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TECTONIC EVOLUTION OF THE PLYMOUTH BAY BASIN

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A synthesis of offshore seismic data in the Plymouth Bay and Western Approaches, and onshore basement structures and mineralisation history has allowed new constraints to be placed on the structural evolution of the late Carboniferous-Triassic Plymouth Bay Basin. These data have been combined to produce a model for the late- and post- Variscan tectonics of the Plymouth Bay area. Additional controls on the timing and magnitude of Variscan uplift and late-Variscan low-angle extensional deformation onshore are used to infer a late Carboniferous age for the earliest basin fill. These sediments were accommodated in a north-east — south-west oriented basin formed during late-orogenic extension. A change in the orientation of the depocentre in the early Permian signalled a switch to a north-west — south-east, strike-slip dominated tectonic environment.

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INTRODUCTION

The presence of Permo-Triassic sediments in Plymouth Bay was recorded during early seabed sampling projects and offshore geophysical surveys (King, 1954; Day *et al*., 1956). Structure maps constructed using seismic refraction data (Avedic, 1975) failed to identify a major depocentre in Plymouth Bay but re-definition of seismic velocities by Bott (1970) allowed interpretation of these early data in terms of a 10 km thick upper crustal layer. This layer was confirmed as a sedimentary basin from deep seismic data obtained as part of the South-West Approaches Traverse (BIRPS and ECORS, 1986) which image an approximately symmetrical un-faulted basin exceeding 10 km in depth.

The study area forms part of an extensive Permo-Triassic extensional system developed across north-western Europe during the post-Variscan break-up of Pangea. Permo-Triassic non-marine red bed sequences accumulated in the Dorset - Channel Basin and Paris Basin to the east, the Western Approaches Basin system to the west and in the North and South Celtic Sea Basins to the north (Figure 1). Late Carboniferous-early Permian basic lavas underlie the Permo-Triassic sediments onshore in east Devon and offshore in the Melville sub-basin in the Western Approaches. These basins were controlled by steep normal faults, often interpreted as having formed above re-activated Variscan structures (Stoneley, 1982; Van Hoorn, 1987; Chapman, 1989) and rarely accommodate more than 3 km of Permo-Triassic sediment. In contrast, the anomalous thickness of pre-Jurassic sediments in the Plymouth Bay Basin, its bullseye geometry and the absence of major, controlling normal faults indicate that a different process may have been responsible for its formation. Day et al. (1989) proposed that the circular shape of the basin resulted from a pull-apart geometry. Coward (1990) suggested that dip-slip movement over ramps on Variscan thrusts produced the deep basin. These models are tested here using new onshore and offshore data.

BASEMENT 'TECTONICS

This section presents a summary of the 3D geometry of Variscan strictures in south Devon and Cornwall, based largely upon previous reviews (Leveridge *et al*., 1984; 1990; Holder and Leveridge, 1986; Holdsworth, 1989a). The study area lies south of the east-west - trending Start-Perranporth Zone (SPZ, Figure 2), which is a postulated long-lived structural lineament that may have been an important basin-bounding fault structure during Devonian basin evolution (Sadler, 1974; Holdsworth, 1989a). In Cornwall, the SPZ is associated with the contact between Lower Devonian shales (*Meadfoot Group*) and younger flysch of the Gramscatho Group lying to the south and in south Devon the SPZ separates a thrust sequence in the Meadfoot Shales from the Start Complex metamorphics. Variscan structures associated with the SPZ in both Devon and Cornwall show evidence of dextral transpression (Holdsworth, 1989a). Dextral transpression on east-west - trending structures is a feature of regional Variscan tectonic models (e.g. Brun and Burg, 1982; Matte, 1991) and has been documented at outcrop in Pembrokeshire (McClelland-Brown, 1983) and north Devon (Andrews, 1993).

South of the SPZ in Cornwall the sediments within the Devonian Gramscatho Basin consist of a Frasnian deep water fan (*Porthtowan Formation*), overlain by Famennian marine deposits of the *Mylor Slate Formation* (Leveridge *et al*., 1990). Although affected by several phases of penetrative Variscan deformation, these sediments are regarded as parautochthonous by Leveridge *et al*., (1984; 1990), having been deformed during emplacement of a thrust system which now crops out on the Lizard peninsula (Figure 2). The nappes of this thrust system were emplaced towards the north-north-west (Leveridge *et al*., 1984) and comprise further portions of Gramscatho Basin sediment. At progressively higher structural levels in the thrust system, older hangingwall sediments are in contact with the floor thrust - from the Frasnian *Portscatho Formation* in the lowest allochthon (*Carrick Nappe*) to the Eifelian *Pendower Formation* in the Veryan Nappe (Leveridge *et al*., 1990). This relationship is consistent with a ramp-flat geometry, with the sole thrust climbing in the direction of thrust system emplacement (Boyer and Elliott, 1982), a geometry also suggested by Holder and Leveridge (1986) on the basis of offshore seismic reflection data. The higher allochthons (the Dodman, Lizard and Normannian nappes) contain fragments of metamorphosed Gramscatho Basin sediment, oceanic crust and exotic continental material respectively (Holder and Leveridge, 1986). The internal structure of the higher allochthons has been the subject of some debate (e.g. Sadler, 1974), and they are grouped together here as a metamorphic nappe complex.

The thrust system shows marked variation in geometry along strike. The Carrick Thrust has a sinuous trace in map view, cutting down stratigraphy north-eastwards (Holder *et al*,, 1990) and defining an oblique or lateral footwall ramp (Figure 2). This curvature may be accentuated by doming around the post-thrusting Carnmenellis Granite (Leveridge *et al*., 1990) and displacements on north-west—south-east - trending faults (Holder *et al*., 1990). Similar curvature of the thrust system has been noted offshore (Day and Edwards, 1983; Edwards *et al*, 1989). Variscan displacements on north-west— south-east - trending wrench faults north of Plymouth Bay (Figure 5) were

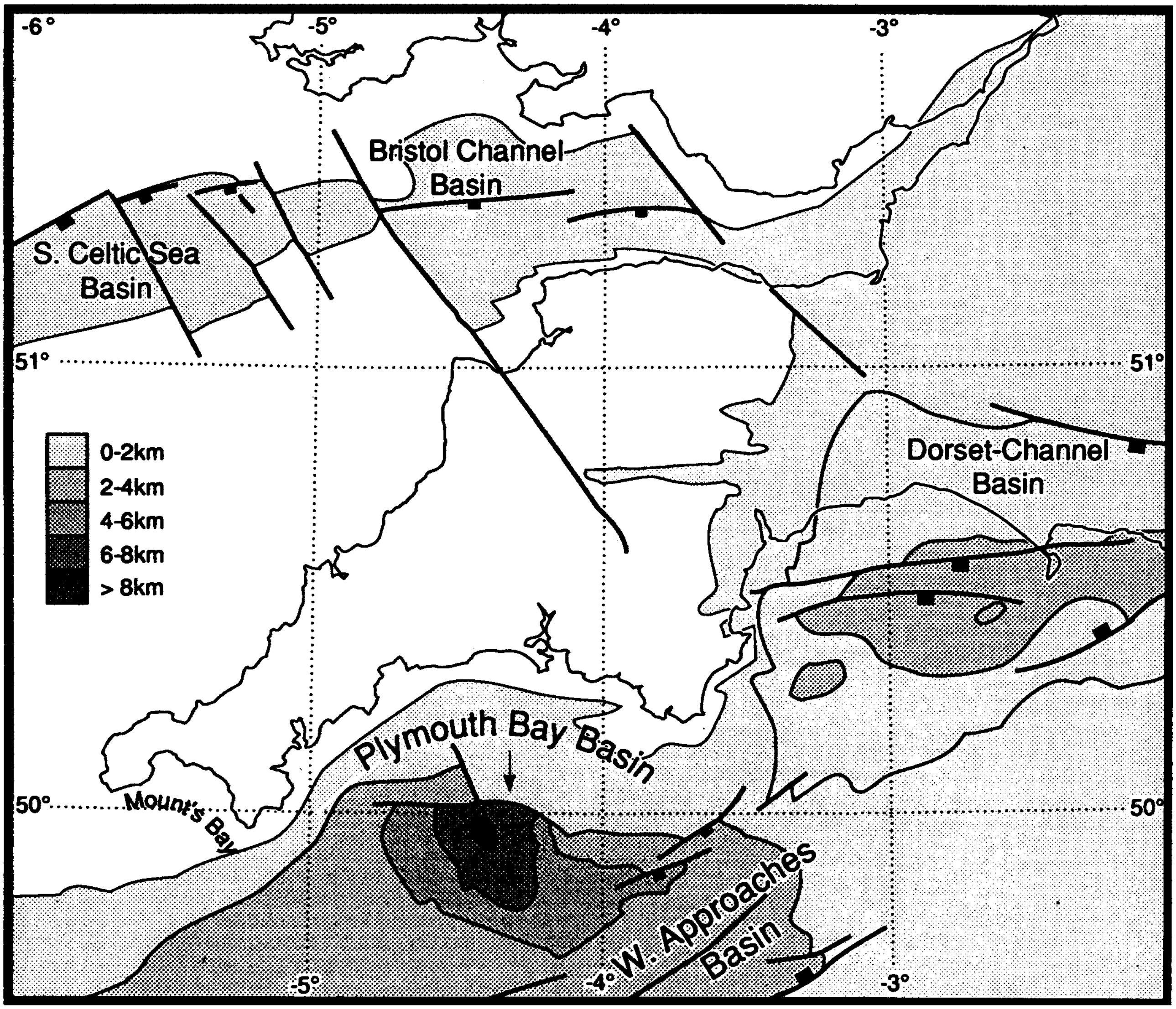

Figure 1. Location of the Plymouth Bay Basin and adjacent Permo-Triassic basins, with isopachs of Permo-Triassic sediments (in part after Evans, 1990; Hamblin et al., 1992).

demonstrated by Burton and Tanner (1986) and regional north-west —south-east lineaments constituted important lateral structures during Variscan deformation elsewhere (e.g. Matte *et al.,* 1986).

There is little doubt that basement structures exert a fundamental control upon the location and tectonics of overlying sedimentary basins during both extension and compression (e.g. Gillchrist *et al.,* 1987) and one might expect the shape of any post-Variscan sedimentary basin to reflect the geometry of the basement structures. In addition it is common for tectonically thickened crust to experience gravity-driven extensional collapse in the late stages of orogenesis (Dewey, 1988). Late Variscan backslip on thrusts has already been noted in south Cornwall (Day, 1986; Holdsworth *et al.,* 1993).

VARISCAN UPLIFT HISTORY

Variscan compression in south Cornwall resulted in deformation and low grade metamorphism of the Gramscatho Basin sediments within the nappe sequence described above. Early low angle ductile-brittle thrusting (D_1) led to the stacking of a series of nappes, contemporaneous with pumpellyite-actinolite regional metamorphism (Barnes and Andrews, 1981). Brittle imbrication on moderate - angle thrusts occurred during later deformation events (D_2) concomitant with exhumation of the nappe pile. Fluid inclusions present in quartz veins generated during D_1 and D_2, in conjunction with mineral assemblage, mineral chemistry and vitrinite reflectance constraints, have been used to reconstruct the temperature-pressure (depth) evolution of the Variscan crust during compression (Wilkinson, 1990a). This has been combined with known time constraints and data on the subsequent extension and subsidence history to produce a time-depth evolution diagram for the Plymouth Bay area (Figure 3).

K-Ar dating of micas froth the Portscatho Formation at Gunwalloe and elsewhere in south Cornwall suggests an early Visean age (c. 350 Ma) for closure through the K-Ar blocking temperature (Dodson and Rex, 1971). This cooling age, combined with the late Famennian age recorded for sediments affected by D_1 on the east side of Mount's Bay (Wilkinson and Knight, 1989), constrains D_1 to the early Carboniferous. The end of D_2 is constrained by the post- D emplacement of the earliest Cornubian granites in the late Carboniferous at around 300 Ma (Chesley *et al.,* 1993). The maximum duration of Variscan compression is therefore 65 My, giving a minimum exhumation rate from D_1 to end-D_2 of around 0.01 cm/yr. However, tentative correlation of D_2 with peak deformation in north Cornwall and south Devon (320-340 Ma K-Ar closure dates; Dodson and Rex, 1971) gives a syn-compressional exhumation rate closer to 0.02 cm/yr. One mechanism for syn-compressional exhumation is isostatic re-equilibration during erosion of the over-thickened orogenic crust. Rates of isostatically-driven exhumation have been calculated in the Himalayas (Treloar *et al.,* 1992) and Alps (Sinclair and Allan, 1992) at 0.05 cm/yr and 0.08 cm/yr respectively. This mechansim, therefore, may account for the D_1-D_2 exhumation in south Cornwall, even at the highest rate proposed above (0.02cm/yr).

South-east - dipping post-D_2 fabrics within the Carrick Nappe and parautochthon around Mount's Bay indicate south-easterly vergent extensional deformation, sub-parallel to the compressional fabrics (see Shail and Wilkinson, 1994, their Figure 2), and are here termed D_3. Rattey (1979) interpreted this low-angle extensional deformation as having resulted from doming during early emplacement of the granite batholith, pre-dating the final intrusion events. Leveridge *et al.* (1990) reported no direct link between these structures (their D_5) and the granite outcrops and followed Day (1986) in proposing late Carboniferous extensional shear during backslip on major thrusts. Fluid inclusion data presented by Wilkinson (1990b) from syn- to post- D_3 veins suggest that post-compressional uplift of at least 1 km must have occurred prior to emplacement of the Tregonning Granite at 280 Ma (Darbyshire and Shepherd, 1987). This uplift may be associated with early extension prior to, or during granite emplacement. Late orogenic low-angle extensional systems associated with gravity collapse and back-slip on existing compressional structures have been described from the Caledonides of northern Europe (Serrane and Seguret, 1987; Holdsworth, 1989b) and from the French and Iberian Variscides during the Upper Carboniferous (Malavieille *et al.,*1990; Aranguren and Tuçÿa, 1992). The effect of low-angle extension on the nappe pile exposed around Plymouth Bay can be studied in more detail using commercial and deep seismic data across the offshore post-compressional basin.

SEISMIC MAPPING OF THE PLYMOUTH BAY BASIN

Seismic reflection profiles recorded to 6 seconds two-way-time (TWT) across the northern part of Plymouth Bay have been described by Day and Edwards (1983) and Edwards *et al.* (1989). These show southward - dipping reflections interpreted as Variscan thrusts bounding the Carrick, Dodman and Lizard Nappes in the basement, overlain by presumed Permo-Triassic sediments of the Plymouth Bay Basin, which onlap the basement surface. The BIRPS deep seismic lines SWAT 8 and SWAT 9 were recorded to 15 seconds TWT and image the entire Plymouth Bay Basin. South-dipping fabrics within the underlying basement appear to flatten into a zone of bright mid-crustal reflections at around 7 seconds TWT and have also been correlated with the Carrick and Lizard Thrusts (Klemperer and Hobbs 1991).

Continuous reflectors on SWAT 9 define a largely un-faulted and undeformed basin sequence above a dear top basement reflection at up to 4 seconds two-way time (Figure 4). Shallow boreholes and gravity cores indicate that Permo-Triassic red beds crop out at the seabed above the deepest part of the basin (e.g. borehole SLS 18; Lott, 1983). Assuming an average sonic velocity of 5300 m/s for the basin fill (RMS stacking velocity at shot-point 2798), a minimum thickness of 11 km can be postulated for the pre-Jurassic sediments in the basin depocentre. A possible constraint on the age of the lower part of the basin-fill is the presence of anomalously high-amplitude reflectors half-way up the sequence (Figure 4b). These have been interpreted as extrusive volcanics by BIRPS and ECORS (1986) after 3D modelling of the positive magnetic anomaly overlying the basin centre (Allan, 1961). We correlate these horizons with the Exeter Volcanics of Devon, dated at 291±6 Ma by Thorpe *et al.* (1986), and base Permian lavas drilled in the Melville Basin to the west (Chapman, 1989), inferring that approximately 4 km of sediments beneath this reflector accumulated during the late Carboniferous.

Pronounced truncation and onlap surfaces within the basin fill imaged on SWAT 8 and SWAT 9 have been used here to define four megasequences, i.e. packages of sediment bounded by regional unconformity surfaces. These megasequences, labelled A to D from the lowest upward (Figure 4a), have been mapped across the Plymouth Bay area using the SWAT lines and data from earlier commercial seismic surveys tied to offshore wells. Two of the resulting isochore maps (vertical thickness in TWT) are presented in Figure 5 along with locations of the seismic data and boreholes. Folding of the base-Cretaceous unconformity over the basin centre (Figure 4a) provides evidence of post-Cretaceous inversion. Tertiary uplift may be the cause of relatively high interval velocities within the basin but reasonable lateral continuity of velocities within each interval enables interpretation of the isochore maps in terms of original depositional trends.

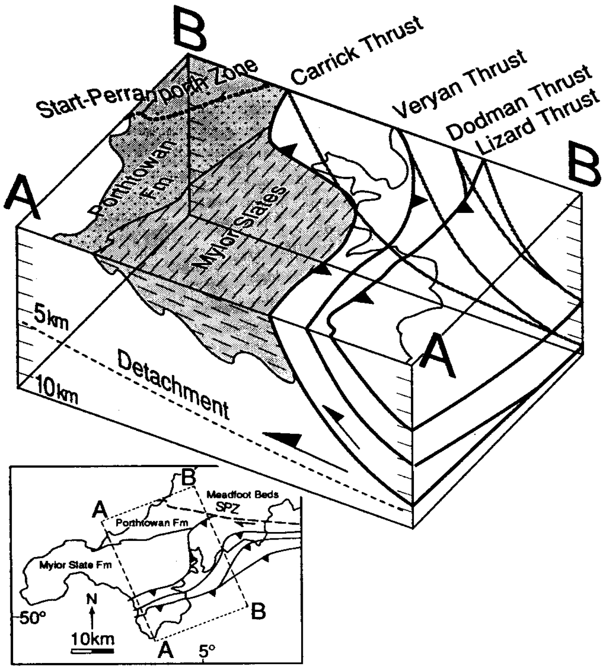

Figure 2. Block diagram, viewed from the southwest, depicting variation in thrust geometry and footwall relationships along structural trend in south Cornwall. Nappe units and parautochthonous sedimentary formations after Leveridge et al., (1990); igneous lithologies omitted. Figure based on cross section s A-A and B-B, originally drawn at 1:50,000.

Megasequence A, immediately overlying top-basement reflectors, is preserved along a north-east — south-west trend from Plymouth Bay to the southwest of the Lizard Peninsula (lower contours on Figure 5). The main depocentre, near shot-point 2800 on Swat 9, is elongate, parallel to regional Variscan strike. Here the sequence isochore exceeds 1 second in TWT, representing approximately 3500 m thickness (from seismic stacking velocities). To the north the sediments of megasequence A are shown to be cut by north-east — south-west - trending normal faults. Despite problems of resolution over this area on SWAT 9 it is clear that the sediments bury pre-existing fault scarps, and do not show the divergent geometries characteristic of sequences controlled by normal fault movement.

Megasequence B is thinner and more restricted than that below, defines a more circular isochore trend, and is bounded above by the high amplitude reflectors correlated with base Permian lavas elsewhere. Megasequence C overlies these reflectors and the isochore map (Figure 5, upper contours) defines a marked change in basin orientation compared with megasequence A. The perimeter of the illustrated isochore map is defined by the limit of sediments of megasequence C that have not been truncated by the overlying megasequence D or by erosion at the seabed. The true depositional trend clearly switched to a north-west — south-east orientation, although the depocentre (representing approximately 2500 m of sediment) is roughly coincident with that of the lowest megasequence. Megasequence D is more restricted still, due to erosion and truncation during the Permian or Triassic (Figure 4a) and seabed erosion to the north, but shares the trend of the sequence below.

The north-west - south-east isochore trend of the two upper megasequences parallels syn- and post-Variscan strike-slip faults onshore and the offshore Plymouth Bay Fault of Day and Edwards (1983). Doody and Brooks (1986) noted down-to-the west displacement on the Plymouth Bay Fault during a seismic refraction survey. This fault coincides with a north-west - southeast - oriented aeromagnetic lineament which separates the positive magnetic anomaly in the Plymouth Bay Basin (coincident with megasequence C) from a negative anomaly to the north-east (Allan, 1961). It seems reasonable to infer that, if the anomalies reflect the presence of lavas within the basin, late Carboniferous volcanic extrusion was controlled by movement on north-west — south-east faults which continued to exert a control on the basin during deposition of megasequences C and D.

DISCUSSION

The evolving architecture of the megasequences offshore suggests changing tectonic influence on the basin. The earliest sediments in the basin were deposited in a north-east — south-west -trending depocentre, approximately parallel to the Variscan thrust trend. Correlation of high amplitude mid-basinal reflectors with base Permian volcanics would indicate that this early phase of subsidence coincided with the earliest extensional deformation recorded

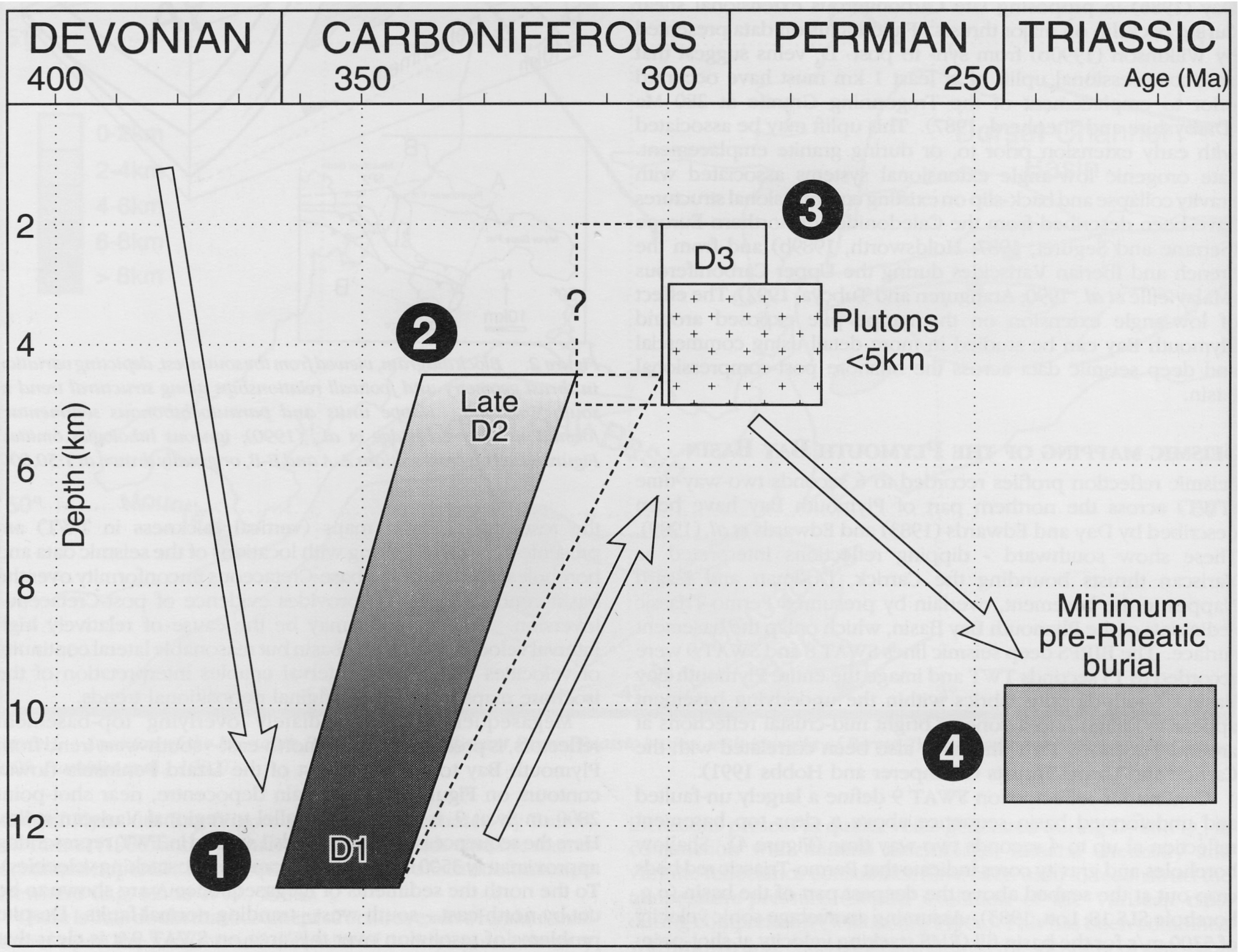

Figure 3. Time-depth evolution diagram for south Cornwall and the Plymouth Bay area. ***1.*** *Peak Hercynian regional metamorphic conditions for the allocthonous Gramscatho Group estimated at 3.2 ± 0.3 kbar and 320±10°C. This estimate is based on the presence of a syn-*D_1 *pumpellyite-actinolite mineral assemblage (Barnes and Andrews, 1981) and the petrogenetic grid of Liou et al. (1985); syn-*D_1 *fluid inclusion isochores constructed using homogenisation temperature and fluid composition data from Wilkinson (1990a) and the equation of state of Bowers and Helgeson (1983), in combination with geothermometry* on *cogenetic chlorites using the model of Walshe (1986) and vitrinite reflectance data reported by Wilkinson (1990a) indicating maximum temperatures of 320-340°C. Assuming lithostatic fluid pressures yields a maximum burial depth of 13 km during* D_1 *(see Wilkinson, 1990a for details). Time constraints imposed by late Famennian age of youngest deformed sediments (Wilkinson and Knight, 1989) and minimum 345 Ma K-Ar cooling age for Gramscatho metasediments (Dodson and Rex, 1971).* ***2.*** *Progressive coaxial deformation from* D_1 *to* D_2 *is assumed, with approximately isothermal uplift indicated by syn-*D_2 *fluid inclusion isochores in combination with geothermometry on cogenetic chlorites. Minimum temperature at the end of* D_2 *was approximately 270°C at about 1200 bars fluid pressure, indicating a minimum depth of 4.5 km at close to lithostatic fluid pressures. Sub-lithostatic fluid pressures would imply greater depths.* D_2 *inferred to continue at least until the 320 Ma cooling date recorded for Trevone Basin metasediments (Dodson and Rex, 1971); minimum age constrained by oldest granite pluton (Hemerdon) at -300 Ma (Chesley et al., 1993) which crosscuts* D_2 *fabrics.* ***3.*** D_3 *conditions reported by Wilkinson (1990b) based on fluid inclusion data from syn- to past* D_3 *veins in the contact aureole of the Tregonning Granite indicating minimum fluid pressures of -500 bars, equivalent to depths of 2-5km depending on fluid pressure conditions. Maximum possible age of* D_3 *taken as 320 Ma K-Ar cooling date; minimum age fixed by emplacement of Tregonning Granite at 284 Ma (Darbyshire and Shepherd, 1987) which crosscuts* D_3 *fabrics. Pluton emplacement depth estimated by Willis-Richards and Jackson (1989); emplacement ages of 300-275 Ma discussed by Chesley et al. (1993).* ***4.*** *Present (un-decompacted) thickness of sediments in Plymouth Bay based on seismic data. If all sediments are pre-Rhaetian a minimum subsidence rate of 0.01cm/yr is inferred.*

onshore. Late Variscan D_3 fabrics (Shail and Wilkinson, 1994) indicate north-west — south-east - directed extension, perpendicular to the Variscan trend. Coward (1990) argued that a simple stretching model could not be applied to the basin as thinning of the basement to under 20 km occurred without significant uplift of the MOHO (only 3 km of uplift, calculated by Klemperer and Hobbs, 1991). Extensional collapse of the nappe pile prior to or during granite emplacement may have led to the initiation of a pronounced basin, where extending nappes passed southward over the steep thrust ramps in Plymouth Bay. This geometry is imaged as steep fabrics to the north of the basin, that flatten onto a mid-crustal zone to the south of the early depocentre (Figure 4a).

If D_3 extensional collapse is accepted as an important control

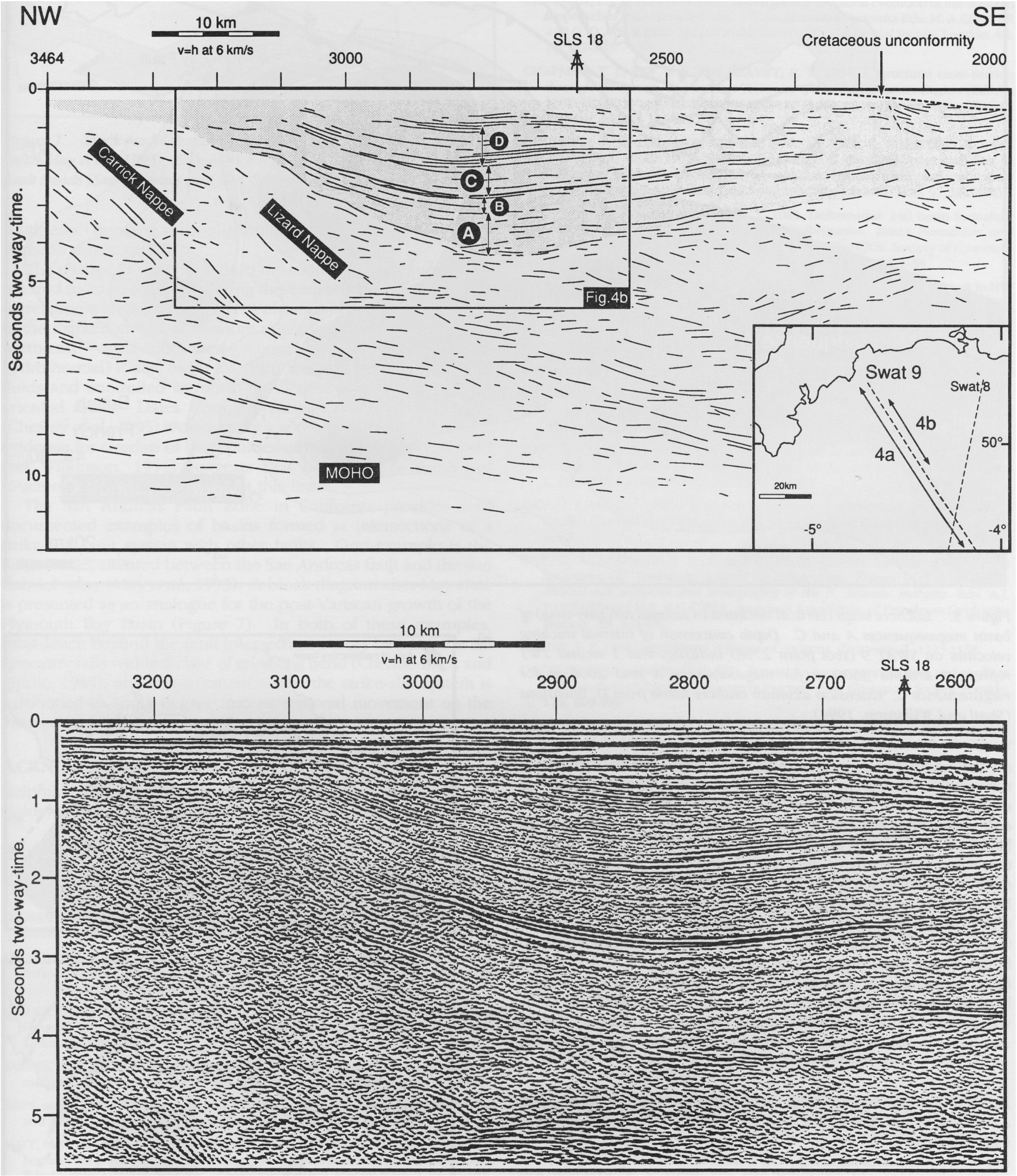

Figure 4. a) Line drawing of BIRPS deep seismic line SWAT 9 showing Plymouth Bay Basin (shaded). Labels A to D refer to megasequences discussed in text. Correlation of south-dipping basement relectors with onshore structures from Klemperer and Hobbs (1991).

b) *Detail of SWAT 9 migrated seismic line over the depocentre and northern margin of the Plymouth Bay Basin. Reproduced from Klemperer and Hobbs (1991).*

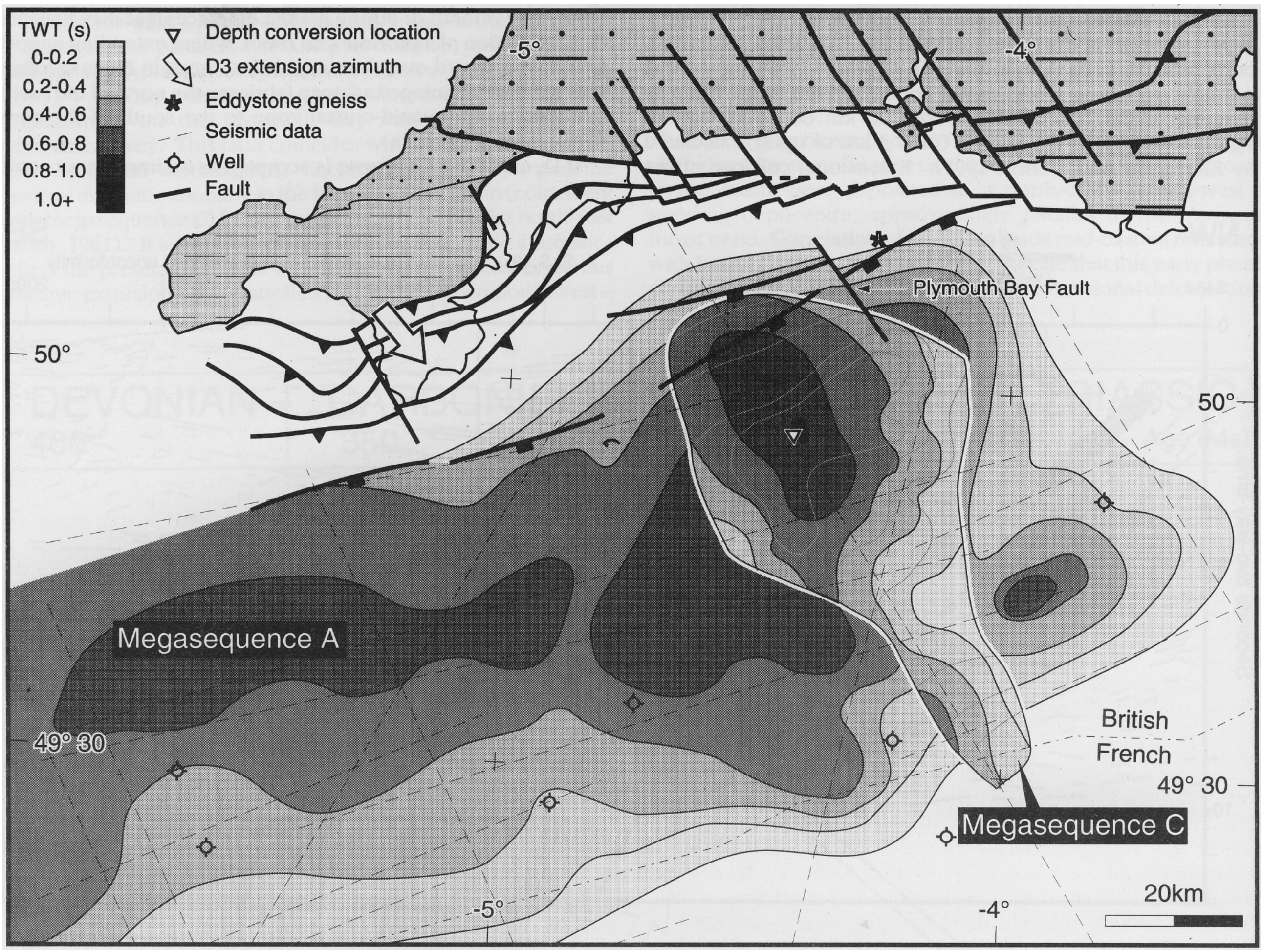

Figure 5. Isochore maps (vertical thickness in seconds two-way-time) of basin megasequences A and C. Depth conversion of interval stacking velocities on SWAT 9 (shot point 2798) indicates that 1 second TWT represents around 3500 m for megasequence A and 2000 m for megasequence C. Extension azimuth onshore taken from D_3 lineations (Shall and Wilkinson, 1994).

on the geometry of megasequences A and B, then a different tectonic environment is required for the accumulation of megasequences C and D. In south Devon, north-west — southeast - trending structures bear mineralisation associated with basin - derived fluids (Shepherd and Scrivener, 1987) indicating that some displacement occurred during basin formation. This suite of structures (e.g. Portnadler, Portwrinkle, Cawsand and Dutson faults) generally records net dextral strike-slip displacement (Hobson and Sanderson, 1983), although there may be exceptions (Gayer and Cornford, 1992). The sense of movement on these faults during the deposition of megasequences C and D is not clear, but since net dextral movement is prevalent, this is used here in the construction of a local tectonic model (Figure 6b) in which subsidence is localised at the intersection of north-west —

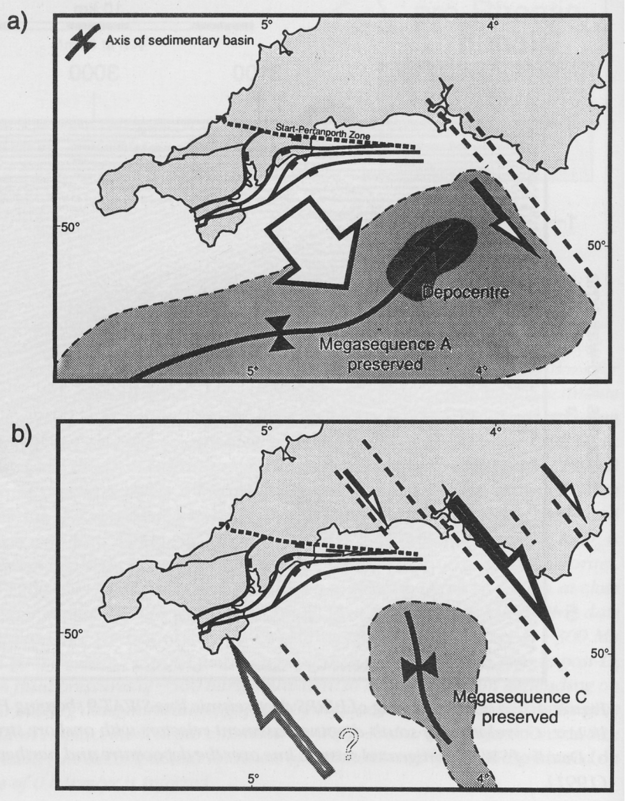

Figure 6. a) Summary of Variscan D_3 extension, suggesting a temporal correlation of late extensional structures onshore with the deposition of megasequence A.

b) Post D_3 kinematics resulting from a dextral shear couple imparted to north-west - south-east - trending faults. Subsidence in the Plymouth Bay is related to the intersection of north-west - south-east strike-slip structures (eg. Cawsand, Portwrinkle Faults) with the east-west - trending thrust system. Based on published models of the San Joaquin and Ridge Basin areas of the San Andreas fault system (Sylvester, 1988; May et al., 1993).

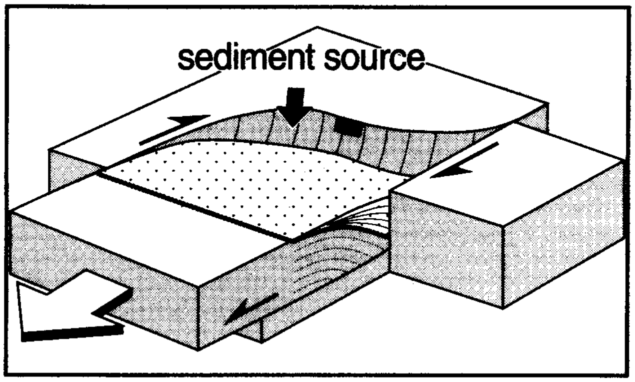

Figure 7. Block model showing the development of the Ridge Basin, USA (after May et al., 1993). Subsidence is greatest at the intersection of two fault trends (San Andreas and San Gabriel Faults).

south-east - trending strike-slip faults and the east-west - trending Variscan thrust system.

The change in tectonic style at the base of megasequence C is inferred to have occurred during the earliest Permian, following correlation with the dated Exeter Volcanics. This may correspond to the marked switch in onshore mineralisation style from east-north-east — west-south-west - oriented polymetallic (granite-hydrothermal) lodes, to Pb-Zn veins formed from basin-derived fluids and controlled by north-north-west — south-south-east -oriented faults. Dates from polymetallic veins of 259-267Ma (Chesley *et a1.,* 1993) would imply a younger age for this change, evidence for overlap of both phases of mineralisation (e.g. Shail and Wilkinson, 1994) suggests that north-west - south-east structures were already active at this time.

The San Andreas Fault Zone in California provides well documented examples of basins formed at intersections of a strike-slip fault system with other faults. One example is the Ridge Basin, situated between the San Andreas fault and the San Gabriel splay (May *et al,* 1993). A block diagram after May *et al.* is presented as an analogue for the post-Variscan growth of the Plymouth Bay Basin (Figure 7). In both of these examples, subsidence beyond the fault intersection occurs because the 3D geometry falls within a class of releasing bend (Christie-Blick and Biddle, 1985), and displacement across the strike-slip system is partitioned to some degree into extensional movement on the intersected faults.

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