale unit in the Sherwood Sandstone (Figure 9A). A similar example occurs 50 m east of the mouth of the River Sid, where a shale unit is associated with several vertically stepping echelon segments along a small normal fault (Figure 9B). This geometry provides a logical starting point for shale to become entrained into the fault zone as slip accumulates (Aydin and Eyal, 1996; Childs et al., 1996): slip is accommodated in segment stepovers at shale horizons by smearing of the shale into the fault zone. In this way, the vertically stepping segments do not have to be physically linked to behave as a kinematically continuous fault.

**Figure 7.** Systematic patchwork geometry defined by fault surfaces within a faulted volume, each fault surface filling in a gap in the patchwork. View direction is from above.

![View from above](image-url)
MECHANICAL MODELING

Methodology

Numerical models of normal faults that examine slip distributions and displacement fields can provide many insights into fault evolution that can be applied to 3-D seismic data where the fault geometries are similar to the models (Pollard et al., 1997; Maerten et al., 2000). This introduces a mechanical evaluation of interpreted slip distributions and displacement fields to determine whether they are consistent with rock fracture mechanics principles for a given fault interpretation. We use a boundary element computer program called Poly3D (Thomas, 1993) based upon linear elasticity in a half-space (i.e., containing a free surface, analogous to the surface of the Earth). Faults are approximated as planar surfaces of displacement discontinuity (comprised of 400 boundary elements) that undergo a complete stress drop during slip under the influence of an effective remote tension perpendicular to fault strike. Such models simulate crustal extension by normal faulting, with all accumulated shear stresses being relieved along the fault during slip. These conditions adequately approximate slip episodes on pure dip-slip normal faults at Wytch Farm that were once active at or very near to the Earth’s surface. Poly3D can be used to calculate slip distributions on fault surfaces and the displacement field in an elastic body containing faults of specified spatial geometry and shape. These results can be compared directly with seismic data interpretations.

As described previously, the normal faults in the Wytch Farm oil field are segmented above the scale of seismic resolution. Fault segments have variable lengths and variable amounts of overlap and spacing in relay zones. The amount of mechanical interaction between adjacent fault segments is affected by these parameters and is evidenced in the slip distributions and displacement fields (Willems et al., 1996; Willems, 1997). Therefore, we examine slip and displacement fields for the simple cases of single faults, overlapping echelon faults, and conjugate faults. We approximate all faults as semielliptical slip surfaces intersecting the Earth’s surface and having an aspect ratio of 3, which approximates some tip-line shapes interpreted at Wytch Farm. We thus illustrate the general characteristics of slip and displacements for such fault geometries and show how they may be used to improve the seismic interpretation of faults at Wytch Farm.

Model Results

Slip Distributions

Slip characteristics on fault surfaces vary with the geometrical arrangement of faults (Figure 10), whether adjacent fault segments are partially overlapping, fully
overlapping, or conjugate to each other. Isolated faults in an elastic half-space have maximum slip values at the free surface (Figure 10A), halfway between the fault tips. Slip gradients steepen toward the lower fault tip line (Figure 10B). Faults that are not isolated from each other have different slip patterns because of the mechanical interaction effect between adjacent fault segments, resulting from deformation in the elastic body being partitioned between the fault segments. Partially overlapping fault segments exhibit similar slip distributions to isolated faults except that slip gradients are steepest within relay zones between fault segments (Figure 10C) and have increasing prominence as overlap increases. For fully overlapped faults (Figure 10D), the leading fault (as defined in Figure 10) has a more localized slip distribution peak than the trailing fault (situated in the footwall of the leading fault), which has a broader peak and steeper slip gradient toward its lower tip. Conjugate faults exhibit particularly steep slip gradients toward the lower tips (Figure 10E), where the oppositely dipping faults are closest to each other.

Displacement Fields
The pattern of displacement contours at the free surface (Figure 11) indicates the expected dip direction of beds deformed by slip on the faults (bed dips are perpendicular to contour lines). Beds dip toward points of slip maxima along faults. We illustrate how the amount of overlap affects the orientation of beds within a relay zone for faults spaced at 5% of the fault length. Faults are more prone to mechanical interaction as the spacing between them decreases (Bürgmann et al., 1994). Bed dip directions are accordingly affected; therefore, the overlap-to-spacing ratio becomes the controlling factor when modeling bed dips. As the amount of overlap increases, bed dip directions rotate to progressively higher angles with respect to fault strike (Figure 11A, B) until they are perpendicular to fault strike from the leading fault toward the trailing fault, for the case of fully overlapped faults. Models of displacement fields in the vicinity of vertical steps along a fault (Figure 11C) can illustrate the effects of vertical heterogeneities along a fault surface on horizon displacements.

Comparison to Seismic Data
Slip distribution models can be compared with contoured horizon offsets across interpreted fault surfaces, whereas displacement field models can be compared with seismic horizon structure-contour maps (e.g., autopicked horizons). For example, comparison between numerically modeled displacement fields and horizon-contour maps may enable the deduction of locations of segmentation along fault strike. Because fault spacing can be more accurately measured than fault overlap in seismic data, it can be used as an input parameter in numerical models to then deduce the amount of overlap of segments based on calculated bed dip directions (Figure 11). The magnitudes of bed dips are related to cumulative fault slip magnitudes; however, bed dip directions are a function of fault overlap geometry and may thus be used to aid in fault interpretations in seismic data.

Figure 12 shows profiles of the displacement field along a line through the relay zone oriented parallel to fault strike. Profile shapes vary with amount of fault overlap and can thus be compared to profiles across seismic horizon contour maps along fault-parallel traverses to determine the amount of overlap between
Figure 10. Modeled slip distributions on semielliptical faults piercing the surface of the Earth. Slip distributions are noticeably impacted by fault configuration, as are slip gradients between the surface and the lower fault tips (B). Slip maxima (black dots) occur at the surface approximately halfway between the fault tips (A, D, E), except echelon faults (C), which have slip maxima skewed toward relay zones. Fault spacings with respect to fault lengths (measured at the Earth's surface) are as follows: (C) echelon faults $\approx 5\%$; (D) fully overlapped faults $= 16.7\%$; (E) conjugate faults $= 33.3\%$. For echelon and fully overlapped configurations, the trailing fault is situated on the footwall side of the leading fault. Conjugate faults meet at the lower tips and have mutually identical slip distributions.

fault segments. Estimates can also be made of fault tip-line locations as projected onto the traverse line (Figure 12). As overlap increases, the point of zero vertical displacement within the relay zone (intersection point with the horizontal axis) moves progressively toward the leading fault.
Figure 11. (A) Effect of fault configuration on displacement fields at the Earth's surface. Contoured displacements are normalized to the maximum downthrow in each example. Arrows between faults represent the direction of bed dip in the relay zone. Faults (thick lines) are all semielliptical and dip in the direction of the ball and stick symbols. Axes are in km; all faults are 3 km long and 1 km high. Faults have spacings of 5% of the fault length and variable overlaps as labeled. Fully overlapped faults have a 16.7% spacing. (B) Plot of obliquity between fault strike and bed dip direction as a function of overlap. (C) Displacement field through the center of a vertical compressive step.
The slip distribution and displacement field models described previously represent single-slip events on faults that pierce the Earth's surface. No assumptions are made with regard to evolutionary history for each fault configuration or the cumulative impact on the final slip distributions, both of which may be highly complex in natural fault environments. The numerical models thus greatly idealize the complex
faulting process. Nonetheless, several normal fault studies suggest that the distribution of cumulative slip is somewhat systematic in nature over a range of scales (Walsh and Watterson, 1988, 1989; Dawers et al., 1993) and bears a strong resemblance to single-slip event elastic model results (Willemse, 1997) despite the fact that natural faults accumulate slip through multiple slip events. Single-slip event numerical models may thus provide reliable analogs for describing slip distributions in nature. For example, comparisons between numerical models and seismic horizon contour maps have been successfully used to predict regions of subseismic deformation and fault linkage points in a North Sea oil field (Maerten et al., 2000).

**REFINING FAULT INTERPRETATIONS**

First-order fault interpretations from 3-D seismic data, such as those described previously for Wytch Farm oil field, can be improved through the use of seismic attribute tools in conjunction with fault mechanics principles and numerical model results. In addition, integrating detailed seismic data analyses with the salient field analog observations (i.e., conjugate fault styles, interfault deformation characteristics, shale smear across clay horizons) allows us to refine the interpreted normal fault characteristics and thus improve the reservoir characterization. We place emphasis on fault segmentation, fault linkage, slip distributions, and tip-line locations.

**Segmentation and Linkage**

Sinuous fault traces mapped at the Sherwood Sandstone level appear to be continuous along strike (Figure 5). This interpretation, however, uses possibly erroneous assumptions as to whether faults should be correlated from one inline to the next. Whether or not the interpretation is satisfactory is subjective. For example, if the feature of interest is the broad-scale mechanical behavior of the entire fault system (i.e., the cumulative behavior of individual segments, either linked or behaving in a kinematically coherent fashion), the continuous trace interpretation may be appropriate. If the parameter of interest is specific to fault architecture, however, such as the permeability across a fault, the existence and nature of segments and relay zones may be of particular importance (e.g., for determining water breakthrough or hydrocarbon leakage points along a fault in an oil field), thus requiring a more finely honed interpretation.

The variation in fault geometries through the stratigraphic section (Figure 5) illustrates fault segmentation at a scale greater than the seismic resolution. For example, numerous east-west striking fault segments occur at the level of the Bridport Sands, mostly between 1 and 3 km long. At the deeper level of the Sherwood Sandstone, the segmentation is lost in favor of sinuous faults (e.g., NF/HEF), suggesting that linkage of echelon segments may have occurred at depth. In light of interpreted segmentation at shallower levels in the stratigraphy (Figure 5), we reexamine our initial fault interpretations at deeper levels in an attempt to isolate potential hydrocarbon leakage points using evidence of relict segmentation that may provide insights into the genesis and evolution of the deeper level faults.

To capture evidence for segmentation near to and perhaps below the limits of seismic resolution, use was made of dip magnitude maps and time slices. Dip magnitude maps reflect the maximum change in dip (in ms/m) along a seismic reflector, computed as the difference in TWTT between a particular peak or trough along a seismic trace and all traces immediately surrounding it. Time slices are contoured maps of seismic amplitudes at a particular TWTT (depth). Both types of display are very sensitive to sudden dip changes that may occur at a fault discontinuity or in the relay zone between overlapping fault segments.

A dip magnitude map of the D Anhydrite horizon of the Mercia Mudstone in the vicinity of the Arne fault (Figure 13A) corresponds in the fault trace maps to a region of sudden direction change along the predominantly west-northwest–east-southeast fault trend (Figure 5). The dip magnitude map (~13 m pixel resolution) shows several east-west–oriented lineaments 100–200 m long in a predominantly right-stepping echelon arrangement. This pattern provides an impetus to consider the Arne fault as being comprised of several segments that may or may not be linked and provides clues to the evolutionary history of the faulting in general.

A reexamination of the seismic data at an apparent segment boundary in the dip magnitude map (i.e., a fault step larger than the pixel resolution) suggests the presence of a combined vertical and lateral step in the Arne fault (Figure 13B). Seismic traverses in several orientations through the stepover region indicate that the segments are linked across the relay from the trailing segment to the footwall of the leading segment via
Figure 13. (A) Dip magnitude map of the D Anhydrite horizon. Faults form lineaments of high dip magnitude and show evidence of being comprised of numerous segments. (B) Initial and refined interpretations of the Arne fault in seismic section at the fault step indicated in (A). The new interpretation introduces a vertical step in the Arne fault. (C) Conceptual illustration of segment linkage through an upper ramp breach. (D) 3-D representation of the stepover zone, indicating a possible window across the fault.

Abrupt variations in the general orientation of the pre–Lower Jurassic part of the NF/HEF system (Figures 5, 13A) may similarly signify segment linkage features. A seismic time slice at a 140 m–wide jog between two east-west fault segments displays a distinct northeast-southwest lineament (Figure 14) that suggests that the slightly overlapping segments were linked from the tip of the leading segment to the hanging wall of the trailing segment, forming a lower ramp breach and producing an abandoned footwall splay (e.g., Trudgill and Cartwright, 1994). Time slices may thus be used to identify seismically resolvable fault linkage sites, enabling an evaluation of the sealing.
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Figure 14. Interpretation of a fault linkage structure using time slice attributes. (A) Time slice for a region of the NF/HEF system (inset map). Closely spaced amplitude contours indicate fault locations. (B) Interpreted linkage geometry having a lower ramp breach and an abandoned footwall splay.

In addition to lateralsegmentationat Wytch Farm, 3-D fault surface rendering (Figure 6), outcrop fault styles (Figures 8, 9), and seismic attribute characteristics (Figure 13B) indicate the presence of vertical segmentation. Outcrop-scale analogs include areas where fault continuity is broken by (1) a through-going fault of opposite dip (Figure 8) and (2) clay horizons (Figure 9). A corollary of (1) is the large-scale vertical segmentation of the NF/HEF system associated with the oppositely dipping North Graben fault (Figure 6). To examine the significance of observation (2) for seismic-scale faults, we reexamined our initial interpretations of faults cutting through clay-rich units in an attempt to locate evidence of vertical segmentation. We thus focused on the Mercia Mudstone (which also contains anhydrite layers), Lias Mudstone, and Fuller’s Earth horizons.

Initial fault interpretations showed irregularities in fault geometries across clay-rich units in section view, possibly indicating vertical steps and implying a significant lithological control on large-scale vertical segmentation of normal faults. Childs et al. (1996) documented how mechanically weak interfaces similarly control step locations along outcrop-scale normal faults in Cretaceous Chalk in Yorkshire, England. At Wytch Farm, contractional steps predominate, analogous to the outcrop example in Devon (Figure 9). Abrupt decreases in shale thickness at the vertical steps suggest that mechanically weak units accommodate the compression at the steps through unit attenuation (e.g., Peacock and Sanderson, 1992; Kattenhorn, 1994; Childs et al., 1996). In Figure 15A, the Mercia Mudstone is noticeably attenuated at a vertical step in the HEF. In addition, bed dips change suddenly in the region of the postulated vertical step, similar to the Arne fault in Figure 13.

Analogous to shale attenuation at compressive vertical steps, clay-rich horizons appear to focus the points of convergence of all major conjugate faults at Wytch Farm (Figure 15B). The fault trace patterns in Figure 5 indicate that major graben-bounding faults converge at either the Fuller’s Earth horizon (e.g., NF/Fault A; NF/Fault B) or the Mercia Mudstone horizon (e.g., NF/North Graben fault; HEF/East Graben North fault), emphasizing lithological control on fault geometries and indicating that graben fault spacing at any particular depth may be a function of distance above a specific horizon, such as a thick shale unit.

Based on the aforementioned criteria, we reinterpreted faults at Wytch Farm to capture both lateral and vertical segmentation effects. For example, a refined interpretation of the NF/HEF system (Figure 16) revealed a greater degree of segmentation than was initially interpreted (Figure 6).

Slip Distributions

Slip profiles along fault traces at the Earth’s surface commonly contain multiple slip maxima along a fault that formed through the linkage of two or more fault segments (Cartwright et al., 1995; Dawers and Anders, 1995; Cartwright and Mansfield, 1998). Analogously, multiple slip maxima across a fault surface provide evidence of segmentation (Mansfield and Cartwright, 1996) and linkage (Maerten et al., 2000), indicating both lateral and vertical loci of the original segments. We adopted this interpretation rationale to evaluate 3-D segmentation at Wytch Farm, where multiple slip maxima are present on all major faults (Figure 17).

The Arne fault slip maxima are consistently at the level of the top of the Sherwood Sandstone (Figure 17), indicating that segmentation in faulted Triassic units was a precursor to laterally continuous faults that formed through subsequent linkage of the segments.
This observation is in agreement with both fault-trace maps in the Sherwood Sandstone (Figure 5) and seismic attribute map analyses (Figure 13). Slip distributions that have multiple maxima may thus be used to isolate potential locations of segment linkage sites, which would occur near the slip minima.

The NF/HEF system displays slip maxima in two parts of the stratigraphy (Figure 17): Triassic units (Sherwood Sandstone) and mid-Jurassic units (Bridport Sands through Cornbrash limestone). This indicates two loci of fault nucleation in the Wytch Farm field, apparently lithologically controlled by the locations of brittle limestone and sandstone units. Propagation and mutual approach of faults in these respective parts of the stratigraphy resulted in vertical segmentation and partial linkages, consistent with

Figure 15. (A) Vertical segmentation along the Horst East fault. Compressional vertical steps occur within Mercia Mudstone that is attenuated within the relay. (B) Convergence of conjugate faults within attenuated Mercia Mudstone.

Figure 16. 3-D perspective view of segmented NF/HEF system. The refined interpretation accounts for numerous instances of vertical and lateral segmentation. Arrows represent lines of linkage of two segments. Tip lines are horizontal along vertical steps between segments.
interpreted vertical steps at the level of the Mercia Mudstone (Figure 15A). The two main segments of the HEF have slip maxima and associated steep slip gradients close to the relay zone between them, in agreement with numerical predictions of slip gradients near the region of overlap between contemporaneous faults (Figure 10).

The North fault and North Graben fault both display localized slip maxima at the level of the Mid Lias horizon (Figure 17). These represent locations where underlying Mercia Mudstone has been attenuated, resulting in increased apparent offset of faulted units. Analogous lithological contributions to localized slip profile heterogeneity have been described in outcrop.

Figure 17. 3-D slip distributions for several normal faults at Wytch Farm, as labeled. White and red are regions of maximum slip. Black and purple are regions of lowest slip. Note multiple slip maxima in all examples. Horst East fault examples are spatially arranged with respect to each other as shown by arrows and fault tip-line outlines.
scale faults (Muraoka and Kamata, 1983; Kattenhorn and McConnell, 1994). The NF example is analogous to the vertical step case in Figure 15A. The North Graben fault example reflects a point of conjugate fault convergence, as shown in Figure 15B. The spatial association of local slip maxima and clay-rich units should thus be treated with caution and should not be casually classified as fault segment nucleation locations.

**Tip-Line Locations**

Seismic resolution constraints inhibit accurate location of fault tip lines, where fault displacements decrease to zero. Pickering et al. (1997) suggest the addition of a length of fault beyond the seismic resolution tips using throw and length scaling relationships. This approach, however, may be inaccurate where slip gradients are variable because of mechanical interaction effects (Figure 10) or the impact of lithology (Muraoka and Kamata, 1983).

We applied our methodology for predicting fault geometries at fault relay zones (based on displacement field models) (Figures 11, 12) to the East Graben North (EGN) and East Graben North 2 (EGN2) faults (Figure 5), both of which were active at the surface in the Late Jurassic. First, we determined the dip direction of beds in the relay zone using dip azimuth maps and seismic lines intersecting the relay at a range of orientations. The so-determined obliquity between bed dip direction and fault strike suggests an overlap of 10–20% (Figure 11). The corresponding displacement profile (Figure 12) was then compared to the displacement of the Fuller’s Earth seismic horizon within the relay zone (Figure 18A). The predicted tip-line location using this method is located approximately 150 m beyond the location deduced using horizon offsets in seismic section view and corresponds to a dip magnitude perturbation in the tip-line vicinity (Figure 18B, C). A connecting segment between the faults is also evident, having formed an upper ramp breach (Figure 18D).

Slip distributions on the EGN and EGN2 faults (Figure 18E) have maxima in different parts of the stratigraphy (Cornbrash and Bridport horizons, respectively). The shape of the slip contours on EGN2 appears to reflect the projected shape of the EGN fault tip line in the region of overlap (Figure 18F), perhaps due to mechanical interaction between the two segments.

Application of numerical results to seismic interpretation may thus aid in constraining tip-line locations; however, care should be taken to not apply these models indiscriminately. The displacement fields in the vicinity of relay zones (Figures 11, 12) are highly dependent on individual fault parameters such as fault shape, relative slip magnitude, slip sense, and slip distribution, in addition to initial bed dips (Gibson et al., 1989; Peacock and Sanderson, 1994). Furthermore, horizon displacements produced by growth folding above an active fault should not be confused with relay zone deformation. Model estimates of fault tip-line shape are thus case specific; however, the overall methodology described in this article is generally applicable.

**DISCUSSION**

A detailed characterization of normal fault architectures at the Wytch Farm oil field has been achieved through the integration of seismic data interpretation, outcrop-scale analog observations, and numerical models. This methodology has enabled the recognition of a significant amount of segmentation of the fault system at Wytch Farm. This finding is particularly important because segmentation affects both water breakthrough and sweep efficiency between wells (G. Watts, 2000, personal communication). Exact knowledge of segmentation characteristics is thus important for designing optimal well trajectories in the oil field. Breaks between fault segments provide potential points of communication between otherwise compartmentalized oil traps; therefore, the recognition of such breaks can provide petroleum geologists with an indication of the sealing effectiveness along a particular fault system, as well as isolating particular locations along faults where detailed mapping is necessary to determine evidence of fault segment linkages.

For example, the Arne fault in the Wytch Farm oil field is laterally continuous in initial interpretations (Figure 5) but shows numerous east-west linear patterns along the west-northwest–east-southeast fault trend in the dip magnitude map (Figure 13) and multiple slip maxima (Figure 17). The Arne fault may thus have been initially segmented, having the individual segments oriented east-west in a predominantly right-stepping echelon arrangement. Linkages between these segments then occurred through the development of northwest-southeast–oriented connecting faults, the existence of which has been suggested by production-related data as well as previous analyses of the Arne fault (P. Kelly, 1997, personal communication) that influenced subsequent decisions about...
Figure 18. (A) Estimation of tip-line location using a displacement profile through the relay zone between overlapping faults (see Figure 12). (B) The fault tip is predicted to occur 150 m beyond the initial interpreted tip location on the trailing fault. (C) Dip magnitude anomalies near the fault tips suggest continuation of faults beyond the initial interpretation. (D) Reinterpreted faults with new tip locations and addition of a linking fault segment forming an upper ramp breach. (E) Slip distributions on EGN and EGN2 (oblique view toward the NW). Slip maxima (colors as in Figure 17) are in the Cornbrash (EGN) and Bridport (EGN2). (F) The contours of slip on EGN2 trace out the tip-line shape of EGN across the relay zone.
well trajectories in the oil field (G. Watts, 2000, personal communication).

Analogously, numerous jogs along the trace of the HEF imply an initially left-stepping arrangement of east-west fault segments having an overall west-southwest–east-northeast trend and subsequent northeast–southwest–oriented connecting faults (Figure 14). Staggered fault traces in 3-D seismic interpretations may thus result from closely spaced echelon segments that were erroneously correlated, or perhaps a relict segmented geometry that, through segment linkage, produced a through-going fault oriented along the trend of the array of initial echelon segments. This scenario is consistent with both the east-west orientations of smaller faults higher in the stratigraphy (Figure 5) and the postulated north-south major extension axis in the region during the period of Atlantic opening in the Jurassic and Cretaceous (Hawkes et al., 1998; Miliorizos and Ruffell, 1998).

Outcrop analogs demonstrate vertical segmentation of faults in the vicinity of clay beds (Figure 9B), the significance of which was overlooked in initial seismic interpretations. At the seismic scale in the Wytch Farm oil field, this outcrop characteristic is manifested as vertical segmentation of large-scale faults within clay-rich units such as the Mercia Mudstone, Lias Mudstone, and Fuller’s Earth. Vertical segmentation is difficult to capture in seismic sections in cases where fault separation is small. If a through-going fault interpretation requires the insertion of a bend in the fault plane to match up the fault-induced breaks in horizon continuity from one part of the stratigraphy to another, then a segmented interpretation may be more appropriate (for exceptions, see Peacock and Sanderson, 1992; Childs et al., 1996). Beds have increased dips in vertical step relay zones in seismic section (Figures 13B, 15A) and in mechanical models of displacement fields around vertical fault steps (Figure 11C). Bed dips can thus be used as indicators of the lateral extent of linkage between vertical segments. For example, vertically confined bed dip increases along a fault traceable parallel with fault strike for a significant lateral distance in time slice maps, are a possible indicator of relay ramps between vertically stepping segments (Figure 19).

It may be difficult to determine the lateral extent of linkage of vertically stepping fault segments. In some instances, fault-perpendicular spacing of vertically stepping segments increases with increasing distance from the point of linkage, providing unambiguous segmentation indicators in seismic section view (Figure 15A). Where segments are closely spaced, the point of linkage across a vertical step may be approximated as the location in the 3-D seismic data where the dipping horizons in the relay are no longer resolvable in seismic lines or seismic attribute maps such as time slices (Figure 19).

The consistency of vertical steps occurring in low-competency units implies a significant lithological control on fault evolution, in agreement with outcrop-scale structures (Muraoaka and Kamata, 1983; Childs et al., 1996). Softer units respond to compressional steps by attenuating, resulting in thickness variations across faults that could erroneously be interpreted as being a result of syntectonic sedimentation. Slip distributions further indicate the importance of lithology on fault evolution. Fault segments initiated predominantly at two levels in the stratigraphy (Figure 17): an early nucleation event within or below the Sherwood Sandstone and a later event in the shallower Bridport to Cornbrash part of the stratigraphy. Both faulting episodes can be reconciled with the documented tectonic history of the region (Jenkyns and Senior, 1991; Hawkes et al., 1998). The deeper faults were most likely Permian early Atlantic rifting-related normal faults that were reactivated during Early Jurassic Atlantic rifting. This conclusion is corroborated by the fact that synrift Permian units, such as the Aylesbeare Mudstone, show significant thickness variations across the deeper faults, whereas postrift units, such as the Sherwood Sandstone and Mercia Mudstone, do not (Butler, 1998). The shallower faults probably formed later, during Late Jurassic Atlantic opening, nucleating in Middle Jurassic postrift units that postdated the early Atlantic rifting. These faults subsequently approached or pierced the Late Jurassic paleosurface, resulting in thickness variations across faults in Late Jurassic (post-Cornbrash) units, whereas there are no thickness variations in the underlying Middle Jurassic (Bridport to Cornbrash) units.

Each of the two faulting episodes produced arrays of laterally stepping fault segments. Lateral propagation and subsequent linkages between these segments resulted in composite faults longer than they are tall (aspect ratio > 1). Where linkages formed between the deeper and shallower fault arrays, the resultant faults are continuous through the entire stratigraphy, reducing fault aspect ratios.

The evolution of normal faults at Wytch Farm through lateral and vertical segmentation and subsequent linkage is conceptualized in Figure 20. Individual fault segments that are widely spaced from other faults
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may be more likely to propagate upward toward the surface than to propagate laterally, in response to the decreasing lithostatic confining stress (Kattenhorn and Pollard, 1999). This behavior preserves the segmented geometry as faults propagate upward through the stratigraphic section and is reflected in the fault-trace maps at higher stratigraphic levels (Figure 5). Where upward growth of the Wytch Farm faults was impeded by ductile shale units, lateral propagation predominated, probably facilitated by mechanical interaction effects between laterally stepping faults, which have been shown to increase both lateral tip-line growth tendency (Kattenhorn and Pollard, 1999; Willemse and Pollard, 2000) and the likelihood of segment linkage (Trudgill and Cartwright, 1994; Cartwright et al., 1995; Crider and Pollard, 1998).

The staggered fault trends in the Triassic and Lower Jurassic rocks imply a geometrically more advanced state of fault evolution produced by the linkage of east-west segments that formed at depth during the Early Jurassic. Late Jurassic fault segments were syn-sedimentary faults at or near the surface. The younger age of fault development is reflected in both the absence of large-scale linkage geometries and the lower spatial density of faulting, which reflects a shorter and lesser strain history.

Recognition of extensive fault segmentation at Wytch Farm is important for evaluating hydrocarbon flow paths in the oil field. Unlinked fault segments provide fluid migration pathways through the relay zones connecting hanging-wall and footwall blocks. Linkage zones may nonetheless provide leakage points through composite fault surfaces. Fault segments in the Triassic rocks, such as the Sherwood Sandstone, are apparently linked across relays, resulting in laterally continuous fault geometries. Individual fault blocks are thus
Figure 20. Conceptual evolution of normal faults at Wytch Farm. (A) Formation of east-west striking echelon segments in the Triassic section, possibly above reactivated basement structures. A younger system of segmented faults subsequently nucleated in the Middle Jurassic section, forming vertical steps with deeper segments across ductile shale units. (B) Deeper segments linked together across lateral steps to form continuous fault traces that have curves or kinks at linkage points. Some linkages occurred across vertical steps. The shallower, less-evolved faults are segmented and possibly pierced the Late Jurassic paleosurface.
compartmentalized, in agreement with measured high-pressure differentials across faults (Smith and Hogg, 1997). The identification of several segment boundaries at the Sherwood Sandstone level, however, provides justification for petroleum geologists considering these locations as potential leakage points across the fault system. Faults in Jurassic unit reservoirs (Bridport Sands and Frome Clay Limestone) are more segmented with less linkages (Figure 5). Lateral continuity is thus reduced, suggesting greater connectivity between fault blocks and less compartmentalization of the reservoir. Well path trajectory planning may thus continue to benefit from this fault characterization through the choice of well paths that avoid fault segments and regions of potential hydrocarbon leakage or water breakthrough.

Vertical steps along faults may provide leakage points for hydrocarbons migrating vertically through the field and may complicate fault location identification at the deeper levels of the oil field where seismic resolution is poor. The predominantly contractional vertical steps, however, are confined to low-permeability clay-rich units such as the Mercia Mudstone, which may reduce the leakage tendency through vertical-step relays in the absence of significant fracturing. In outcrop, clay becomes entrained along fault zones at vertical steps. At the seismic scale, this phenomenon may result in a significant reduction of cross-fault permeabilities (≤ 0.01 md) (R. Knipe, 1994, personal communication).

CONCLUSIONS

We have proposed a procedure for normal fault interpretation that integrates 3-D seismic data analyses with several techniques for the recognition of segmentation features. The procedure involves (1) a standard interpretation of faults from 3-D seismic data, (2) mapping of outcrop-scale fault analog geometries, (3) numerical modeling of slip and displacements associated with segmented fault geometries, and (4) the application of insights gained from outcrop observations and modeling to seismic interpretations to develop a more finely honed fault model with the aid of seismic attribute tools.

A large volume of literature exists to characterize the mechanics of normal fault systems, and such principles should be incorporated into the seismic interpretations. Outcrop-scale analogs may provide important insights into the nature of faulting at the seismic scale, and some fault geometries exhibit a degree of scale independence between the outcrop and seismic scale. Numerical models based on the principles of linear elastic fracture mechanics provide a means of calculating displacement fields associated with overlapping faults and can be used to hone the locations of fault tips below the level of seismic resolution. Seismic attribute maps are sensitive to faulting and bed dip variations and can thus be used to pinpoint deformation near to and perhaps below the conventional limits of seismic resolution.

The integration of all these techniques provides a logical basis for maximizing the utility of 3-D seismic data to construct accurate fault interpretations, which may then be applied to oil field development such as through the design of optimal well trajectories into potential fault-controlled hydrocarbon traps or for predicting leakage points along a fault zone. When these methods are collectively applied to Wytch Farm, interpreted faults are found to exhibit significant lateral and vertical segmentation, particularly in the shallower hydrocarbon-producing units. This places emphasis on segmentation and linkage effects in terms of developing an instructive oil field characterization that isolates potential flow zones across the faulted reservoir. Future development of the Wytch Farm oil field will benefit from attempts to target traps in regions of confirmed fault continuity rather than zones of potential segment boundaries, hydrocarbon leakage, and water breakthrough.

Tip-line shapes and slip distributions indicate that segments impact on the growth tendencies and slip behaviors of each other and may be used to isolate locations of potential fault segment boundaries. Steep tip lines and slip contours formed in zones of lateral fault overlaps, whereas horizontal tip lines formed where conjugate faults converged and along regions of vertical segment overlap, resulting in a tendency toward rectangular fault shapes. Lithology is a major factor in controlling both fault nucleation locations in brittle sandstones and limestones and the development of vertical steps across thick shale units.

Irregular fault traces in the deeper parts of the stratigraphy result from linkage of echelon fault segments across relay zones. Higher in the stratigraphic section, such fault geometries are lost in favor of unlinked east-west-trending segments, implying that upward and lateral growth of segments is the first step of an evolutionary process in which fault continuity increases through time as slip accumulates and segments mechanically interact and link together. The resultant
fault orientation is thus controlled by the initial configuration of echelon fault segments (e.g., left-stepping vs. right-stepping). This hypothesis for segmented fault evolution at Wytch Farm is consistent with the documented north-south extension direction for southern England during the Mesozoic.

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