THE NORTHWESTWARDS CONTINUATION OF THE STICKLEPATH FAULT: BRISTOL CHANNEL, SW WALES, ST. GEORGES CHANNEL AND IRELAND

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The continuation of the Sticklepath Fault northwestwards from Lundy Island and SW Wales is not known. A NW–SE-oriented fault observed on seismic data in the St. George's Channel Basin is interpreted to be a flower structure. This fault is considered to be an extension of the Sticklepath - Lustleigh Fault Zone of Devon and the Bristol Channel. The NW-SE fault and associated salt-wall crop out at the sea-bed, their relative chronology is unknown except there was significant post-Oligocene movement of both: this fault, and others can be observed on gravity data modelled over the area. The Sticklepath Fault, along with other, minor faults, may display dextral offset of Tertiary features. The north-west extension of the Sticklepath Fault strongly suggests late breaching of Tertiary and Mesozoic hydrocarbon topseals in the St. George's Channel Basin.

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INTRODUCTION

There is abundant literature on the location and kinematics of NW-SE oriented faults in the Variscan foldbelt in southern England and South Wales (see below for references). However, there is little consensus on the continuation of such faults north into Wales, the Irish Sea and onshore midlands of Ireland itself. This is perhaps not surprising given that north of the proposed Variscan Front (Figure 1) E-W fold/thrust and NW-SE strike-slip basement fabrics intersect in a complex pattern with those of a NE - SW trend. NW-SE oriented strike-slip faults are also well known in the Irish Variscides to the south (Cooper *et al.*, 1984). South of the "Variscan Front", numerous authors have cited evidence of the Mesozoic and Tertiary reactivation of basement thrust fabrics in the development of the (broadly) east-west Wessex, Channel, Western Approaches, Bristol Channel and Celtic Seas basins (Chadwick, 1985; Lake and Karner, 1987; Coward and Trudgill, 1989; Petrie *et al.*, 1989; Ruffell and Coward, 1992). Similarly, the NW-SE oriented strike-slip fault zones that acted as lateral ramps and transfer faults during Variscan convergence were reactivated throughout subsequent rifting and inversion episodes (Holloway and Chadwick, 1986) although this is not proven in all areas. In some cases this strike-slip reactivation caused the formation of pull-apart basins (Holloway and Chadwick, 1986). Tectonic maps of the British Isles (Chadwick, 1985; Zeigler, 1987) show that the intersection of NE-SW and E-W structural grains occurs in many places, yet none so obviously as in the area between the Pembroke Peninsula in South Wales and Co. Wexford in southern Ireland. This intersection of NE-SW and E-W structures has complicated the geology of the study area. The intersection of Caledonian, Variscan and Mesozoic - Cenozoic structural trends (Van Hoorn, 1987) occurs in, and is focused upon the study area. The aim of this paper is to examine whether the Sticklepath Fault extends beyond its current mapped limits in the Bristol Channel and provide an account of the form and influence of NW-SE oriented faults in the St. Georges Channel Basin. Reactivation of these long-lived NW–SE basement faults is of great importance, creating lignite- or kaolinite-bearing pull-apart basins, possibly breaching Tertiary – Mesozoic hydrocarbon reservoirs and providing a tectonic linkeage with the Wessex Basin to the south. Before attempting to locate the Sticklepath Fault in the study area, the stratigraphy of the rocks the putative fault would deform must be considered along with what previous authors have said about geological structure in the area.

BASIN STRATIGRAPHY – PREVIOUS WORK

The nature of the stratigraphic infill to the series of basins developed from Cardigan Bay through the St. George's Channel to the Celtic Seas is known largely from the works of Barr *et al.* (1981), Dobson and Whittington (1987), BIRPS and ECORS (1986), McGeary *et al.* (1987), Tappin *et al.* (1994) and Welch and Turner (2000). The mildly deformed Mesozoic and Cenozoic sediments of the Cardigan Bay Basin (CBB); St. George's Channel Basin (SGCB) and North or South Celtic Sea Basin(s) (NCSB, SCSB, respectively) are the subject of this work. The development of sedimentary basins in the study area began in Permian times when rifting (following the Variscan orogeny) initiated subsidence in some areas. Continued rifting (Manspeizer, 1988; Musgrove *et al.*, 1995) led to the expansion of these basins throughout the Triassic and Jurassic. Non-marine sedimentation became progressively more common throughout the latest Jurassic ("Purbeck facies") and earliest Cretaceous ("Wealden facies", sensu Allen, 1981). Marine transgression in the mid-Cretaceous led to the deposition of shelf sands (greensands) and Chalk throughout many of the basins adjacent to the study area (Petrie *et al.*, 1989). These Upper Cretaceous sediments have subsequently been removed in the SGCB and CBB, but are found complete in the Celtic Seas. This, and the preservation of early Cretaceous strata in synclines in the SGCB led Van Hoorn (1987) to conclude that a major period of basin inversion took place in the earliest Tertiary (probably mid-Palaeocene). The Tertiary sediments of the CBB and SGCB are considered to be mostly non-marine with more permanent marine conditions occurring in the South Celtic Sea Basin (Dobson and Whittington, 1987). During brief periods of transgression, marine sedimentation occurred as far north as Cardigan Bay. Tappin *et al.* (1994) suggest that the oldest preserved Tertiary sediments of the SGCB are of mid-Eocene age and that the remaining strata (above) may be split into two successions (after Dobson and Whittington, 1987). These comprise a lower, coarse unit (mostly of early Eocene age) and an upper, finer-grained unit (mostly late Eocene to Oligocene age). These two Tertiary sequences are separated by a widespread calcareous horizon: on borehole logs and regional descriptions (Tappin *et al.*, 1994) this unit is described as up to 20 m of dolomitic, sideritic freshwater limestone. This mid-Tertiary calcareous unit is utilised in structure mapping in the present study.

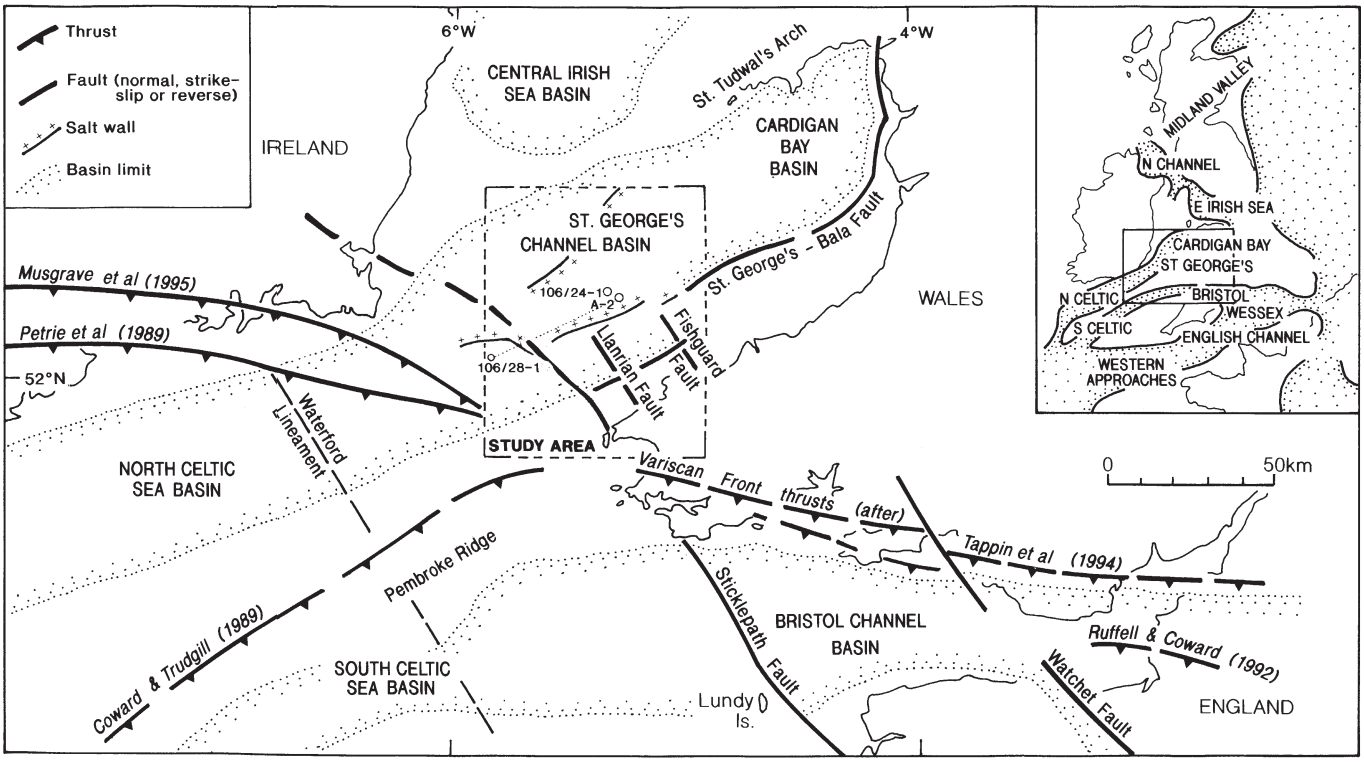

***Figure 1.** Location and tectonic framework of the study area, including distribution of major sedimentary basins (inset) and the (dashed) putative line of the Sticklepath Fault (and other faults) from the evidence presented in this work. Dots = location of seismic line shown in Figures 3 and 4. Only approximate location is given due to data confidentiality.*

Previous work on basin structure

Our knowledge of the basin structure in the study area is derived from many works, summarised in Tappin *et al.* (1994) and including the key studies of Barr *et al.* (1981); Dimitropoulos and Donato (1983); Van Hoorn (1987); Dobson and Whittington (1987) and Welch and Turner (2000). Geological and geographical terminology follows the definition of Tappin *et al.* (1994) who located the margins of each basin at areas of major increases in sediment thickness, commonly corresponding to basin-bounding faults. The study area is situated within the geographical and geological area termed the St. George's Channel. However, the southern limits of the study area encompasses the Lower Palaeozoic and Precambrian rocks of the Pembroke Ridge and the Mesozoic sediments of the North Celtic Sea Basin. Similarly, the eastern margin of the area under examination encroaches into Cardigan Bay and the western margin includes the Central Irish Sea (and its underlying Permian - Triassic basin). This mosaic of basin terminology and distribution reflects two aspects of the regional geology. First, that basin depocentres changed from the Mesozoic through to the Cenozoic (due to basin inversion); second that the focus of the study (St. Georges Channel) includes tectonic elements of all the surrounding areas (basins and basement). The four main basins of the study area (North Celtic; St. George's Channel; Cardigan Bay; Central Irish Sea) were all initiated during Permian - Triassic rifting but follow distinct trends in the north and south of the study area (Figure 1). Northern basins follow a distinctive NE-SW Caledonian trend whereas southern basins are closer to an E-W orientation (coincident with the main Variscan fold and thrust belts). In addition, these E-W basins and the underlying Variscan fabric are cut by NW-SE strike-slip faults. These formed synchronously with Variscan thrusting, but have remained active thereafter (occasionally to the present-day: Holloway and Chadwick, 1986).

The SGCB is one of the deepest basins of the UK continental shelf (McGeary *et al.*, 1987), containing over 7000 m of Mesozoic - Cenozoic strata and up to 3000 m of a folded and faulted Carboniferous "foreland" succession (limestones, sandstones and coals). The deeper parts of the Mesozoic basin-fill comprise over 4000 m of salt-bearing Triassic strata that are rarely imaged clearly on seismic data, except in the basin-margins. A low gravity field is commonly the best indicator of the presence of salt in this area (Dimitropoulos and Donato, 1983). On a regional scale, the structure of the SGCB appears simple, comprising a syncline (coincident with a Mesozoic depocentre) developed in the hanging wall of the St. George's - Bala fault system (cross-section 2, figure 18 of Tappin *et al.*, 1994). The St. George's Fault is accurately located on gravity and seismic data as salt has penetrated along the greater part (50 km) of its length. Dimitropoulos and Donato (1983) provide a model of combined sediment-loading and fault-triggered halokinesis to explain the development of a salt wall (as opposed to discrete diapirs) in this area. Tappin *et al.* (1994) suggest that the timing of salt migration is difficult to establish, although coincidentally the same salt-exploited fault is suggested to be reactivated during Palaeocene inversion (Van Hoorn, 1987).

Data and methods

Data used in this study includes previously published work (summarised above); 5 released exploration boreholes in the SGCB and immediate area (three of which are displayed here on Figure 2); 24 commercial seismic lines (on a 5 km line spacing) and a 3-line set of deep lines shot by BIRPS (British Institutions Reflection Profiling Syndicate) around the margins of the basin. The faults observed on seismic data were checked with reference to regional gravity data, thus providing a finer resolution (summarised below) in considering fault offsets and the location of salt-walls and thinned sediments. Gravity data comprised a gridded gravity dataset of the whole area, purchased from BGS (Edinburgh). This data was processed via Surfer™ (Volume 7) which krigs the data and produces a shaded relief image. This was viewed using a variety of azimuths and aspects, one of which is shown.

Post Cretaceous deformation history

The structure of the Permian - Triassic SGCB is incompletely known due to poor seismic resolution below the 3000 m of overlying Jurassic sediment. Nonetheless Barr *et al.* (1981) were

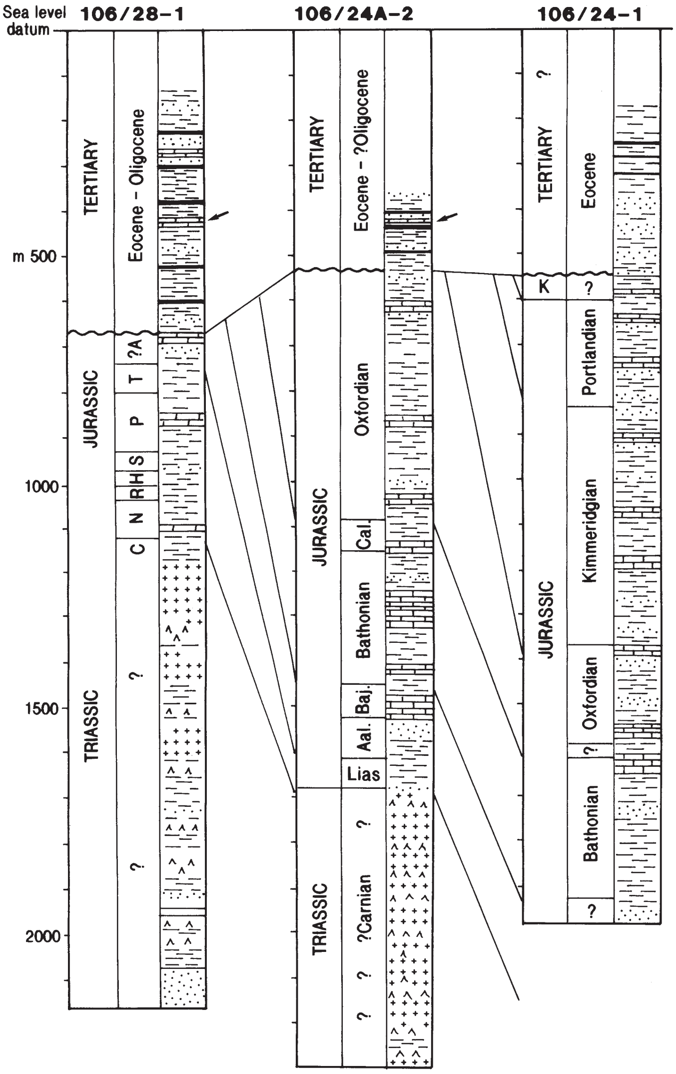

Figure 2. Released well-logs from the study area, showing the widespread occurrence of thick Jurassic, base Tertiary unconformity and intra-Tertiary (Eocene marker) calcareous beds (arrow) used in structural mapping. These three key wells are used to locate the stratigraphic position of reflections (through ties to other lines in the grid) displayed on seismic line in Figure 3.

confident of correlating an intra-Permian - Triassic event over most of the basin and mapping this surface in two-way time (their figure 5). The Jurassic section is resolved with excellent clarity on all seismic data from this area (Figure 3a). The base Tertiary unconformity is imaged throughout the study area (Figure 3a). Lastly, the low gravity field associated with salt intrusions makes this an ideal technique in the SGCB where salt intrusions are well known (Dimitropoulos and Donato, 1983) and occur close to basin margins and major faults.

Throughout the study area (Figure 1), the base Tertiary unconformity surface cuts Jurassic and early Cretaceous strata that were folded by intrusion of a salt wall (Tappin *et al.*, 1994). A minor (first phase) of salt intrusion took place before the cutting of the pre-Eocene unconformity and subsequent deposition. Early salt intrusion may thus be prior to, or synchronous with the Cretaceous - Tertiary period of basin inversion (Van Hoorn, 1987). Parts of the salt intrusion have exploited and thus accentuated the Jurassic anticline complimentary to the main SGCB syncline. This salt-induced or accentuated anticline was cut by the pre-Eocene unconformity, when the salt wall itself may have been partially eroded. Within the preserved Tertiary succession, two distinct phases of sedimentation can be inferred, separated by the widely correlated calcareous layer (see above). There was little or no tectonism or salt movement in the Eocene – Oligocene, as this structure remains similar to that at base Tertiary level (Figure 3a, 3b). Following Tertiary sedimentation, a second phase of salt movement occurred. Most of this salt movement was along the pre-existing salt wall, although new salt-induced folds and salt-exploited faults are interpreted in the north and east of the study area.

Post- ?Oligocene deformation history

Major folds and the salt wall are both traceable on seismic data from the Jurassic through the unconformity to the Tertiary (Figure 3a). Closer inspection reveals some significant differences. There are two major Cenozoic synclines, one centered on the SGCB and coincident with the underlying structure (Figure 3a), the other south of (and parallel to) the salt wall. The larger, northern structure displays synsedimentary thickening and was presumably also a depocentre in the Tertiary. The small, southern syncline, plus others along the margin of the salt wall are all typical rim synclines, accentuated by recent erosional preservation in the hanging wall blocks to the salt. They are most likely to be post-depositional and not associated with any minor depocentre as no synsedimentary thickening into the syncline cores is observed.

The timing of Tertiary events is critical in evaluating activity on the Sticklepath Fault. Following the Cretaceous - Tertiary (?Palaeocene) uplift and erosion that initially truncated the salt wall and associated anticline, sedimentation commenced in the Eocene, continuing through to the Oligocene (dating from Tappin *et al.*, 1994). The depocentre for this (mainly clastic) input was the inherited Jurassic synclinal axis of the SGCB. One of the next post-depositional Tertiary events was a second phase of salt diapirism which occurred in the same location as the post-Jurassic/?early Cretaceous halokinesis. To explain the coincidence of a truncated Jurassic anticline and salt wall, plus the preservation of small rim synclines that only affect Tertiary strata (all displayed on Figure 3a), two phases of salt movement are implied. What is intriguing is if the Jurassic SGCB syncline is a product of the early phase of halokinesis (i.e. a large rim syncline), then why does it have five times the amplitude (see Figure 3) of the Tertiary rim synclines, produced from movement of the same salt wall? The salt intrusions of the study area appear to show all the classic features of salt diapirism. However, it should be noted that although the greater amplitude of the Jurassic folds may be produced by a primary rim syncline, this structure has been accentuated by Cretaceous - Tertiary erosion. The withdrawal basin and formation of the (Tertiary) secondary rim syncline is considered to be the product of a separate phase of halokinesis, primarily because of the time gap and unconformity) between the two. It may be that the Jurassic syncline was the product of regional tectonism, which triggered, or was followed by halokinesis that exploited the complimentary Jurassic anticline. Whilst we do not know whether salt intruded the anticline or caused the anticline, we do know that this salt intrusion was in existence in the pre-Eocene because it is eroded at the base Eocene reflection. This explanation avoids the need for salt intrusion causing the synclinal fold that preserves the greater part of the SGCB. Conversely, if most of the Triassic salt available was forced into the salt-wall then this would leave less for Tertiary halokinesis, with a consequent reduction in the size of the salt wall and rim-syncline.

Strike-slip

Tectonic fabrics in the area are dominated by a NE-SW oriented Caledonian trend on which a system of NW-SE Variscan faults have been superimposed. The Variscan NW-SE oriented faults that dominate the English Variscides to the south have been observed in the Celtic and Irish sea basins (Beach, 1987; Lake and Karner 1987; Ziegler, 1987). During the past fifteen years, the NW-SE strike-slip faults of the English Variscides have been interpreted as occurring progressively further north. The kinematics of such NW-SE strike-slip faults in southern England and in the Celtic Sea are well-known: they originated during

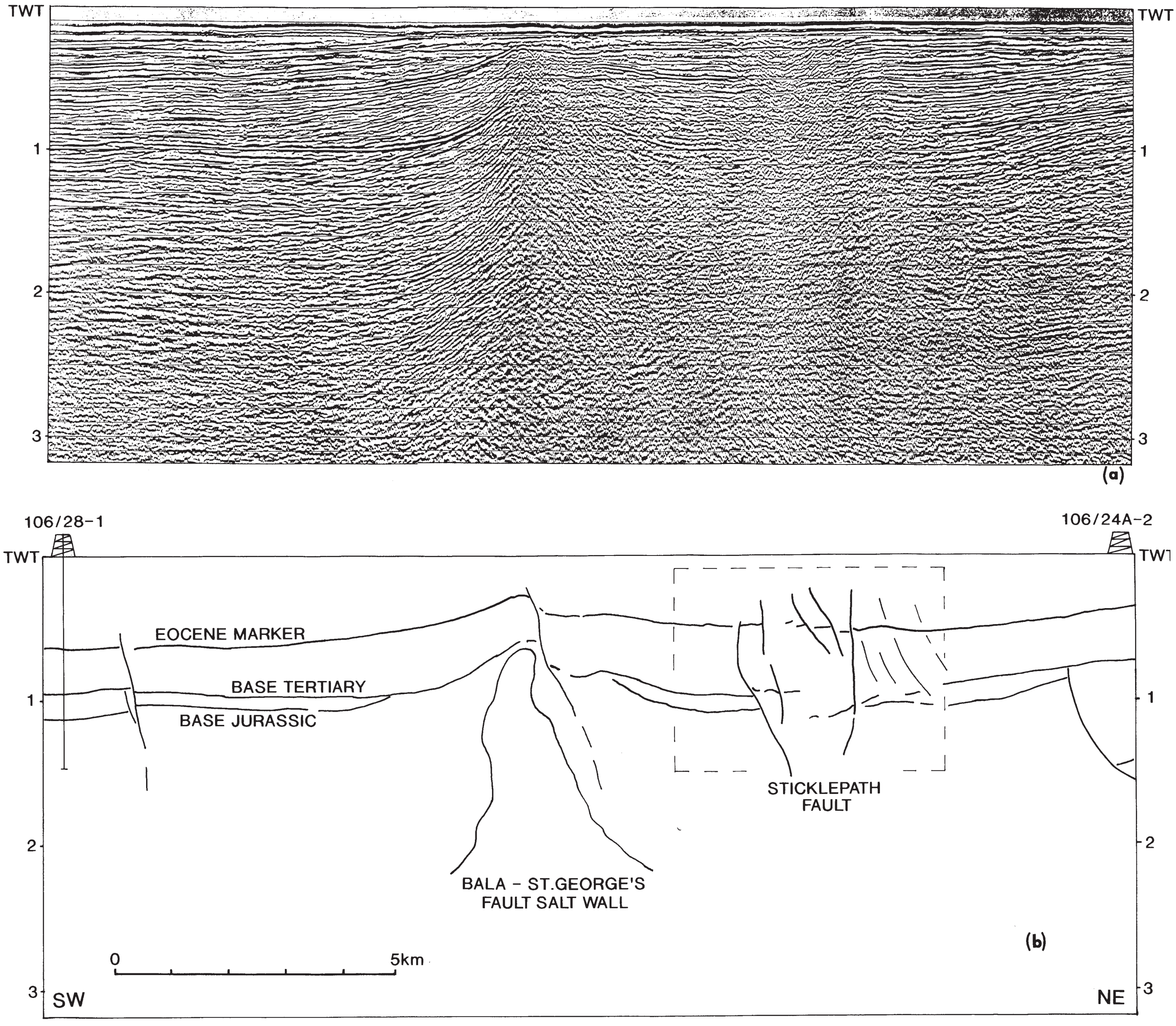

Figure 3. (a). Portion of a NE - SW oriented seismic line (approximate location shown by line of dots on Figure 1) and (b). interpretation across the St. George's Channel and bounding salt wall. The key reflections used in mapping are indicated. Location on Fiure 1. Data courtesy Western Geophysical Ltd.

Variscan convergence (Beach, 1987; Ziegler, 1987), were reactivated during Permian - Mesozoic extension (Shearman, 1967; Chadwick, 1985) and later aided Tertiary basin inversion through transpression (Coward and Trudgill, 1989; Petrie *et al.*, 1989). Given such an important role in the tectonic evolution of the Wessex, Channel and Celtic Sea basins, the new models continuing such NW-SE faults into the SGCB and CBB have repercussions for how we consider these areas. Do Variscan structures like the Sticklepath Fault really continue into Cardigan Bay and the St. George's Channel? If they have similar kinematics to those elucidated further south (Holloway and Chadwick, 1986; Arthur, 1989), late Tertiary breaching of hydrocarbon reservoirs may be expected.

Recently, geophysical datasets have become available that allow identification of the NW-SE strike-slip faults of the English Variscides in the Irish Sea and Irish mainland. One of the best known of these NW-SE faults is the Sticklepath Fault (Figure 1) of Devon and the Bristol Channel (Holloway and Chadwick, 1986; Arthur, 1989). The continuation of this fault (more accurately, a fault zone, as above) north-westwards brings it across the western tip of Pembroke (where it is mapped along the Flimston Basin), into the St. Georges Channel area. Here, gravity, seismic and borehole information has clearly shown the existence of a NE-SW trending salt wall, intruded into the Bala Fault system (Dimitropoulos and Donato, 1983; Tappin *et al.*, 1994).

The evidence for NW-SE oriented faults in the SGCB comes from seismic and gravity data. On a NE-SW oriented seismic line across the basin (Figure 3a) the distinctive continuous reflections of the mid-Tertiary, base Tertiary and base Jurassic (described above) are all clearly cut by the salt wall. Close examination also reveals a zone where reflection continuity is lost, to be replaced by highly faulted segments of the typical stratigraphy or by a chaotic appearance. Enlargement of this zone forces a different and more detailed interpretation of a potential flower structure (Figure 4). The north-eastern side of this faulted zone shows minor anticlines and fault reversals, indicative of a compressional or positive flower structure (Woodcock, 1986). The central and south-western part of the structure is down-faulted and thus more akin to a negative flower. North-westerly projection of the last known location of the Sticklepath Fault onshore (Flimston in Wales) crosses the seismic line at the location of this structure. Comparison of the seismic lines across this area shows an offset of all fold axes (including those affecting the youngest Tertiary strata) and the salt wall by NW-SE oriented strike-slip faults. The

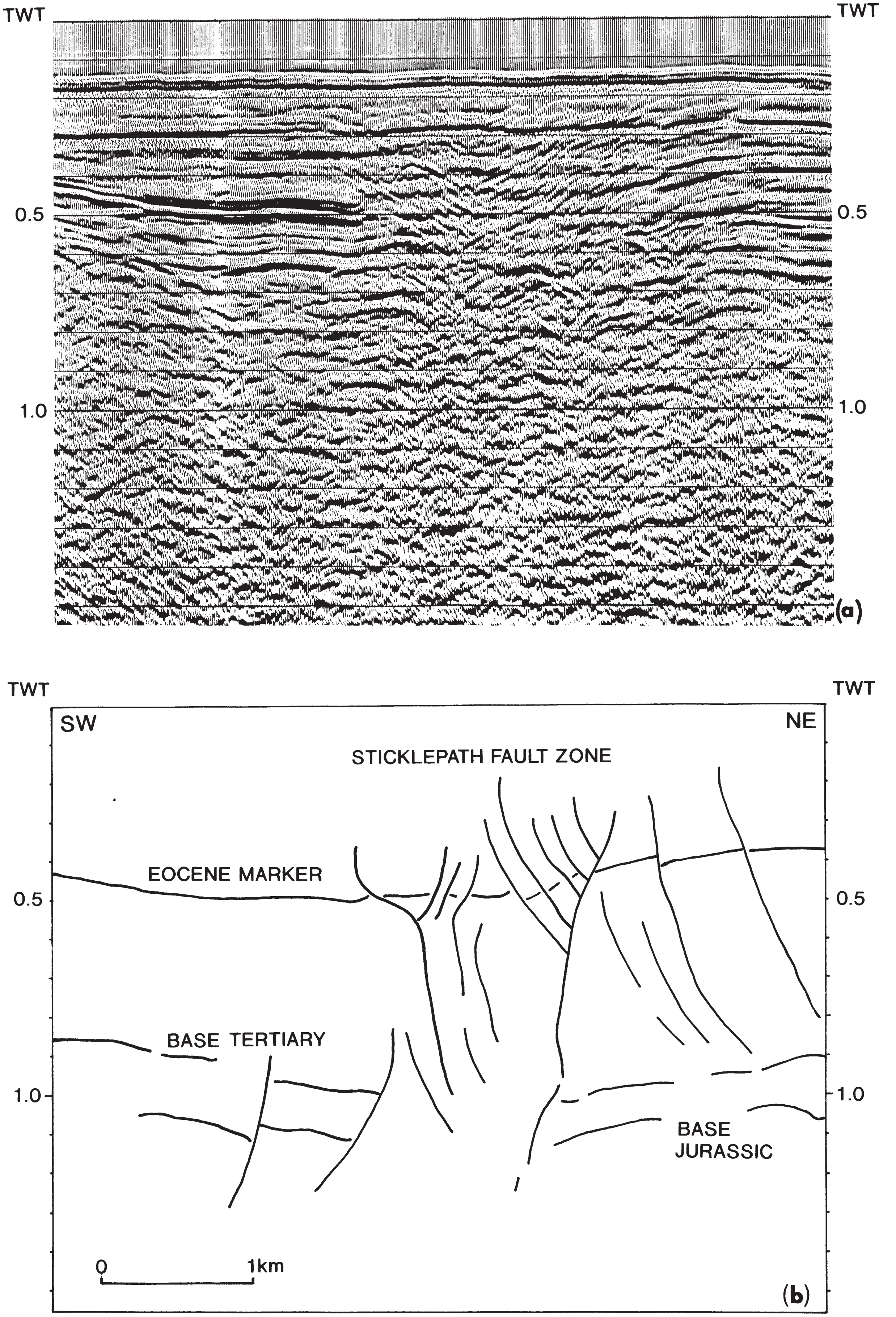

Figure 4. (a). *Enlargement of part of Figure 3 across the interpreted Sticklepath Fault.* ***(b).*** *Here the loss of reflection characteristic and faulted nature of the Tertiary strata are interpreted as a flower structure.*

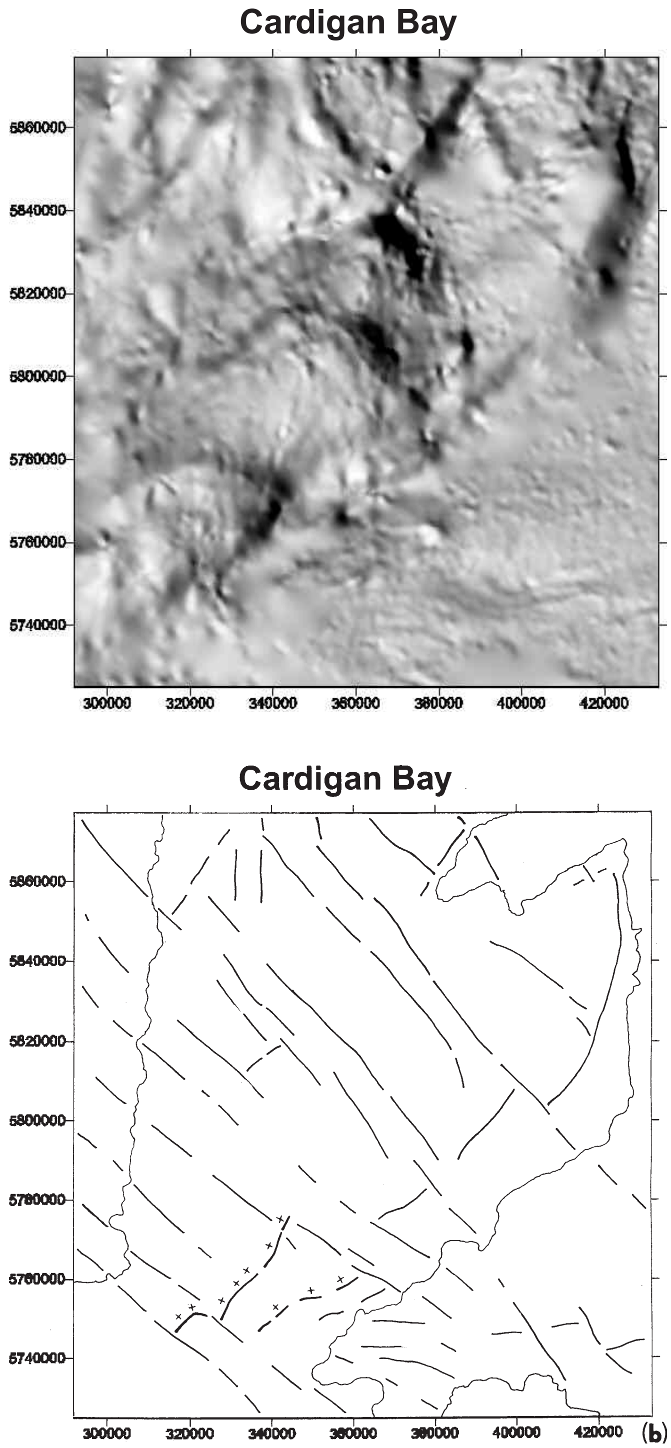

***Figure 5 (a)**. Shaded relief image of gridded gravity data from the study area, derived from BGS regional surveys and illuminated at 450 from the north-east using Surfer™ (Version 7) Interpretation used in Figure 1. Image is 120 km x 120 km. **(b)**. Lineament interpretation from this data alone. + + = salt wall.*

projected Sticklepath Fault displaces the salt wall by a consistent 3 km in a dextral sense at near base Jurassic (Figure 1), base Tertiary, and Eocene marker horizons. It also displaces the main Jurassic syncline by around 11 km in a sinistral sense. Whether the fault shifted the salt wall and syncline after their formation, or whether the sites of this deformation were merely separated by the NW-SE faults cannot be discerned as it is unproven whether either (especially the salt wall) were ever one continuous structure. Seismic data clearly shows the one major Jurassic syncline of the area, centred on the SGCB (Figures 1 and 3a). This fold is partly a synsedimentary feature, showing thickening into the axis, and partly the product of post-sedimentary deformation. The fold is cut by a number of NW-SE trending vertical faults. The south-western fault is here suggested to be a continuation of the Sticklepath Fault (after Petrie *et al.*, 1989; Tappin *et al.*, 1994): it displaces both a post-Jurassic salt wall and throws the syncline down to the west. Indications of sinistral movement have been observed before in the study area. Tappin *et al.* (1994) also describe sinistral offsets to Jurassic - Cretaceous strata, noting how Mesozoic depocentres are oriented NE-SW in both the SGCB and South Celtic Seas, yet offset from one another (in a sinistral sense) along a zone from Pembroke to Wexford. This zone is defined by the Waterford Lineament to the SW and Sticklepath Fault to the NE by Petrie *et al.* (1989).

Gravity data from the area shows both the salt wall and the edge of the SGCB (Figure 5a). Whilst the salt is shown to be discontinuous, the edge of the basin appears continuous, but with a distinctive bend just to the north-east of the projected intersection with the Sticklepath Fault. This bend defines a change from an east - west structural grain parallel with the coastline to a NE - SW grain west of the Pembrokeshire coast. This gravity data has been compared to the original seismic data and the published maps (mostly in Tappin *et al.*, 1994) to produce a lineament map (Figure 5b). This shows the dextral offset of salt walls and basin-margin faults by the Sticklepath Fault. Some of the other lineaments identified on gravity data are close to mapped faults. The Llanrian (or Llanhrian) Fault of Figure 1 is clearly observed on gravity data but appears to be approximately 5 km to the south-west of its mapped location (Bazley and Gallois, 1992). This is not an inconsistency as the gravity data is illuminated from the NE, throwing an effective "shadow" to the SW. The Sticklepath Fault is interpreted to control the final location of salt, folds and the edge of the basin (in the south-east). Whether this implies late displacement of these features or the earlier activity of the fault (compartmentalising the basin) is hard to tell. As the Sticklepath Fault reaches the seabed and deforms reflections representing the base Tertiary unconformity (which cuts the first salt intrusion), it is suggested here that the last movement on the fault is later than the salt or synclines. Previously published lineament and fault maps of the area (e.g. Musgrove *et al.*, 1995) show the Sticklepath Fault as a zone of faulting appearing in Wexford Harbour (Co. Wexford) and continuing (as a zone) through Ireland and into Connemarra and Sligo.

Conclusions: tectonic evolution

Synsedimentary and post-sedimentary folding (through salt-intrusion) of Mesozoic strata (probably up to and including the early Cretaceous) produced a 25 km-wavelength, NE-SW trending syncline, centred on the present-day SGCB, that is offset by a NW-SE trending strike-slip fault (the projected Sticklepath Fault of Figure 1). Continuation of this fault to the south-east places it on trend with the Sticklepath Fault. The sinistral offset between the SGCB and NCSB noted by Tappin *et al.* (1994) is suggestive of greater sinistral offset than that observed here. Holloway and Chadwick (1986) and Arthur (1989) both describe early Tertiary sinistral motion on the Sticklepath Fault in Devon and the Bristol Channel based on the geometry of the associated pull-apart basins. The first phase of halokinesis occurred along the anticline pair to the SGCB syncline (Figure 3a). Salt movement may have been triggered by the same phase of folding and strike-slip tectonics and thus may be synchronous. However, as Van Hoorn (1987) suggested, the timing of salt movement along the length of the main salt wall may have varied and be difficult to define with accuracy. The observations made by Van Hoorn (1987) and confirmed in this study seem to be supported by the experimental models of Guglielmo *et al.* (1997), who suggest a complex set of controls on the evolution of salt walls, one of which includes the problem of dating episodes of movement. Nonetheless, the base Tertiary unconformity, which cuts a post-Jurassic rim syncline, allows interpretation of at least two phases of salt diapirism in the area, with possible minor movement, including some along parts of the Sticklepath Fault (Figure 6). The separate nature of NW-SE trending (at this location through deflection) salt wall and

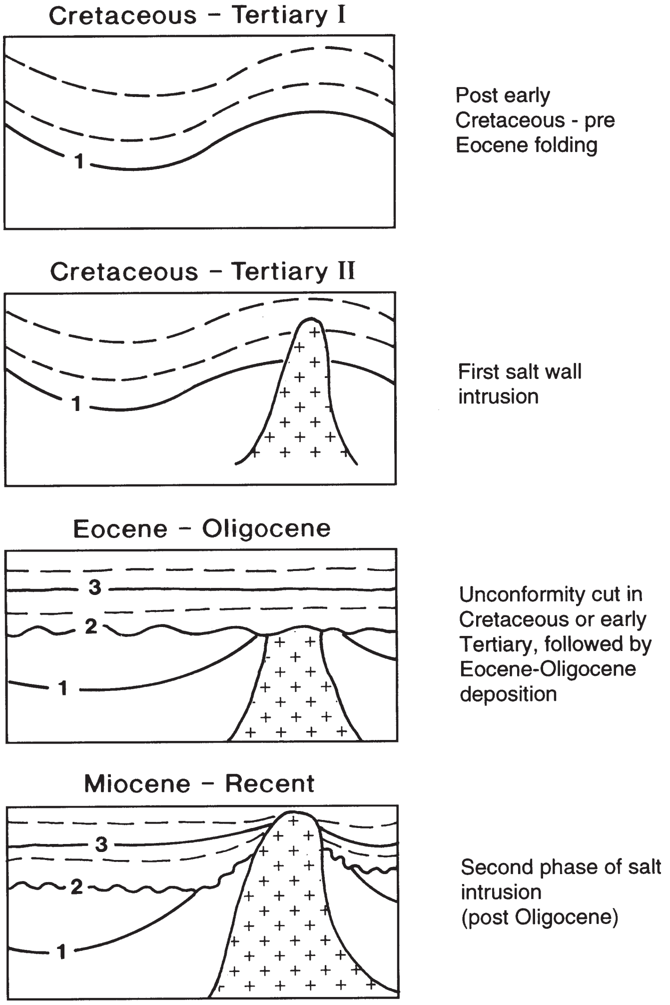

Figure 6. *Cartoon interpretation of the sequence of halokinetic events described in text.*

interpreted flower structure on Figure 3 is an indication that early strike-slip fault and salt movement were synchronous, whereas the last (post-Oligocene, possibly through to the present-day) movement on the Sticklepath Fault was separate to the salt-wall. Possibly, the salt intrusion at this shallow (and thus more brittle) level had annealed the earlier, deeper and thus lubricated, Sticklepath Fault.

This study, Tappin *et al.* (1994) and Musgrove *et al.* (1995) suggest that a continuous NW-SE fault crossing the SGCB is on the same trend as the Lundy - Sticklepath - Lustleigh - Bovey system described by Holloway and Chadwick (1986) and Arthur (1989). In the Bristol Channel and Devon this structure shows a late Tertiary dextral motion (dated as Miocene by Holloway and Chadwick, 1986) and an earlier (?early Tertiary) sinistral movement. The kinematics recorded in the SGCB appear similar to those seen to the south, with the Sticklepath Fault in the study area showing evidence (in its present-day structure) of early sinistral offset to Jurassic structures and dextral offset and deflection to the post-Tertiary salt-wall movement. Whether these movements occurred during or after folding and halokinesis is not known; the two structures simply appear to show different displacement and both sinistral and dextral motion is known on the same fault to the south-east (Holloway and Chadwick, 1986; Arthur, 1989). Musson (2000) suggested that earthquakes in the Devon and Cornwall area were probably related to deep, E-W trending structures. However, examination of figure 1 in Musson (2000) shows an alignment of earthquakes along the Sticklepath Fault, although their foci may be too deep to be directly related. This, coupled with the post-Oligocene movement evidenced from this study (St. George's Channel) and the obvious effect the fault has on gravity data, suggests that maybe there has been recent movement on the Sticklepath Fault.

Acknowledgements

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