Franklin and Elgin fields were discovered in 1986 and 1991, respectively, within the U.K. North Sea Central Graben blocks 22/30 and 29/5. The producing reservoirs are contained in the Jurassic Fulmar shallow-marine and Pentland fluvial formations at depths of 5100–5600 m subsea. The fields presented significant development challenges both in terms of seismic imaging complexity and being in a state of exceptionally high pressure/high temperature (HPHT). Addressing these challenges meant that production could not commence until 2001.

In 1996, the imaging challenge was addressed by acquiring a 3D seismic survey using aggressive parameters for the time—a single source and six 4500-m streamers separated by 75 m with vessel traverses interleaved to give a fine line spacing of 18.75 m. This data set was processed through various imaging schemes that eventually led to an early example of 3D anisotropic prestack depth migration (PSDM). The progressive improvements of the processing schemes have been described by Suiter et al. (2003).

At project sanction in 1997, the HPHT challenge presented by reservoirs that were initially overpressured by 550 bar at 1100 bar/190º C was formidable. The development program required predrilling all production wells because at that time drilling into HP reservoirs depleted by more than 100 bars was not thought possible. However, newly evolved drilling techniques will now permit infill drilling into reservoirs depleted by 500 bar, the amount of depletion that has now occurred in both Franklin and Elgin. Positioning these infill wells needs careful planning to maximize reserves and to minimize wellbore stability problems caused by reservoir compaction.

Hatchell et al. (2003) showed that the nearby producing Shearwater Field created geomechanical effects throughout much of the subsurface in and around the reservoir, whereby the compaction of the reservoir caused stretching or extensional stresses in the overburden and underburden. This resulted in small variations in layer thickness and seismic velocity within the strata that manifested themselves as time shifts between the seismic arrivals of the base survey with the same reflection arrivals of repeat surveys (time-lapse time shifts). Encouraged by this case study, a 4D repeat seismic survey was acquired over Franklin and Elgin fields in 2005 with the intent of using the geomechanical behavior to help monitor the reservoirs. This 4D monitor survey was acquired with parameters that, as far as possible, matched those of the 1996 base survey. The 4D survey area also includes a large part of the Shell-operated Shearwater Field, as well as the Glenelg and West Franklin fields that in 2005 were yet to be produced.

In this article, we (1) demonstrate the extension of the approach employed by Hatchell et al. by inverting for production-induced stresses directly from observed time shifts between 4D data sets; (2) use a 4D synthetic to illustrate the time-shift dependency on recording offset that is used in the inversion; and (3) use the resulting stresses and measured 4D time shifts to contrast and compare the interesting geomechanical behavior observed over all the above mentioned fields, but particularly Franklin and Elgin.

Geomechanics methodology background. The geomechanical emphasis of the project required processing techniques that preserved any production-induced time-lapse time shifts. This involved such things as deriving all survey matching parameters far away from producing areas. The
repeatability was optimized by 4D binning using source and receiver position variation between vintages as selection criteria. The monitor survey has undershoots beneath the wellhead platforms of both Franklin and Elgin fields. Extensive interpolation techniques were used on data in the undershoot zones in an attempt to preserve repeatability while avoiding artefacts resulting from too many empty 4D bins. The 4D time shifts were measured throughout the processing, and the final Kirchhoff anisotropic PSDMs were driven by the same velocity model for both vintages, so as to preserve the time-shift integrity.

This application extends the approach employed by Hatchell et al. and modified by Hatchell and Bourne (2005). They used geomechanical modeling to predict the observed 4D time shifts by relying on the consistency of a rock physics constraint parameter $R$ that defines the ratio of 4D fractional velocity changes to fractional thickness changes. They used $R$ to relate 4D time shifts to 4D strains using

$$\Delta t / t = (1 + R) \cdot \Delta z / z$$

where $\Delta t / t$ is the 4D fractional time shift within a layer and $\Delta z / z$ is the fractional thickness change, or 4D strain within the same layer. However, the consistency of the parameter $R$ has been the subject of some discussion. Hatchell and Bourne pointed out that $R$ in compacting reservoirs might be expected to be less than half of the values seen in the extended surrounding strata. They suggest that, based on a number of case studies, typical $R$ values of 4–6 apply outside the reservoir and 1–3 apply within the contracting reservoirs. Staples et al. (in this special section) propose $R$ factors in excess of 10 in some lithologies that occur above sandstone HPHT reservoirs very similar to Franklin and Elgin. The estimation of $R$ is not helped by the lack of hard calibration data. Even the hard data that do exist appear contradictory. Janssen et al. (2006) using Ekofisk reservoir core analysis measured $R$ values as high as 30. This contrasted with the 4D time shifts which, in conjunction with the single compaction log into the reservoir using radioactive marker bullets, inferred values of $R$ consistent with those proposed by Hatchell and Bourne.

In this work, we try to complement the approach of Hatchell and Bourne by directly inverting for the velocity and thickness changes from prestack, finite-offset time-shift data, thus avoiding the need to rely on an assumed $R$ value.

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**Table 1. The model parameters used to generate the synthetic of Figure 1 at location 5 on the right of the reservoir.**

<table>
<thead>
<tr>
<th>Layer</th>
<th>TWT (ms)</th>
<th>$V$ (m/s)</th>
<th>$\Delta z / z$</th>
<th>$\Delta v / v$</th>
<th>$R$</th>
<th>$\rho$ (g/cc)</th>
<th>$\sigma$ (g/cc)</th>
<th>$\Delta \sigma_{\text{eff}}$ (MPa)</th>
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<td>1500</td>
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<td>0.0000</td>
<td>0.0000</td>
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<td>1.30</td>
<td>0.00</td>
</tr>
<tr>
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<td>-0.0005</td>
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<td>1.40</td>
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<tr>
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<tr>
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<td>-0.0020</td>
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<tr>
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<td>2.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

**Figure 2. SVO behavior of the ray-traced synthetic by plotting (a) actual time shifts at five subsurface locations against the square of the offset and (b) after normalization the SVO can be described by a single trend. The five locations vary from completely off reservoir (location 1) to center of reservoir (location 5) and correspond to the top reservoir event, as indicated in Figure 1d.**
The mathematical details of the inversion process (from the offset behavior of prestack time shifts) and its verification on synthetic data are available in Hawkins et al. (2006). In this case study, we just illustrate the offset-dependent behavior of the time-shift data using a 4D synthetic loosely based on the Franklin and Elgin reservoirs.

**4D time-shift characteristics.** Figure 1 shows the three model parameters for all layers of the 4D synthetic: (a) base survey velocity model, (b) 4D fractional velocity change between base and monitor surveys, and (c) 4D fractional thickness changes between base and monitor surveys. These model parameters are associated with two reservoirs in separate fault blocks which have undergone depletion with associated stress changes. The HPHT reservoirs are beneath the thick and relatively fast Cretaceous chalk. Although used for illustration here, the synthetic’s original purpose was for benchmarking the inversion process to estimate 4D velocity and thickness changes from supplied 4D time shifts. The 4D time shifts were chosen to be roughly similar to those seen across Elgin Field. Typical reservoir depletions from the area were used to derive 4D strain and velocity changes using a constant $R$ value of 5 throughout. This is consistent with the $R$ value suggested at the time by Hatchell et al. prior to the modification of Hatchell and Bourne that recommended a lower $R$ value within the reservoir. Table 1 details the parameters used to generate the synthetic at the location of the reservoir on the right.

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**Figure 3.** Top reservoir maps of (a) depth structure, (b) 4D time shifts between base and monitor survey. Note the smaller Franklin time shift relative to Elgin and Shearwater.

**Figure 4.** (a) 4D time shifts across Elgin, (b) 4D time shifts across Franklin and Shearwater. Compared to Elgin and Shearwater, the Franklin time shifts are relatively small.
The base and monitor isotropic velocity-depth models were then ray-traced to produce the 4D time shifts in a manner that is consistent with isotropic ray-traced prestack time migration. In this procedure, for both base and monitor models, rays are propagated into the subsurface from source positions. According to Snell’s law, the rays travel down to each model layer and then reflect back to a surface receiver with a specific source-receiver offset. The computed traveltimes of these rays were used to generate synthetic prestack seismic gathers for both base and monitor surveys. These base and monitor synthetics were then passed through a time-shift measurement program to produce 4D time shifts at each layer, for all offsets up to a specified incidence angle. Figure 1d shows the resulting zero-offset 4D time shifts with a gather inset showing the time shift and base synthetic as a function of offset at the reservoir. Figure 1e illustrates the offset dependency by displaying the shift-versus-offset (SVO) gradient that is produced by applying standard AVO techniques to the synthetic’s moveout-corrected time-shift data.

To further emphasise the SVO behavior, Figure 2 shows the time shifts at five different locations on the synthetic.
The existing strain ($\varepsilon_{zz}$) to Elgin and Shearwater. Extensional stress changes above Franklin are relatively small compared to the lower part of the chalk formations (Hod to Plenus Marl). The effective stress computation.

The 4D change in stress is derived by differentiating (Equation 2). So that,

$$\Delta \sigma_{zz} = -M\Delta \varepsilon_{zz} + \Delta e_{zz}$$

where the sign convention is that a negative change of strain (compaction) creates a positive stress change and is associated with a positive change in modulus. Acoustic-wave theory equates the static modulus $M$, to the dynamic P-wave modulus ($\rho v^2$). This leads to

$$\Delta \sigma_{zz} = - \rho v^2 \frac{\Delta z}{z} + \left(2v \rho \Delta v + \sigma_{\text{lith}} \beta \rho \right) \varepsilon_{zz}$$

Using the P-wave modulus in Equation 2, $e_{zz}$ can be replaced by $\sigma_{zz}/\rho v^2$. The effective stress $\sigma_{zz}$ can be equated to $\sigma_{\text{lith}} - \beta P$, where $\sigma_{\text{lith}}$ is the lithostatic pressure, $\beta$ is the Biot-Willis coefficient, and $P$ the pore pressure at the time of the base survey. Hence, we derive the expression for the 4D effective stress $\Delta \sigma_{zz}$,

$$\Delta \sigma_{zz} = - \rho v^2 \frac{\Delta z}{z} + \left(2v \rho \Delta v + \sigma_{\text{lith}} \beta \rho \right) \varepsilon_{zz}$$

where $\Delta v/\rho$ and $\Delta z/z$ are our inverted 4D fractional velocity change and 4D strain, respectively, while $\Delta P$ is the 4D change in density, which can be related to the 4D strain. Lithostatic pressure, pore pressure, and density data are normally readily available from appraisal wells. Figure 1f shows the 4D stress estimation for our simplistic synthetic that has been derived directly from the 4D time shifts shown in Figure 1d. The synthetic’s estimated stress field gives a rough indication of what we might expect to see in and around the Franklin and Elgin reservoirs, very high compressional stress changes within the reservoirs and significant extensional stresses in the overburden and, perhaps, the underburden.

Before looking at the application to real data it should be mentioned that the stress (Equation 3) relies on the dynamic modulus which, despite acoustic theory, is not always found to be equivalent to the static modulus. In some situations, the measured difference between the two is significant. Olsen et al. (2004) suggested that the two moduli diverge during nonelastic deformation that might for instance occur during prolonged burial, but the two are equivalent during elastic deformation such as that due to unloading, or stretch arching as a result of production. Consequently, the right side of Equation 3 is indicated as approximate and should be multiplied by a layer-dependent modulus correction factor. It should also be noted that for the application shown in this article, the Biot-Willis coefficient was assumed to be 1.0. Consequently, for these and other uncertainties, the quantitative results would benefit from calibration procedures with reliable hard data. As in many other applications, the main benefit of seismic data is to provide spatial interpolation and resolution to any available hard data. In the case of 4D stress and strain measurements within challenging HPHT environments, such hard data are often scarce.

**Application to Franklin and Elgin data.** Figure 3 shows the Top Reservoir (Franklin C) maps for: (a) the depth structure, and (b) the measured 4D time shift. The field outlines on

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**Figure 7.** The 4D stress changes computed above the reservoirs within the lower part of the chalk formations (Hod to Plenus Marl). The extensional stress changes above Franklin are relatively small compared to Elgin and Shearwater.

The locations indicated in Figure 1d vary from almost no 4D change away from the reservoirs at location 1 to the maximum change seen in the center of one reservoir at location 5. The raw time shifts of Figure 2a are plotted against the square of the offset. There is a clear linear relationship that, assuming $R$ is lithology consistent, can be normalized and condensed to the single trend shown in Figure 2b. The Figure 2b result is important because it provides a means whereby the SVO behavior can be analyzed over the entire reservoir and then used to constrain the inversion of prestack time-shift data to produce the required 4D fractional velocity and thickness changes. This helps to make the process more robust when applied to real data, which are invariably contaminated by various noise effects.

The use of isotropic ray tracing to produce the synthetic might be considered questionable. The base anisotropy is removed from the equation by the fact that we are looking at 4D differences and, as in this case, the data have been processed through anisotropic PSDM, but the issue of 4D anisotropy changes remain. Compacting reservoirs generate anisotropic stress changes and anisotropic 4D velocity changes that will impact the SVO behavior, particularly for large angles of incidence. Because of this, for both synthetic and real data, the SVO analysis was performed with offsets restricted to a maximum aperture of $30^\circ$. Within this angle range, the impact of production-induced anisotropy on 4D velocity change is considered small. The potential exists to use longer-offset information (aperture $>30^\circ$) to investigate 4D anisotropy changes, but that challenge is outside the scope of this article. For the initial field results shown in this article, the rock physics constraint of Hatchell and Bourne has been employed at depth where the 4700 m maximum recorded offset restricted the aperture of the SVO analysis to less than $25^\circ$.

**Effective stress computation.** The equation used to estimate effective stress changes from the inverted fractional velocity changes and strain (fractional thickness changes) is derived from the uniaxial compaction assumption. The effective stress at the time of the base survey ($\sigma_{zz}$) is related to the existing strain ($\varepsilon_{zz}$) by the uniaxial strain modulus $M$. 

$$\sigma_{zz} = M\varepsilon_{zz}$$

($2$)

The 4D change in stress is derived by differentiating (Equation 2). So that,
the maps are taken from the Department of Trade and Industry database. They provide an indication of the field locations, but their positional accuracy is variable. On Figure 3b, the production effects are clearly seen over Shearwater and Elgin with time shifts of ~5 ms, yet Franklin (that has similar pressure depletion to Elgin) exhibits a much smaller time shift of ~2 ms. As expected, the still to be produced Glenelg and West Franklin fields exhibit no time shifts. Also shown in Figure 3 are the locations of lines A and B that cross Elgin and Franklin, respectively. Figure 4 shows the time shifts of these lines and emphasizes the unusually small time shifts in, above, and below Franklin, relative to those seen in the vicinity of Elgin and Shearwater.

Figure 5 shows the inverted 4D stress maps for the same cross-sections. Despite the small time shifts associated with Franklin, we see that the stress changes within the Franklin reservoir are in fact similar to those in Elgin, reflecting the similar pressure depletions of the two reservoirs. Also, while the extensional stress changes are relatively small in Franklin’s overburden, they are seen to be larger in the underburden, suggesting a stronger pull down.

Significantly, the 4D reservoir stress map of Figure 6 shows a good correlation between the high estimated stress changes in both the Elgin and Franklin reservoirs and the production well locations. Glenelg exhibits no production effect as expected, while West Franklin, where the reservoir was modeled to be much thinner than was actually encountered, has more erratic stress estimates.

Above the reservoir, the stress changes computed for the lower part of the chalk between Top Hod and Plenus Marl formations are shown in Figure 7. Throughout this mud-prone part of the chalk, strong extensional stresses are seen to be created over Elgin, Shearwater, and to a lesser extent over Franklin.

**Discussion.** 4D time shifts at Top Reservoir are usually the largest time shifts in the vicinity of any producing field. The contrasting behavior of the Top Reservoir 4D time shifts between the Elgin and Franklin fields is intriguing. This behavior highlights the fact that these Top Reservoir time shifts are a function of the stress changes in the overburden (stress arching) resulting from the reservoir depletion. It suggests that Elgin and Franklin structures have significantly different effective stress patterns around them. As suggested by Figures 5 and 7, Elgin and Shearwater are pulling down the overburden while in Franklin, Figure 5 suggests the compaction seems to be more accommodated by underburden stretching beneath the indicated Top Pentland marker. These results provide useful information for constraining the coupled reservoir-geomechanical model and might have an impact on wellbore stability.

The estimation of the production-induced stress changes appears quite realistic within all reservoirs, with the exception of the yet to be produced West Franklin Field due to the inaccuracy of the predrill model. This observation is confirmed by the good correlation of high reservoir effective stress changes with the locations of effective production wells.

The estimated reservoir production stresses of Figure 6 show that the southeastern part of Franklin has small 4D stress changes that, logically, are associated with little reservoir compaction. The two exploration/appraisal wells in this southeastern part of Franklin Field did encounter gas condensate. This is most likely a result of reservoir quality deterioration toward the southeast, where the reservoir is believed to change from a shore face to a deeper marine environment.

This paper reports a continuing study. Even so, the current result provides encouragement that 4D time shifts can be converted to meaningful stress changes. Those stress changes can then be used to constrain the reservoir and geomechanics models and help by then detecting the depleted parts of a reservoir and better anticipate wellbore stability problems. Ideally, in order to improve quantitative estimates of stress, the result should be calibrated to hard data such as compaction logs using radioactive bullet markers or repeat gamma logs, stress measurements during the drilling of infill wells, and pressure measurements in the reservoir. Unfortunately, such hard data do not currently exist in these particular HPHT reservoirs. In due course, it is hoped that the results of the technique will be integrated into the geomechanical modeling and reservoir modeling processes.

At this initial stage, three fundamental conclusions can be made: (1) total reliance on the magnitude of 4D time shifts alone for reservoir depletion estimation can be misleading; (2) conversion to interval parameters such as 4D stress changes within layers provides more clarity; and (3) the careful preservation of even small 4D time shifts of only 1 or 2 ms can give important geomechanical insight.


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**Corresponding author:** Keith.Hawkins@cggveritas.com