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# The present-day stress regime of the southwestern part of the Aquitaine Basin, France, as indicated by oil well data

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**Abstract**—In the Aquitaine Basin, there is little information available for estimating subsurface *in situ* stress magnitudes, but a small number of oil industry drilling leak-off tests suggest that $\sigma_h$ approaches 80% of $\sigma_v$ in magnitude.

Horizontal principal stress orientations have been obtained by analysing drill 'breakout ovalization' in 55 wells. However, there is no clearcut directional homogeneity to the indicated stress trajectories and ovalization commonly parallels well deviation. Around Bordeaux, $\sigma_H$ exhibits a consistent NW–SE orientation. As one approaches the Pyrenees, the situation becomes less definitive. NE–SW $\sigma_H$ orientations are widely present and NW–SE $\sigma_H$ orientations also occur. 'High-grading' the data does not improve the picture significantly.

This lack of directional homogeneity in areas adjacent to the Pyrenees is not completely understood. The data points could straddle a sinuous boundary between two stress provinces, but this explanation is not favoured. Alternatively, they may indicate that there is some local structural control of stress orientations. Whatever the cause, there are grounds for suspecting that horizontal stress anisotropy is weakly developed in this region today.

## INTRODUCTION

IN RECENT years it has become possible to investigate the contemporary stress regimes of sedimentary basins using measurements made during exploratory drilling for hydrocarbons (Bell 1990a). The results have direct application to producing reservoirs, because *in situ* stresses affect the geomechanical behaviour of natural or induced fractures in hydrocarbon-bearing rocks (Maury 1987, Nolte 1988). They also control borehole stability (Guenot 1987, Guenot & Santarelli 1988), and *in situ* stress data have proved extremely useful for designing optimal drilling programmes (Guenot 1990). At a regional scale, stress orientations appear to be related to the contemporary motion of tectonic plates so their configurations may place constraints on the driving mechanisms of global tectonics (Gough 1984, Zoback *et al.* 1989).

This study was undertaken to: (1) map the stress regime of the Aquitaine Basin in France, and (2) assess how it is likely to affect hydrocarbon production. Data from 55 wells were examined. Their locations are shown in Fig. 1.

## STRUCTURAL HISTORY OF THE AQUITAINE BASIN

Before discussing stress measurement, it is necessary to review the structural history of the Aquitaine Basin and consider how this may affect the interpretation of stress data. Excellent summaries have been provided by Winnock (1972), Durand Delga *et al.* (1980) and Mullan (1984) from which this review is derived.

The Aquitaine Basin is a Mesozoic–Cenozoic depocentre that occupies a triangular depression in southwestern France. It is bounded to the north and northeast by the Hercynian basement of Brittany and the Massif Central, and it extends offshore westwards into the Bay of Biscay as far as the continental shelf edge. The basin is surficially covered by Tertiary molasse, which conceals its deeper structure. The latter has become known chiefly through drilling and seismic profiling.

Only 70 wells penetrate the basement, and its structure is poorly understood (Mullan 1984). Paleozoic metasediments crop out in the axial zone of the Pyrenees (Fig. 2) and within uplifted blocks north of the mountain front. They also crop out north of the Aquitaine Basin in the Massif Central where their metamorphic grade is higher than in the Pyrenees. Above the metamorphic rocks, narrow troughs containing Stephanian sediments are present locally, as well as more widely distributed Permian red beds. Both are believed to represent responses to mild N–S extension during Late Paleozoic time.

The Paleozoic rocks are overlain by stable platform deposits of Triassic and Jurassic age. The Triassic succession is characterized by locally thick halite sections. Evaporites continued accumulating in Early Jurassic

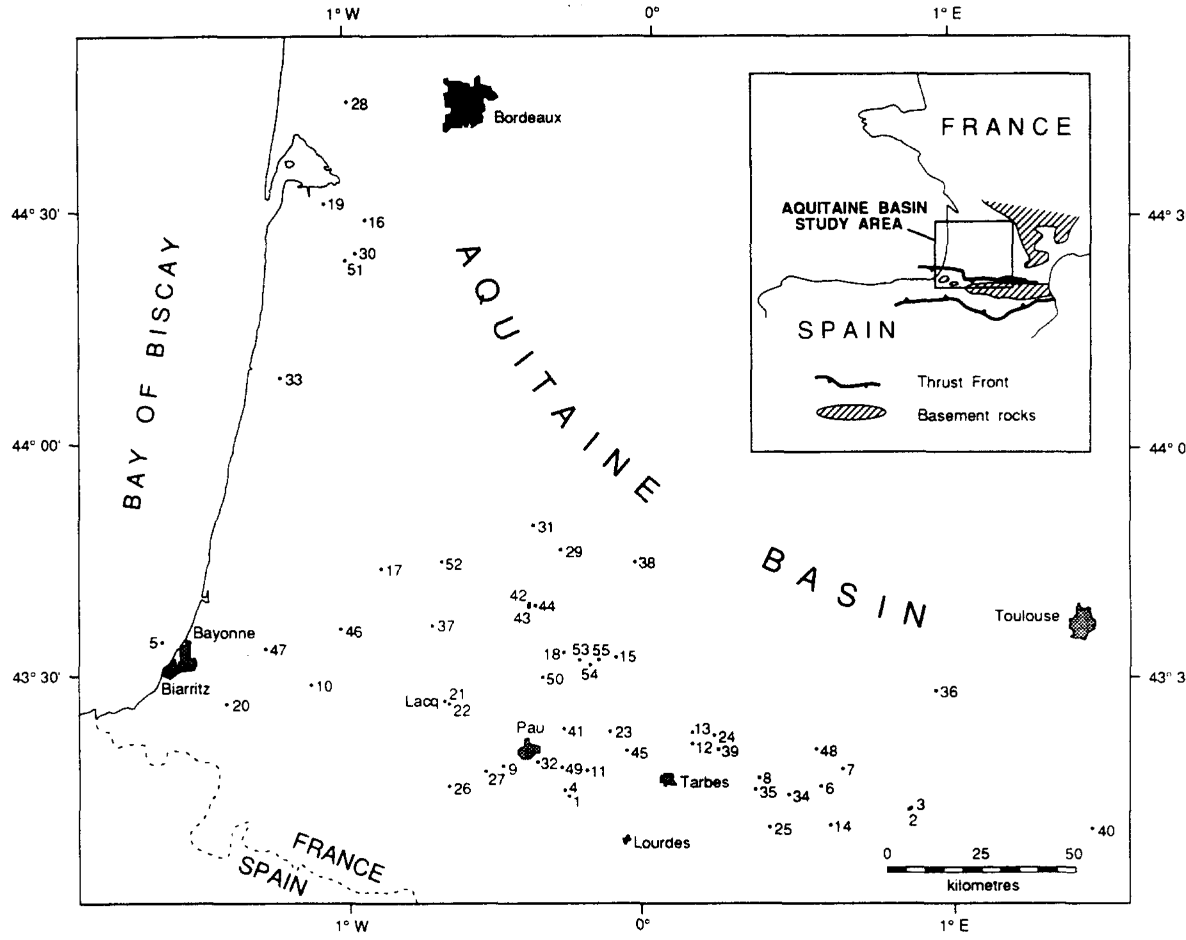

Fig. 1. Study area and well locations.

time together with marine clastics. In Middle and Late Jurassic time, platform carbonates were deposited, except in the southwestern corner where marly beds predominated. By latest Jurassic time, marine sedimentation was restricted to the Parentis Basin and the area within and around the Arzacq Basin (Fig. 2), where shaly limestones interbedded with dolomite and anhydrite were laid down.

Early Cretaceous time saw the onset of rifting. As a result, Neocomian sedimentation was limited to the Parentis Basin and the southwestern part of the Aquitaine Basin, and no deposition is recorded in the north and east of Aquitaine. Subsidence resumed, however, in Barremian time and became intense by Albo-Aptian time, mainly in two areas: the Parentis Basin (>5000 m of silts and shales), and within rhomb-shaped troughs along the Pyrenean Front. Aptian–Albian extensional shearing is accompanied by local diapiric movements of the Triassic salt, and led to minor volcanic eruptions (110–85 Ma).

The Pyrenean orogeny took place between Late Cretaceous and Eocene time. Initially, the Late Cretaceous sea flooded the entire Aquitaine Basin, but major subsidence was later restricted to the Parentis Basin. Along the southern margin, an E–W-trending trough accumulated up to 5000 m of Late Cretaceous flysch. Flysch deposition ended in latest Cretaceous time in the east but continued into the Eocene in the west.

The Iberian plate collided with the European plate in Eocene time. This event caused much folding and reverse faulting in the Pyrenean mountains and led to basin inversions on their flanks, but does not seem to have reactivated, or generated, any major structures within the Aquitaine Basin itself, even though Pyrenean-age reverse faulting has been recognized along the northern margin of the Aquitaine Basin. Orogenic activity ceased at the end of Eocene time.

The Late Tertiary and Quaternary were a time of uplift during which molasse deposits prograded widely to the north and west of the Pyrenees and extended across most of the Aquitaine Basin.

This brief summary of the structural history of the Aquitaine Basin highlights its complexity. It is a region that has seen the development of salt diapirs and ridges, significant local subsidence and inversion, regional tilting, transpression and overthrusting. It is thus a basin where structural discontinuities are the rule and where stress orientations could well be influenced by lateral variations of geomechanical rock properties.

## STRESS MAGNITUDES

### *Measurement methods and results*

No direct measurements of *in situ* stress magnitudes have been made in the Aquitaine Basin, so estimates

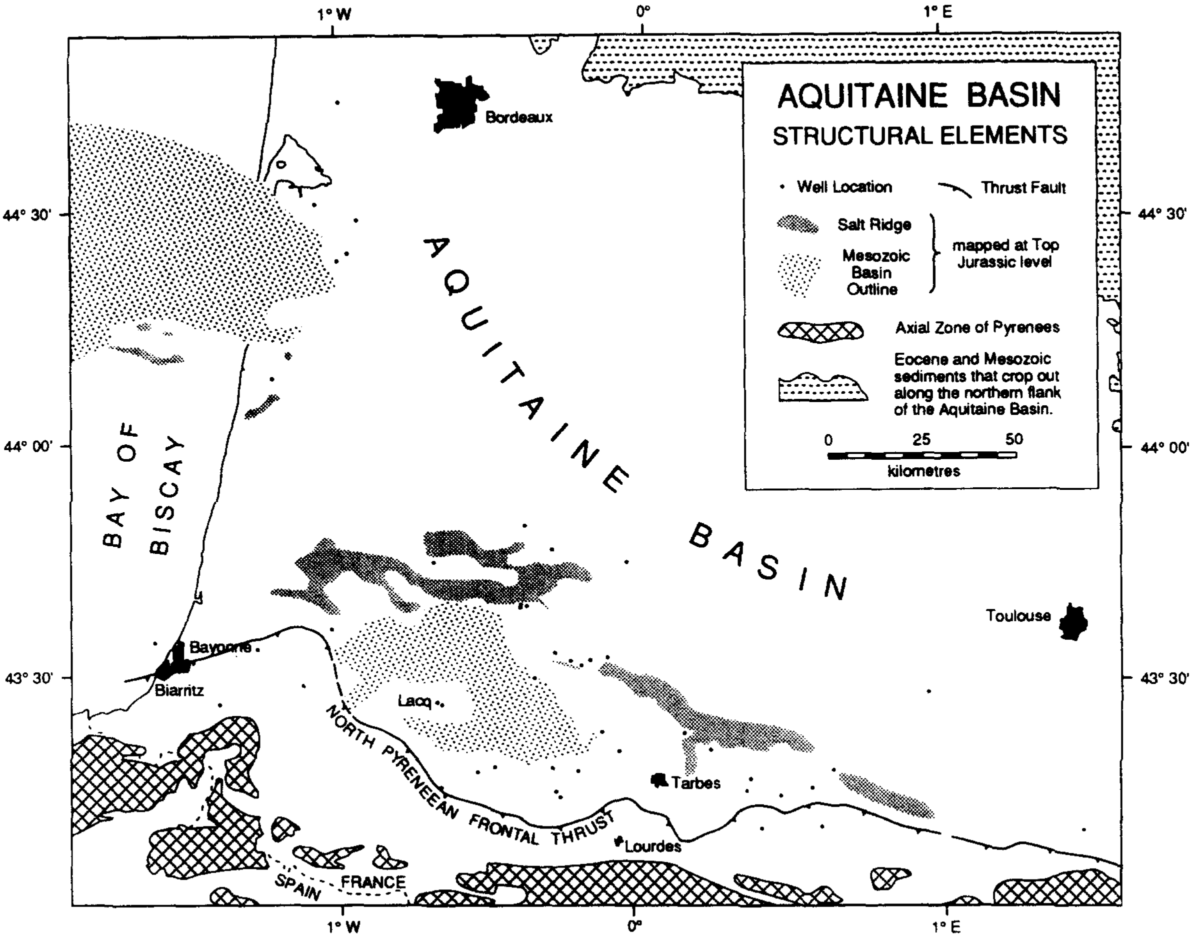

Fig. 2. Structural elements of the Aquitaine Basin.

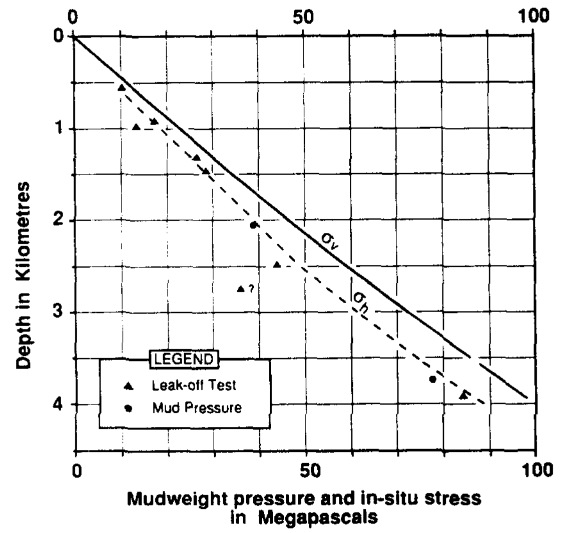

Fig. 3. Magnitudes of the vertical and smaller horizontal principal stresses in the Aquitaine Basin inferred from density logs, leak-off tests and mudweights from six wells.

were used. The vertical principal stress, $\sigma_v$, at a specific depth was equated with the overburden load, and the latter calculated by integrating a density log. The $\sigma_v$/depth profile shown in Fig. 3 comes from well 12, and is similar to profiles generated for other wells in the basin.

Leak-off tests were run in five wells and they give upper limits for the magnitudes of the smallest principal stress (Breckels & Van Eekelen 1981). High mudweights were used to drill the lower part of another well, without initiating any hydraulic fractures, and they provide lower limits for smallest principal stress magnitudes. Whether or not these leak-off pressures and mudweight pressures form a single population, they all point to stress magnitudes of less than $\sigma_v$ for the depths to which they apply. Therefore, they are presumed to refer to $\sigma_h$, the smallest horizontal stress (Fig. 3). It would appear that the magnitude of the smallest horizontal stress is approximately 80% of the vertical stress in the Aquitaine Basin.

These limited data suggest that $\sigma_v$ is greater than $\sigma_h$ in the Aquitaine Basin, but give no indication of the relative magnitude of $\sigma_H$. It is unfortunate that so few leak-off tests were run, but understandable in a basin that is not overpressured.

## STRESS ORIENTATIONS

### *Measurement methods*

In this study it is assumed that one principal stress is approximately vertical (McGarr & Gay 1978, Hoek & Brown 1980). Orientations of the two horizontal principal stresses were obtained from borehole 'breakouts' (ovalized intervals).

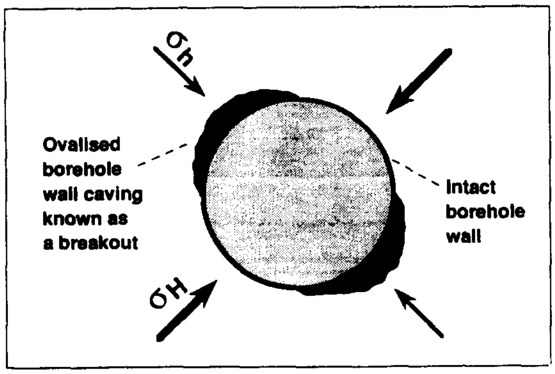

Fig. 4. Vertical view down a well showing a cross-section of an ovalized zone, or breakout, which illustrates the relationship between the long axis of the breakout and the *in situ* stress orientations.

Breakouts have been shown to be sensitive indicators of far field stress directions (Bell & Gough 1979, Bell 1990a). Provided that significant horizontal stress anisotropy exists (Zoback *et al.* 1985) and the well is inclined within 10° of vertical (Mastin 1988), the long axis of a breakout (direction of ovalization) will be parallel to $\sigma_h$ and perpendicular to $\sigma_H$ (Fig. 4). In many sedimentary basins, especially in North America, there is a notable consistency to the orientation of breakouts within individual wells and between neighbouring wells (e.g. Bell & Babcock 1986, Plumb & Cox 1987, Dart & Zoback 1989, Bell 1990b). This directional homogeneity argues strongly that breakouts can map horizontal stresses reliably and that, typically, stress regimes have regionally consistent directional signatures.

For this study, we chose 55 wells for which paper logs were available. The wells were selected because of their regional distribution (Fig. 1), their depths of penetration (Fig. 5) and their near verticality. In fact, they were mostly the first wildcat exploration holes to be drilled on a specific prospect. Subsequent, deviated wells, were deliberately excluded.

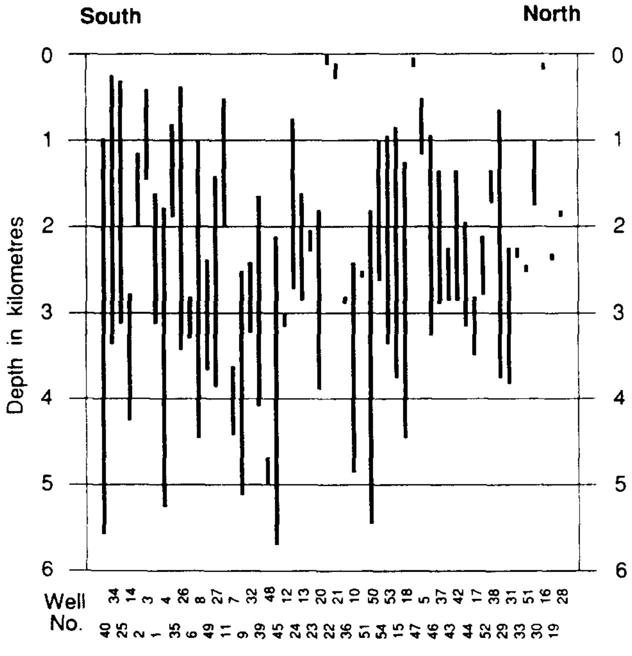

Fig. 5. Depth range of breakouts measured in this study. Numbers along the base refer to wells listed in Table 1. Their locations are shown in Fig. 1. The vertical extent of breakouts in the upper parts of wells is not necessarily a measure of their occurrence, but of the available four-arm dipmeter logs.

Breakouts were recorded by four-arm dipmeter logs, originally run for structural information (Cox 1970). Their oriented caliper extension records provide good information on borehole ovalization and on the orientation of the long axes of breakout intervals (Babcock 1978, Bell & Gough 1983). For breakouts less than 10 m long, a single representative measurement of long axis orientation was made from inspection of the paper logs. For longer breakouts orientation measurements were made at 10 m intervals and averaged. The breakout orientations for each well were histogrammed to identify populations. Mean population azimuths and standard deviations were later calculated for each well, with each individual breakout orientation weighted according to its length (Mardia 1972). The following criteria, evolved during studies by Babcock (1978), Fordjor *et al.* (1983), Springer (1987) and Dart & Zoback (1989), were applied.

(1) The dipmeter log must record sytematic tool rotation above and below a breakout.

(2) Tool rotation must cease over the breakout interval, so that there is a relatively constant azimuth in the range of ±10° for the No. 1 caliper arm.

(3) One pair of calipers should record a diameter larger than hole gauge and the other pair should record a diameter which is not less than hole gauge. Ideally, the smaller caliper curve should remain straight, consistent with an intact borehole wall.

(4) The larger diameter curve should record a vertically rapid increase in diameter at the top and bottom of the breakout.

(5) The borehole should be oriented within 5° of vertical.

In many wells, application of these criteria did not result in identifying homogeneously oriented breakout populations. It was clear that a large number of breakouts, often of the order of 50% in a well, were oriented sub-parallel to the well deviation direction (Fig. 6). This behaviour was almost ubiquitous despite the fact that most of the wells were near vertical holes and only rarely were sections inclined at more than 5° from vertical. Earlier studies of a single heavily drilled oilfield in Aquitaine (Bell *et al.* in press) and in-house investigations had already highlighted this propensity. Ovalized borehole intervals were widely developed, but so many paralleled well deviation directions that it was questionable as to whether they were providing reliable *in situ* stress orientation information. Rather, what seemed to be happening was that borehole ovalization was being produced by drill pipe wear on the walls of mildly inclined holes. Dart & Zoback (1989) noted this problem in North American wells, but found it confined chiefly to holes inclined at more than 5° from vertical. In the Aquitaine Basin, this was not the case. Even in well sections inclined within 1° or less of vertical, breakout long axes frequently followed deviation.

In an attempt to clean the signals of noise, all break-

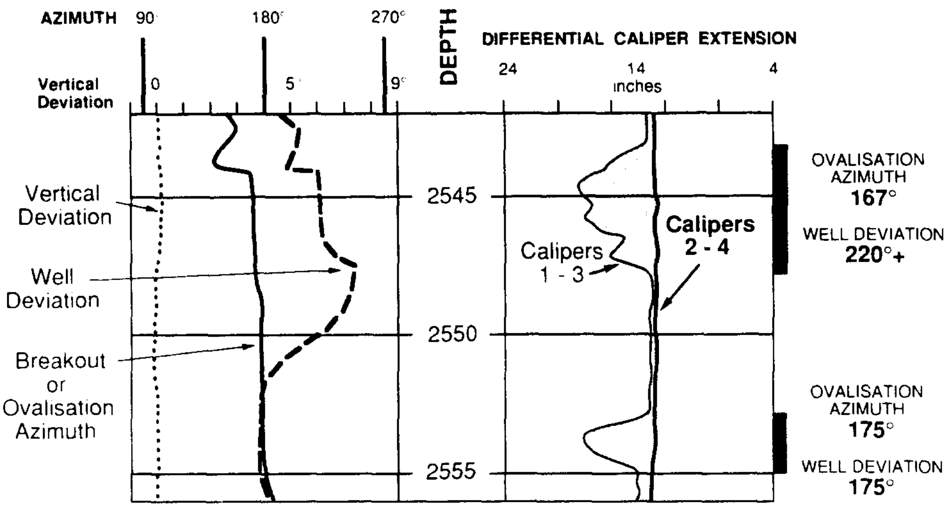

Fig. 6. A typical record of breakout ovalization in a well in the Aquitaine Basin, that illustrates the difficulties encountered in high-grading the measurements. The section shows two morphologically distinctive breakouts in a well with near vertical inclination. Over the upper interval (2543–2548 m), calipers 1 and 3 extend to 18 inches, whereas calipers 2 and 4 record the bit size diameter of 12.5 inches. The long axis of ovalization has a mean azimuth of 167° and the well deviates to a minor degree towards 220°. This interval was interpreted as a *bona fide* stress-induced breakout. On the other hand, in the lower interval of differential caliper extension (2553–2555 m), the ovalization long axis and the well deviation are both oriented at 175° azimuth. The ovalization in this zone was interpreted as being due to pipe wear on the wall of the borehole, despite the almost vertical trajectory of the well, and was excluded from mean well azimuth calculations.

outs that were oriented within 30° of the direction of deviation in inclined wells were deleted. The application of this rather extreme cut-off figure was prompted by earlier experiences in local studies, and it is certainly not proposed here that it should necessarily be applied in other basins. In all probability, a significant amount of genuine stress orientation data was cast out, especially if the borehole happened to deviate close to $\sigma_h$. A degree of increased homogenization resulted, although in part this was due to less data being averaged to obtain azimuth populations.

### *Results*

The resulting selected breakout orientations are listed in Table 1, where they are quality ranked according to the criteria listed in Table 2. Mean well azimuths are mapped in Fig. 7. As can be seen, there is not a uniform configuration of horizontal stress orientations as is found, for example in the Western Canadian Sedimentary Basin (Bell & Babcock 1986), offshore Nova Scotia (Bell 1990b) or the United Kingdom (Brereton & Evans 1987). Furthermore, the standard deviations of the breakout populations are greater than in these other areas. For example, the average standard deviation for wells with more than 100 m of breakouts on the Scotian Shelf is 13.7° (Bell 1990b); in the Aquitaine Basin it is 16.7°. Nevertheless, despite the directional dispersion of breakouts, there is some measure of orthogonality to the whole data set. A rose diagram (Fig. 8) of the selected breakout orientations, weighted by their lengths, illustrates two groupings; a reasonably strongly defined NW–SE population and a less well expressed NE–SW population. The bifurcation of the NW–SE population is due to the inclusion of 1665 m of breakouts from well 40, which is located on the eastern edge of the study area (Fig. 1). If this is removed the population becomes more coherent. Figure 8 suggests that NW–SE-oriented breakouts are well developed in the region, but that the NE–SW signal is less prominent.

Figure 7 shows clearly that the two populations are not areally distinct. NE–SW-trending breakouts are present at relatively shallow depths in wells in the northwest part of the area around the western margin of the Parentis Basin (Fig. 2), southeast of Bordeaux. There are also pockets of NE–SW-trending breakout populations at Lacq, around and to the north of Pau, and northeast and east of Tarbes (Fig. 7). Elsewhere, particularly in the southwestern area between the longitudes of Pau and Biarritz, the breakout populations are dominantly NW–SE trending. In addition, the NW–SE breakout population appears to swing in its general orientation across the region immediately north of the Pyrenees (Fig. 7). In the east, mean well azimuths tend to be oriented NNW–SSE, whereas to the west they become more WNW–ESE in orientation.

Two attempts were made to 'highgrade' the regional picture. First, only breakouts from well sections deeper than 3000 m were considered (Table 2). It was suspected that magnitude contrasts between the principal horizontal stresses might be more pronounced at depth, so that a more directionally coherent configuration would be revealed. This procedure removed all the shallow data from the northwestern part of the study area, and reduced the original 55 wells to 30. To a degree, the resulting configuration is more coherent (Fig. 9). The NW–SE populations in the southwestern and southeasternmost areas are retained, but the NE–SW signal becomes more prominent in the south central region. Again, there is a definite directional orthogonality to the breakout orientation data (Fig. 10).

The second highgrading exercise involved considering

Table 1. Summary of breakout measurements from 55 wells in the Aquitaine Basin, France. The data are plotted on Fig. 7

| | | | | | Major population | | | Minor population | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Well No. | Location (°Greenwich) | Rotary table elevation (m) | Number of breakouts logged | Depth range of breakouts (m) below rotary table | Mean azimuth (°) | (SD) | Net thickness (m) | Mean azimuth (°) | (SD) | Net thickness (m) | Inferred $\sigma_{H\,max}$ azimuth (°) | Quality* |
| 1 | 43.194°N, 0.239°W | 4.6 | 9 | 1620–3100 | 94.1 | (20.7) | 480 | — | — | — | 4.1 | C |
| 2 | 43.160°N, 0.899°E | 7.0 | 6 | 1165–1985 | 29.6 | (6.1) | 380 | — | — | — | 119.6 | A |
| 3 | 43.161°N, 0.881°E | 4.8 | 13 | 445–1453 | 110.0 | (36.7) | 131 | 9.4 | (11.6) | 85 | 20.0 | D D |
| 4 | 43.210°N, 0.249°W | 4.5 | n.a. | 1800–5250 | 102.9 | (20.8) | >300 | — | — | — | 12.9 | C |
| 5 | 43.550°N, 1.578°W | 32.5† | 18 | 555–1148 | 177.7 | (13.2) | 149 | 123.7 | (2.1) | 61 | 87.7 | C D |
| 6 | 43.217°N, 0.582°E | 4.3 | 13 | 2841–3259 | 94.5 | (5.5) | 1004 | — | — | — | 4.5 | C |
| 7 | 43.261°N, 0.654°E | 7.0 | 27 | 3620–4402 | 114.2 | (13.5) | 409 | — | — | — | 24.2 | B |
| 8 | 43.243°N, 0.380°E | 9.3 | 37 | 1017–4423 | 49.1 | (21.2) | 492 | 170.0 | (0.0) | 4 | 139.1 | C E |
| 9 | 43.265°N, 0.454°W | 4.1 | n.a. | 2550–5100 | 127.6 | (26.3) | n.a. | 37.1 | (11.7) | n.a. | 37.6 | C n.a. |
| 10 | 43.454°N, 1.083°W | 5.0 | 7 | 2460–4852 | 139.4 | (19.8) | 294 | — | — | — | 49.4 | B |
| 11 | 43.257°N, 0.181°W | 9.3 | 12 | 519–1967 | 142.6 | (22.4) | 327 | — | — | — | 52.6 | C |
| 12 | 43.324°N, 0.165°E | 5.0 | 3 | 3033–3131 | 2.3 | (0.8) | 9 | — | — | — | 92.3 | E |
| 13 | 43.348°N, 0.169°E | 5.0 | 8 | 1652–2839 | 27.0 | (11.4) | 83 | 159.0 | (18.2) | 10 | 117.0 | D E |
| 14 | 43.126°N, 0.615°E | 7.7 | 11 | 2812–4226 | 148.6 | (12.4) | 234 | 30.2 | (9.8) | 233 | 58.6 | B A |
| 15 | 43.526°N, 0.094°W | 4.6 | 18 | 837–3750 | 26.3 | (6.0) | 205 | 146.2 | (26.8) | 119 | 116.3 | A D |
| 16 | 44.566°N, 0.922°W | 4.8 | 1 | 110–140 | 67.0 | (3.0) | 30 | — | — | — | 157.0 | E |
| 17 | 43.729°N, 0.859°W | 7.4 | 20 | 2825–3458 | 146.8 | (19.6) | 191 | — | — | — | 56.8 | C |
| 18 | 43.533°N, 0.265°W | 4.8 | 26 | 1265–4224 | 25.1 | (16.3) | 185 | 102.0 | (14.3) | 46 | 115.1 | C E |
| 19 | 44.602°N, 1.065°W | 4.8 | 1 | 2329–2333 | 27.0 | (0.0) | 4 | — | — | — | 117.0 | E |
| 20 | 43.406°N, 1.364°W | 7.8 | 12 | 1817–3871 | 84.0 | (7.3) | 240 | 173.0 | (3.0) | 11 | 174.0 | A E |
| 21 | 43.419°N, 0.646°W | 6.7 | 5 | 117–275 | 9.9 | (10.8) | 126 | — | — | — | 99.9 | C |
| 22 | 43.411°N, 0.632°W | 2.5 | 3 | 23–108 | 32.5 | (16.4) | 55 | — | — | — | 122.5 | D |
| 23 | 43.352°N, 0.106°W | 6.7 | 6 | 2081–2273 | 114.5 | (7.8) | 25 | — | — | — | 24.5 | E |
| 24 | 43.341°N, 0.234°E | 4.6 | 21 | 785–2709 | 141.3 | (14.9) | 189 | 10.1 | (18.9) | 101 | 51.3 | C C |
| 25 | 43.122°N, 0.416°E | 6.4 | 12 | 317–3108 | 125.6 | (17.1) | 89 | 25.4 | (14.3) | 70 | 115.4 | D D |
| 26 | 43.216°N, 0.632°W | 7.6 | 39 | 398–3403 | 140.2 | (19.5) | 839 | 43.3 | (13.3) | 439 | 50.2 | B B |
| 27 | 43.253°N, 0.514°W | 4.1 | n.a. | 1420–3850 | 71.2 | (24.8) | >300 | — | — | — | 161.2 | C |
| 28 | 44.841°N, 0.989°W | 5.5 | 1 | 1827–1850 | 32.0 | (3.0) | 23 | — | — | — | 122.0 | E |
| 29 | 43.782°N, 0.273°W | 7.8 | 22 | 672–3745 | 55.4 | (23.0) | 225 | 121.1 | (9.6) | 107 | 145.4 | C C |
| 30 | 44.478°N, 0.885°W | 5.3 | 3 | 1011–1753 | 64.4 | (8.8) | 220 | 158.8 | (7.8) | 200 | 154.4 | A A |
| 31 | 43.842°N, 0.361°W | 5.0 | 32 | 2262–3795 | 106.7 | (9.2) | 247 | — | — | — | 16.7 | A |
| 32 | 43.276°N, 0.342°W | 4.7 | 20 | 2450–3200 | 24.9 | (29.2) | n.a. | — | — | — | 114.9 | n.a. |
| 33 | 44.150°N, 1.124°W | 3.8 | 2 | 2267–2332 | 55.4 | (6.6) | 41 | — | — | — | 145.4 | E |
| 34 | 43.119°N, 0.476°W | 6.5 | 23 | 236–3325 | 53.6 | (20.1) | 548 | — | — | — | 143.6 | C |
| 35 | 43.211°N, 0.370°E | 4.7 | 9 | 820–1862 | 57.0 | (15.0) | 283 | 125.5 | (24.4) | 235 | 147.0 | B C |
| 36 | 43.445°N, 0.961°E | 4.7 | 3 | 3026–3047 | 154.9 | (3.8) | 13 | — | — | — | 64.9 | E |
| 37 | 43.597°N, 0.692°W | 9.3 | 31 | 1335–2876 | 120.3 | (8.0) | 213 | 49.7 | (8.3) | 52 | 30.3 | A D |
| 38 | 43.756°N, 0.026°W | 3.4 | 12 | 360–705 | 153.6 | (15.0) | 65 | — | — | — | 63.6 | D |
| 39 | 43.309°N, 0.248°E | 4.8 | 14 | 1624–4066 | 30.4 | (6.7) | 645 | — | — | — | 120.4 | A |
| 40 | 43.114°N, 1.410°E | 9.2 | 105 | 998–5545 | 92.4 | (16.9) | 1665 | — | — | — | 2.4 | B |
| 41 | 43.355°N, 0.259°W | 7.0 | 15 | 515–2652 | 134.8 | (34.9) | 330 | — | — | — | 44.8 | D |
| 42 | 43.648°N, 0.371°W | 5.0 | 7 | 1370–2823 | 162.2 | (15.8) | 68 | — | — | — | 72.2 | D |
| 43 | 43.641°N, 0.371°W | 5.0 | 8 | 2269–2819 | 151.9 | (15.6) | 126 | — | — | — | 61.9 | C |
| 44 | 43.648°N, 0.353°W | 4.1 | 7 | 1975–3143 | 159.5 | (6.3) | 199 | — | — | — | 69.5 | C |
| 45 | 43.310°N, 0.049°W | 4.3 | 36 | 2119–5659 | 128.8 | (15.5) | 593 | 59.2 | (12.5) | 56 | 38.8 | B D |
| 46 | 43.586°N, 0.994°W | 6.5 | 19 | 986–3261 | 146.3 | (3.4) | 214 | — | — | — | 56.3 | A |
| 47 | 43.539°N, 1.240°W | 7.4 | 3 | 55–145 | 142.7 | (3.4) | 23 | — | — | — | 52.7 | E |
| 48 | 43.309°N, 0.568°E | 7.0 | 16 | 4710–4980 | 58.5 | (11.5) | 113 | — | — | — | 148.5 | C |
| 49 | 43.246°N, 0.167°W | 4.6 | 14 | 2400–3650 | 97.0 | (13.7) | n.a. | 8.5 | (17.1) | n.a. | 7.0 | n.a. |
| 50 | 43.509°N, 0.320°W | 5.0 | 43 | 1855–5447 | 28.8 | (10.9) | 533 | 132.3 | (25.6) | 274 | 118.8 | A C |
| 51 | 44.468°N, 0.990°W | 7.5 | 1 | 2487–2490 | 82.0 | (0.0) | 3 | — | — | — | 172.0 | E |
| 52 | 43.753°N, 0.661°W | 5.0 | 4 | 2131–2768 | 99.9 | (13.3) | 25 | — | — | — | 9.9 | E |
| 53 | 43.523°N, 0.212°W | 4.7 | 40 | 970–3316 | 102.3 | (15.1) | 799 | — | — | — | 12.3 | B |
| 54 | 43.516°N, 0.175°W | 6.5 | 15 | 1014–2597 | 93.4 | (21.2) | 149 | — | — | — | 3.4 | D |
| 55 | 43.520°N, 0.149°W | 6.3 | 14 | 999–2607 | 122.2 | (23.5) | 233 | — | — | — | 32.2 | C |

* See Table 2.
†Metres above sea level.
n.a. = not available.

Table 2. Ranking criteria for breakout populations

| Quality | Criteria |
|---|---|
| A | >200 m of breakouts; standard deviation: <12° |
| B | >200 m of breakouts; standard deviation: 12–20° |
| C | >200 m of breakouts; standard deviation: 20–28° or 100.200 m of breakouts; standard deviation: <20° |
| D | >200 m of breakouts; standard deviation: >28° or 100–200 m of breakouts; standard deviation >20° or 50–100 m of breakouts |
| E | <50 m of breakouts |

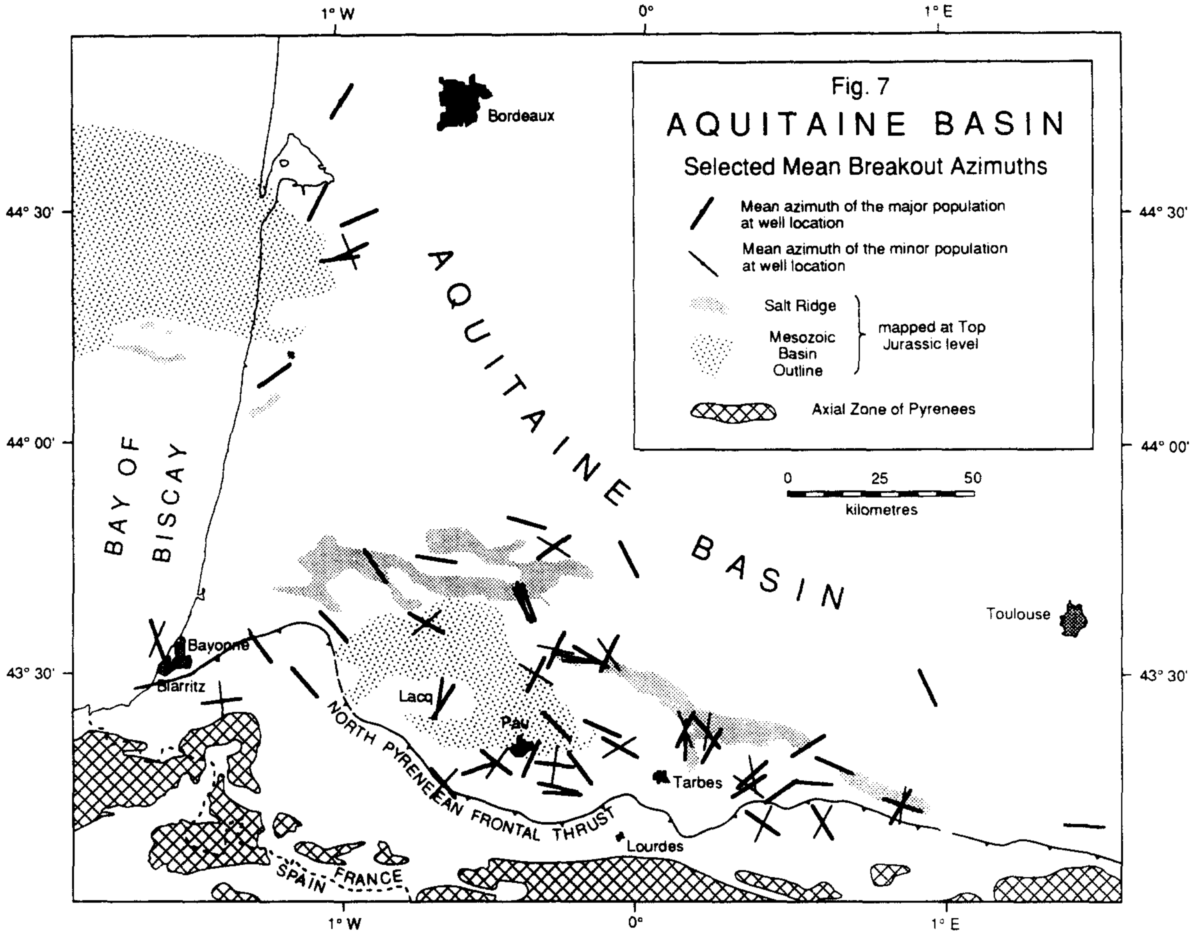

Fig. 7. Map of mean azimuths of selected breakouts from 55 wells distributed across the Aquitaine Basin. Measurements from well intervals inclined at more than 5°, and from ovalized sections that are oriented within 30° of the well deviation direction, have been excluded. The data are listed in Table 1.

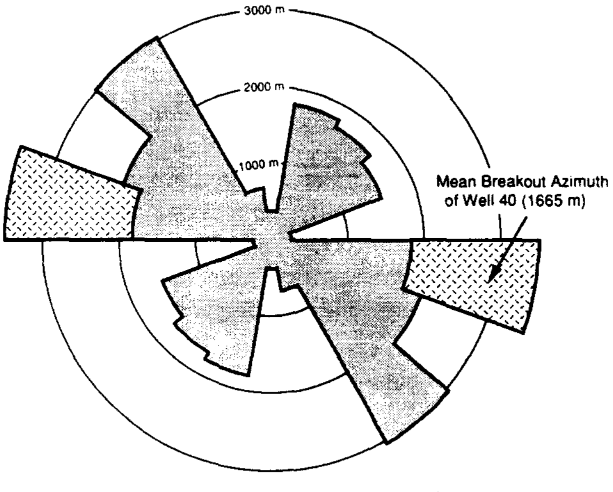

Fig. 8. Rose diagram of breakout populations from 55 wells in the Aquitaine Basin, plotted in terms of net thickness of breakouts. Major and minor populations are plotted. Total breakout thickness is 14,987 m.

only the wells with the best directional statistics; in this case, those where the standard deviation of a breakout population was less than 20° and where the mean azimuth was averaged from more than 200 m of ovalized hole. Only 17 wells met these criteria (Table 1). Their mean breakout orientations are shown in Fig. 11. Once again, NE–SW and NW–SE populations are developed and the resulting directional orthogonality is apparent, but there is less areal concentration of the two families of orientations. In the south central zone particularly, mean azimuth direction alters locally.

## INTERPRETATION

What do these breakout data mean in terms of the stress regime of the Aquitaine Basin? Do the data support a complex pattern of stress trajectories? Could numerous mechanical discontinuities deflect regional stress trajectories to produce the configuration observed? On the other hand, might horizontal stress anisotropy be so weakly developed that it barely determines breakout orientation? Or is this a case of noise dominating the signal, in other words, of poor data? Breakout orientations elsewhere have supported the existence of directionally coherent stress trajectories across sedimentary basins. Why should the Aquitaine Basin be different?

Let us first consider the apparent orthogonality of the breakout orientation data. It can be harnessed to create a horizontal stress trajectory grid (Fig. 12). The grid illustrated was constructed using the deep breakout directions and the wells with the best orientation statistics. However, it is not a unimodal grid since it appears

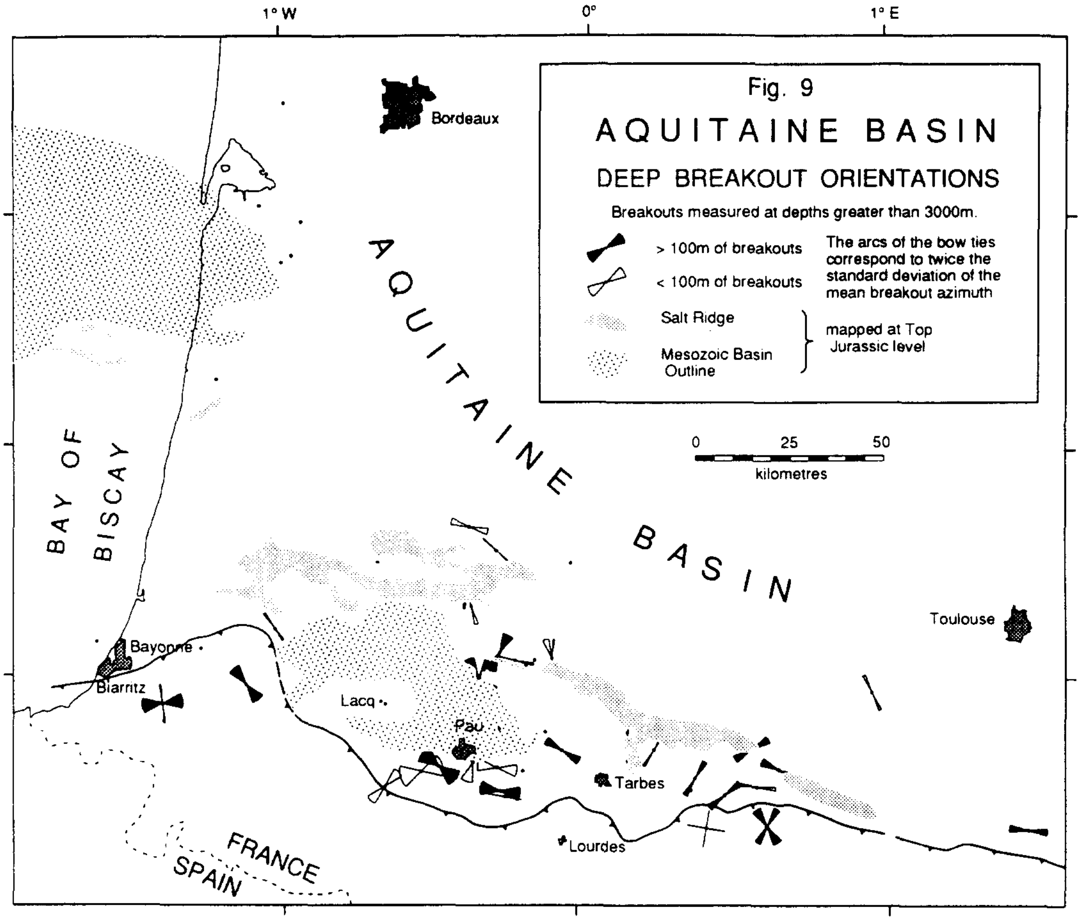

Fig. 9. The map shows the mean azimuths of breakout populations that occur in 30 wells at depths 3000 and 5600 m, as listed in Table 3. Measurements from well intervals inclined at more than 5°, and from ovalized sections that are oriented within 30° of the well deviation direction, have been excluded.

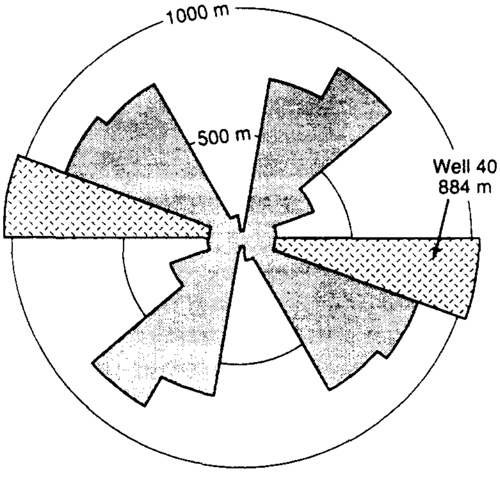

Fig. 10. Rose diagram of breakout populations at depths greater than 3000 m below the rotary table measured in 30 wells in the Aquitaine Basin. Major and minor populations are plotted. Total breakout thickness is 4772 m.

that $\sigma_h$ and $\sigma_H$ (using $\sigma_H > \sigma_h$) alternate along the length of the stress trajectories; notably in the area north of the Pyrenees. How one maps this alternation depends on whether one recognizes all the selected mean breakout azimuths from 55 wells (Fig. 7), the deep breakouts from 30 wells (Fig. 9), those from the 17 statistically best wells (Fig. 11), or some combination of the above. In Fig. 12, the areal extents of the two breakout orientation populations were identified from the mean well azimuths of the latter two groups.

This treatment suggests three possible explanations: (1) the sampled wells traverse a boundary zone between two stress provinces; (2) there are major geomechanical discontinuities in the Aquitaine Basin which locally reorient regional stress trajectories; or (3) there is minimal magnitude difference between the two horizontal principal stresses and they alternate locally.

### *Boundary zone hypothesis*

Regional studies of *in situ* stress orientations in northern Europe (Froidevaux *et al.* 1980, Klein & Barr 1986, Brereton & Evans 1987, Zoback *et al.* 1989) have documented a generally NW–SE orientation for $\sigma_H$, the larger horizontal principal stress (corresponding to breakouts oriented NE–SW). Breakouts in the northwest part of the study area around the Parentis Basin (Figs. 2 and 7) conform with this direction. So do breakouts in a series of areas dispersed along the northern front of the Pyrenees (Fig. 7). These areas, according to the 'boundary zone hypothesis', would lie along the southern edge of a northern European stress province. The areas where the NW–SE-oriented breakouts are dominant, and where $\sigma_H$ is oriented NE–SW, would

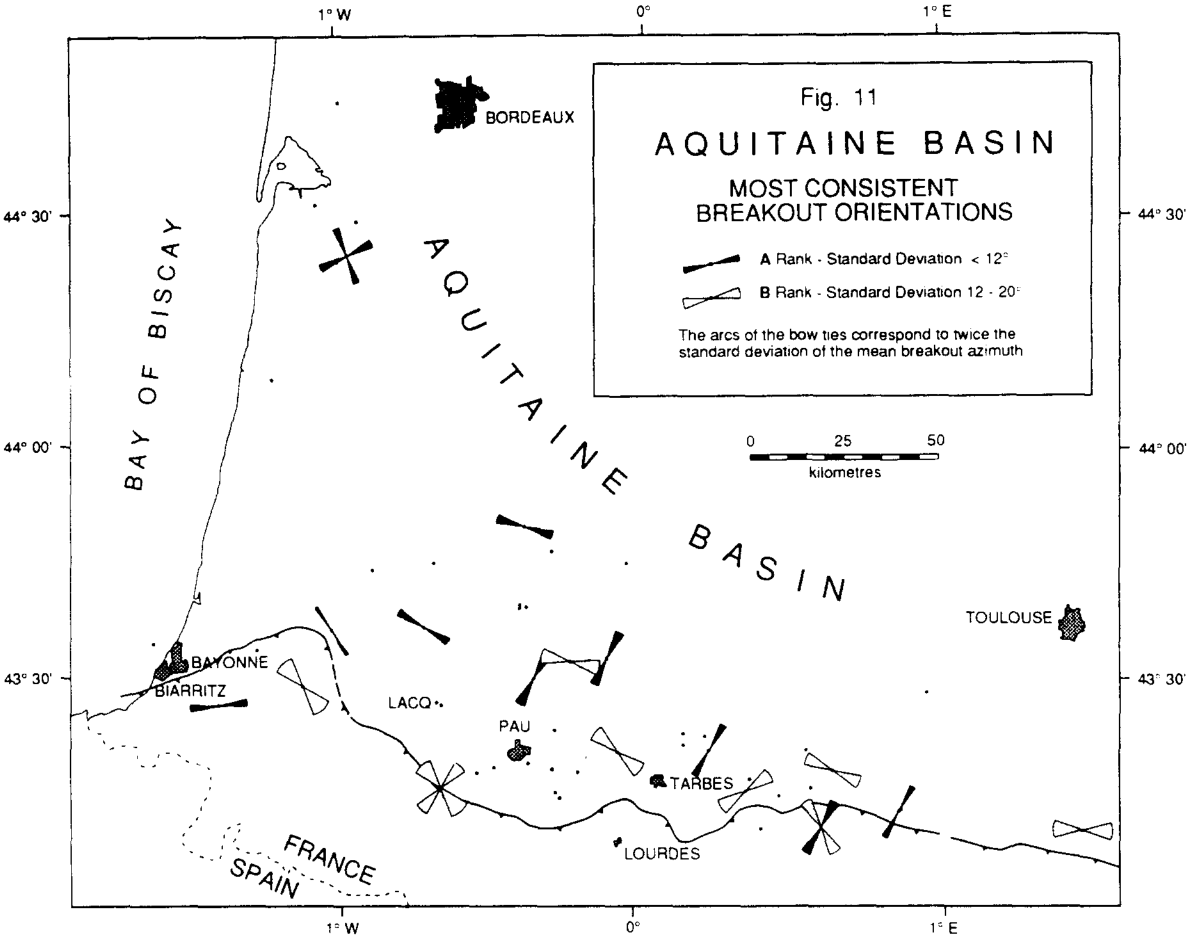

Fig. 11. Breakout azimuths from the 17 wells in the Aquitaine Basin which exhibited the greatest directional consistency. The populations shown are those with A and B quality rankings in Table 1. These data are considered to be the most reliable indicators of horizontal principal stress orientations that were established in this study.

form part of a Pyrenean stress province that is currently being thrust northwards across the northern European stress province (Fig. 13). Supporting this contention is the fact that the deeper breakouts in the south central area immediately to the north of the Pyrenees tend to be oriented NNE–SSW (Fig. 9). This suggests that the northern European stress province might be present at depth there, whereas the stress orientations of the Pyreneean stress province dominate at shallower depths. Moreover, the area is earthquake prone (Janot *et al.* 1988). In this model, the stress province boundary would be envisaged as a complex, interleaved, structural entity with a southward vergence. It might have a surficial configuration similar to that shown on Fig. 13.

This explanation runs into certain difficulties. The proposed stress province boundary bears no obvious relation to any geological features (Fig. 2), nor does it account for the apparent orthogonality of breakout directions. Two abutting stress provinces are unlikely to exhibit matching stress trajectory grids. Also, the lack of clearcut breakout signals weighs against the hypothesis. If two stress provinces were in compression against each other, we would expect strong horizontal stress anisotropy to exist and to find well defined breakout populations. In reality, breakout directional homogeneity is poorly developed. Ovalization is abundant, but much of it appears to be the result of drill pipe wear against the walls of insignificantly inclined wells. If there were strong *in situ* stress anisotropy, the apparent effects of drill pipe wear would be far less dominant.

### *Geomechanical discontinuities hypothesis*

It has been shown experimentally and theoretically that stress trajectories can be bent near mechanical discontinuities (Wu & Chang 1978, Petit & Barquins 1988). Regionally anomalous breakout data have been accounted for in terms of refraction across rock unit boundaries (Bell & Lloyd 1989), and in terms of stress rotation towards free surfaces such as faults and open fractures (Bell 1989, Bell *et al.* in press). The scale of such phenomena is not well understood, but it appears that anomalous stress orientations can be caused by geomechanical discontinuities in rock masses and that, in favourable circumstances, breakouts can detect them.

Is the structural complexity of the Aquitaine Basin likely to give rise to such effects and, if so, can the lack of directional homogeneity on a regional scale be accounted for by numerous local stress deflections and rotations? A contention like this is extremely difficult to disprove. One can always explain aberrant results by invoking local influences. All the same, a portion of the orientation data may be affected. Bell *et al.* (in press) recognized that open fractures in one oil field in the

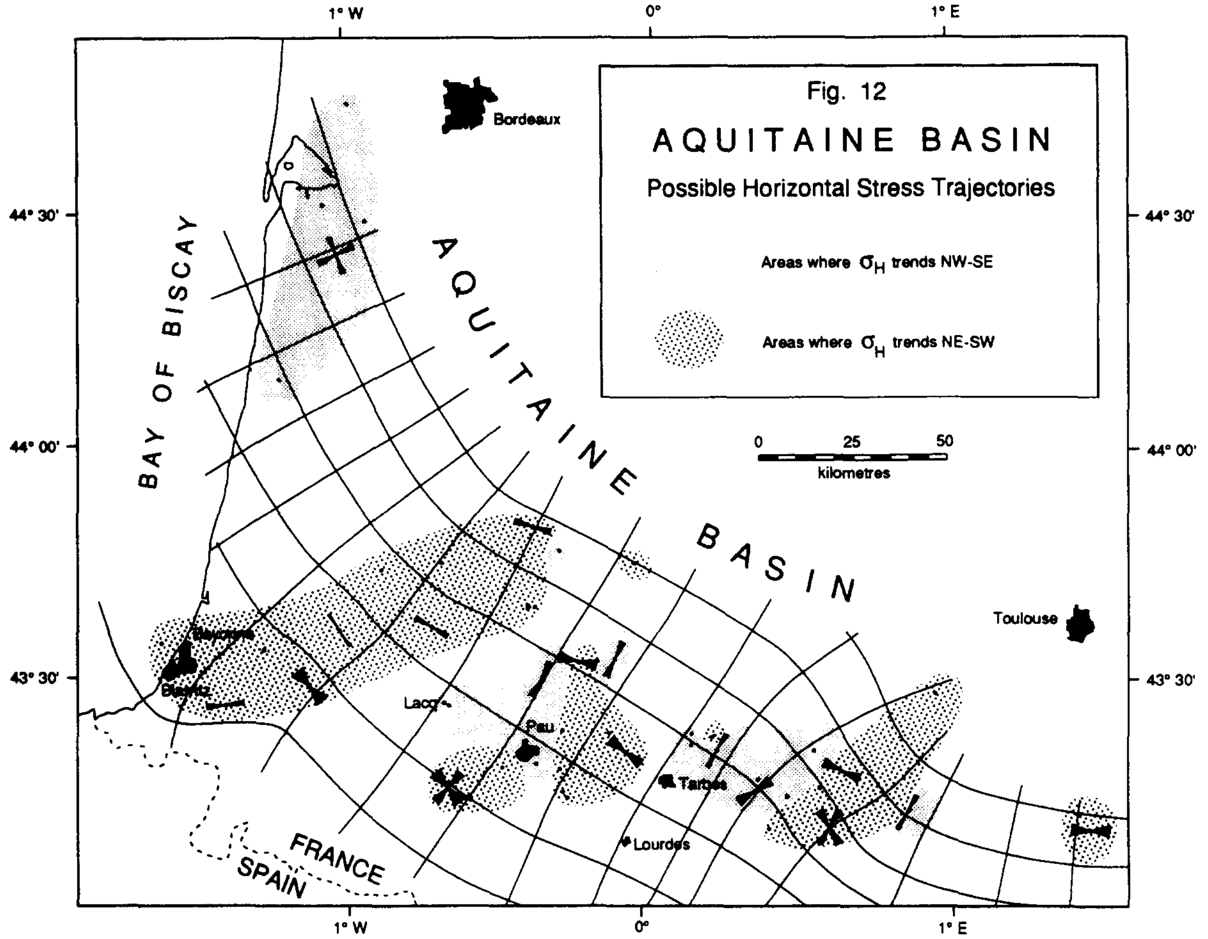

Fig. 12. Map showing a possible horizontal stess trajectory grid in the southwestern part of the Aquitaine Basin. Note that the larger and smaller horizontal principal stresses appear to interchange with each other. Areas where one particular direction is dominant have been outlined.

Aquitaine Basin appear to have rotated stresses locally, although none of the wells which showed this rotation are included here. However, salt ridges have intruded rocks adjacent to some wells, and the geomechanical contrast between halite and denser sediments is likely to refract stress trajectories. As Fig. 7 shows, there is some tendency for wells near salt ridges to exhibit breakout populations approximately normal to the ridge axes. This is particularly the case north and east of Pau. These breakout orientations might be due to stress refraction by the salt masses or, possibly, to local extensional stress zones developed above them. Nevertheless, these possibilities cannot account for all the breakouts with NNE–SSW orientations in that area.

If the geomechanical discontinuity hypothesis is all-embracing, it implies that the regional stress orientations in the Aquitaine Basin are the same as those for the rest of northern Europe and that $\sigma_H$ is oriented in a NW–SE sense. It also implies that horizontal stress anisotropy is pronounced, so that the numerous stress trajectory reorientations generate diagnostic breakouts. In this model, the breakouts around the Parentis Basin southwest of Bordeaux would be responding to the regional stress signature. Any differently oriented breakouts would be due to the local geomechanical situation; to lateral contrasts between rock masses in Young's modulus and Poisson's ratio as well as to sharp discontinuities like open fracture zones. Some of the directional variability in the south central area between the longitudes of Pau and Tarbes might be explained in this way, However, it is difficult to conceive of such mechanisms accounting for the widely developed NE–SW orientations of $\sigma_H$ that are suggested by breakouts in wells between the longitudes of Pau and Biarritz. The problem of the omnipresent breakouts paralleling well deviation also remains. If reorientation was largely caused by geomechanical discontinuities, as diagnosed by breakouts, why should drill pipe wear on borehole walls cause so much ovalization?

### *Weak horizontal stress anisotropy hypothesis*

The major influence on the orientations of breakouts on the walls of semi-vertical wells drilled through rocks which are essentially isotropic in the horizontal plane is the contrast in magnitude between the two horizontal principal stresses (Jaeger 1961, Zoback *et al.* 1985). If the horizontal principal stresses are markedly unequal, stress amplification around those parts of the borehole wall normal to $\sigma_H$ is accentuated, and the potential for shear fracturing is enhanced. Thus, breakouts are diagnostic primarily of stress anisotropy and, if they are commonly oriented, of a coherent far field stress regime. Furthermore, the more breakouts which can be confi-

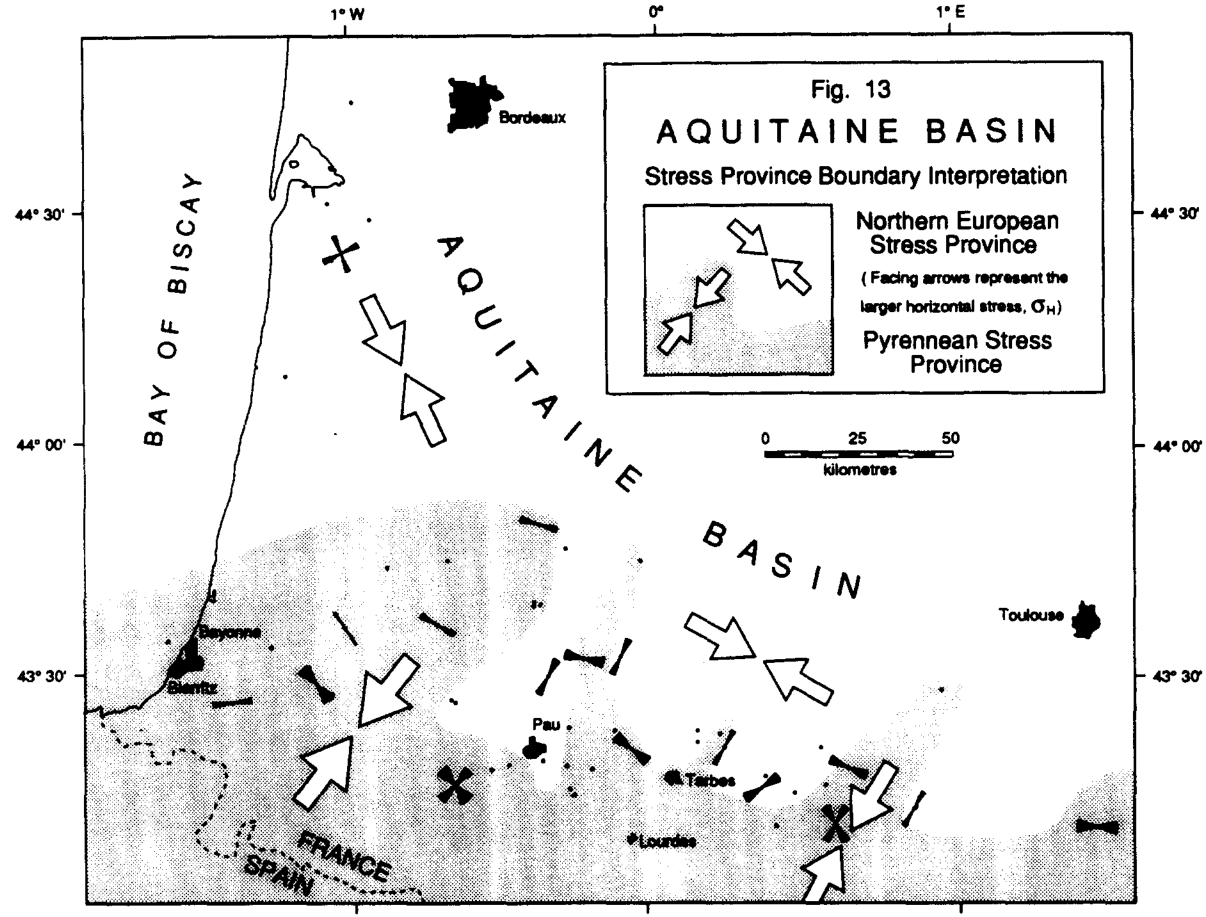

Fig. 13. Map of a hypothetical stress province boundary between a northern European stress province and Pyrenean stress province. This configuration is not considered to be a likely explanation for the directional variability of breakouts in the Aquitaine Basin, as discussed in the text.

dently attributed to amplification of far field *in situ* stress, the more likely it is that principal stress anisotropy is significant.

In the Aquitaine Basin, few holes have well oriented breakout populations. As the standard deviations testify, there is much directional variability between wells (Tables 1 and 3, Fig. 7). Ovalization is widespread, but much of it is semi-parallel to well deviation, implying that drill pipe wear caused it, rather than the amplification of far field stresses. In short, it is difficult to obtain much breakout data that appears to provide reliable indications of *in situ* stress orientations. What has been observed could be accounted for if the difference in magnitudes between the horizontal stresses acting on Aquitaine Basin sediments were small. This would account for the tendency of the breakouts to align themselves weakly along an orthonal grid, it would explain the low precision of the mean well azimuths, it would account for the apparent interchangeability of $\sigma_H$ and $\sigma_h$, and it would explain why many breakouts (or ovalized zones) appear to be caused by effects other than stress amplification on borehole walls. With this model, there is no need to propose an active collision between two stress provinces and, in theory, no need to advocate stress reorientation at natural geomechanical discontinuities. The latter effect cannot, however, be ruled out and is believed to play a role.

It would appear that $\sigma_H$ is oriented NW–SE around the Parentis Basin, but that further south this gives way to a region where the orientation of $\sigma_H$ is NE–SW. In the south central region, particularly at shallow depths, interchangeability of $\sigma_H$ and $\sigma_h$ appears to be the rule. In the southeast, there is insufficient data to indicate what orientation is the most dominant.

Seismic evidence has been cited in favour of significant horizontal stress anisotropy (Janot *et al.* 1988). The southern margin of the Aquitaine Basin and the adjacent Pyrenean mountain range have been subject to historic earthquakes. First motion studies have yielded a variety of *P* axes, but fault plane solutions of three recent earthquakes in the study area suggest orientations of 105°, 120° and 133°. The epicentre depths were calculated to be 15 km or less, thus these quakes would appear to indicate high level lateral compression. However, the movements probably occurred on ancient planes of weakness, so the *P* axes need not coincide closely with contemporary *in situ* stress orientations (McKenzie 1969). Fault plane solutions typically exhibit enormous variability in ancient orogenic belts, and give the greatest directional consistency in Tertiary subduction zones (Zoback *et al.* 1989).

The stress magnitude inferences are not incompatible with minimal horizontal stress anisotropy. They suggest that both horizontal principal stresses are of smaller

Table 3. Details of breakout populations measured at depths greater than 3000 m below K.B. in 30 wells in the Aquitaine Basin. These data are plotted on Fig. 9

| | | Population 1 | | | Population 2 | | |
|---|---|---|---|---|---|---|---|
| Well No. | Interval below K.B. (m) | Mean azimuth (°) | (SD) | Net thickness (m) | Mean azimuth (°) | (SD) | Net thickness (m) |
| 1 | 3000–3100 | 107.0 | (3.0) | 100 | | | |
| 4 | 3000–5250 | 99.2 | (20.5) | >200 | | | |
| 6 | 3163–3259 | 95.8 | (5.1) | 85 | | | |
| 7 | 3620–4402 | 114.4 | (13.5) | 409 | | | |
| 8 | 3172–4423 | 30.9 | (7.9) | 178 | | | |
| 9 | 3100–5100 | 127.6 | (26.3) | >200 | | | |
| 10 | 3080–4852 | 140.6 | (20.0) | 267 | | | |
| 12 | 3033–3086 | 2.3 | (0.2) | 8 | | | |
| 14 | 3000–4226 | 30.2 | (9.8) | 233 | 146.9 | (13.4) | 159 |
| 15 | 3058–3750 | 161.3 | (9.3) | 48 | 7.9 | (2.3) | 10 |
| 17 | 3070–3458 | 135.5 | (10.2) | 104 | | | |
| 18 | 3105–4224 | 27.1 | (16.5) | 166 | | | |
| 20 | 3307–3871 | 82.1 | (21.3) | 155 | 173.0 | (3.0) | 11 |
| 25 | 3028–3108 | 10.0 | (0.0) | 6 | 109.0 | (0.0) | 4 |
| 26 | 3062–3403 | 45.1 | (15.9) | 50 | | | |
| 27 | 3400–3850 | 73.9 | (29.4) | n.a. | | | |
| 29 | 3692–3745 | 133.1 | (1.4) | 24 | | | |
| 31 | 3000–3795 | 105.6 | (10.0) | 48 | | | |
| 32 | 3000–3200 | 18.9 | (17.5) | n.a. | | | |
| 34 | 3035–3325 | 51.7 | (9.5) | 220 | | | |
| 36 | 3026–3047 | 154.9 | (3.8) | 13 | | | |
| 39 | 3152–4066 | 31.7 | (4.0) | 387 | | | |
| 40 | 3000–5545 | 95.7 | (10.8) | 884 | | | |
| 44 | 3057–3143 | 163.6 | (5.9) | 32 | | | |
| 45 | 3211–5659 | 121.5 | (12.5) | 410 | | | |
| 46 | 3052–3269 | 145.2 | (4.0) | 25 | | | |
| 48 | 4710–4980 | 58.5 | (11.5) | 113 | | | |
| 49 | 3000–3650 | 97.0 | (13.7) | n.a. | | | |
| 50 | 3000–5447 | 29.0 | (10.9) | 528 | 142.3 | (25.8) | 189 |
| 53 | 3003–3316 | 102.0 | (4.1) | 6 | | | |

n.a. = not available.

magnitudes than the vertical principal stress at the depths of investigation. A stress regime with $\sigma_v > \sigma_H \approx \sigma_h$ may be widely present.

### *Summary*

The analyses discussed above of oil industry data bearing on the contemporary stress regime of the Aquitaine Basin appears to indicate that horizontal stress anisotropy is weakly developed in at least the southern part. It is difficult to avoid this conclusion bearing in mind the directional variability of the breakout data and the nature of its inconsistency.

## IMPLICATIONS

Limited horizontal anisotropy, and a stress regime where $\sigma_v > \sigma_H \approx \sigma_h$, implies that hydraulic fractures will be vertical, but may not exhibit preferred orientations. This should be borne in mind if they are initiated to enhance hydrocarbon production. It is also unlikely that permeability due to open fracture systems will exhibit much flow anisotropy that can be directly related to the stress regime. With minimal differences in lateral confining pressures, fracture orientation is not likely to determine the degree of openness. However, there may be areas in the Aquitaine Basin where enough horizontal stress anisotropy is present to influence the preferred directions of fluid flow.

It is interesting to speculate how a condition of limited horizontal stress anisotropy might arise in a sedimentary basin. Reorientations of stress trajectories over time are well established. For example, the Appalachian Plateau was clearly compressed about a NW–SE axis in Late Paleozoic time (Engelder & Geiser 1980), but is now compressed from NE to SW (Plumb & Cox 1987). The Aquitaine Basin could currently be in a transitional period between two stress regimes.

Alternatively, we may be seeing an effect of absolute plate motion rates. Zoback *et al.* (1989) showed that $\sigma_H$ orientations in several plates were subparallel to the direction of absolute plate motion, suggesting that the plate-driving forces were responsible for the stress configuration in the plate interior. If this is correct, the absolute motion rate may determine the level of horizontal stress anisotropy. As has been noted, horizontal stress anisotropy appears to be well developed in several North American basins, but poorly in the Aquitaine Basin. It may be significant that the former lie on lithosphere that is moving an order of magnitude faster than that of the Eurasion plate on which the Aquitaine Basin rests (Minster & Jordan 1978).

Ongoing studies of breakouts in North Sea wells give similar results to those reported here for the Aquitaine Basin, suggesting that weak horizontal stress anisotropy may not be confined only to this part of Europe (M. Cowgill personal communication 1991). In apparent conflict with this interpretation are the results of Brereton & Evans (1987), which show significant directional consistency for breakout ovalizations in onshore wells drilled in the United Kingdom. Their results could be interpreted as supporting well-developed stress anisotropy. On the other hand, their method of well analysis involves statistical treatment of digital data and it is not focused on individual breakouts, so it may be suitable for extracting a weak regional signal from wells drilled in areas where stress anisotropy is not pronounced.

This discussion points out the need to make direct stress magnitude measurements at depth, especially in the Aquitaine Basin and, particularly in Europe. It also highlights the need to develop a tool capable of providing reliable $\sigma_H$ magnitudes in the subsurface. At present, no such technology exists, but it should be possible to develop downhole flat jack methods to make direct measurements of $\sigma_h$ and $\sigma_H$. Until both $\sigma_h$ and $\sigma_H$ can be measured independently at depth, the true nature of stress regimes in sedimentary basins will not be known, and it will not be clear whether breakout analysis in Europe is likely to be a useful tool or a troublesome hindrance.

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