STRUCTURES IN JURASSIC ROCKS OF THE WESSEX BASIN, SOUTHERN ENGLAND - I: FIELD EXAMPLE OF DEFORMED CRUSTAL WEDGES

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ABSTRACT Detailed studies of the Purbeck Formation (Jurassic) in the Fossil Forest outcrop, Lulworth Cove (Dorset, southern England) allow to define a ~ 10 m-thick wedge of deformed layers comprising four juxtaposed structural levels (L2-L5) situated between two levels of non deformed layers (L1 and L6). L1 consists of limestone and L6 consists of limestone and intercalated shale / argillite. Within the wedge, the basal structural level (L2) consists of calcareous marls displaying pillow-like structures due to a layer-parallel anastomosed foliation, and evaporite, shale and chert displaying m-scale mushrooms; level L3 consists of evaporite and shale displaying cm- to dm-scale features like normal and thrust faults, folds, foliation and boudins; level L4 consists of evaporite and shale transformed into a tectonic melange; and level L5 consists of evaporite and limestone affected by m-scale folds, contraction and extension faults. Intensive fracturing of the layers around the hinges of the folds transformed L5 in a set of Broken Beds, The wedge deformed progressively, as it slided above a top-down to the west basal detachment along levels L3 and L4, and below a bottom-down to the west detachment established along a layer of calcareous shale (bottom of level L6). The structural analysis, together with other published data, all indicate that an event of extension affected regionally the area, earlier in the Alpine inversion of the Wessex Basin, during which the entire set of rocks tilted to the north and further slip occurred within the Broken Beds. The slide of a detachment-bounded wedge of rocks and the vertical partition of deformation styles and intensity of strain, all place the Fossil Forest outcrop as a key-field locality for direct observation of tectonic processes analogous to those currently recognized for deformation of the continental crust.

Keywords : Wessex (England), Purbeck Formation, structural analysis, crustal deformation, strain partition

RESUMO Levantamento estrutural de detalhe realizado na Formação Purbeck (Jurassico) no afloramento Fossil Forest de Lulworth Cove (Dorset, sul da Inglaterra) permite definir a existência de uma cunha (~10m de espessura) de camadas exibindo diferentes padroes de deformação segundo quatro andares (L2-L5) justapostos na vertical, e situados entre dois andares de camadas nao deformadas (LI e L6). O andar inferior, L1, consiste de carbonates nao deformados e L6 consiste de calcareos e folhelhos / argilitos. No andar L2 da cunha deformada margas calcareniticas exibem estrutura de almofada devida a uma foliação anastomosada sub-horizontal, e sao sotopostas a evaporitos e folhelhos com lentes de *chert,* exibindo dezenas de estruturas na forma de cogumelos de escala me'trica; no andar L3 evaporitos e folhelhos exibem estruturas centimétricas a decimétricas como falhas extensionais e contracionais, dobras, boudins e foliação paralela aos contatos; no andar L4 evaporitos e folhelhos estão envolvidos em melange tectonica; e, no andar L5, camadas de evaporitos e carbonates, com folhelhos e argilitos intercalados, exibem estruturas metricas, como falhas extensionais e contracionais, e dobras associadas a fraturamento ruptil nas charneiras, o que as transforma em Camadas Brechadas. A deformação se deu progressivamente, a medida que cunha movia-se acima de um descolamento extensional ao longo dos andares L3 e L4 (capa deslizando para oeste), e abaixo de um descolamento (lapa deslizando para oeste) formado ao longo de camada de folhelho da base do andar L6. A analise estrutural aqui reportada, conjuntamente com outros dados da literatura, todos indicam que um evento de extensao afetou a area regionalmente, nos estagios iniciais da inversao Alpina que afetou a bacia de Wessex e que resultou ao final no basculamento de toda a Formação Purbeck para norte, incluindo nela a cunha deformada, no interior da qual as Camadas Brechadas foram submetidas a movimentação adicional. O deslizamento da cunha de rochas e a partifao vertical da deformação, tanto em estilo como em intensidade, colocam o afloramento em questao como localidade-tipo para direta observação de processes tectonicos análogos aos que vem sendo reconhecidos correntemente na literatura internacional para deformação da crosta continental.

Palavras-chave : Wessex (Inglaterra), Formação Purbeck, analise estrutural, deformação crustal, partição da deformação

INTRODUCTION The Wessex Basin is a system of Upper Paleozoic to Tertiary (Permian-Paleogene) extensional sedimentary depocentres and intra-basinal highs that developed in post-Variscan terranes across several counties of central southern England, particularly Dorset (Underhill & Paterson 1998). Within this basin, the Upper Jurassic Purbeck Formation, or Purbeck Beds, consists of carbonate and clay marine sediments (West 1975) and forms the general substratum of the surroundings of the village of West Lulworth (Fig. la), together with Upper Jurassic Portland limestones, Alpine
Cretaceous argillites and arenites (Wealden Group), gault, greensands and chalk, as well as Tertiary (Paleogene) sands, gravel and clays, as summarized in House (1993). All these rocks are part of the Purbeck monocline, in fact a sequence of north dipping strata occupying the northern side of a large scale, open to gentle anticline associated to south dipping high-angle thrusts that record the tectonic inversion of normal faults (Fig. Ib). The monocline is part of a series of east-west trending regional folds, that exist nearby the area of Fig. 1 (according to the first geological map in House 1993). The inverted normal faults are original features of the Permian-Paleogene extensional history of the Wessex Basin, during which three conformable but unconformity bound megasequences developed (Underhill & Paterson 1998). The two younger of these unconformities are recorded around West Lulworth (Fig. 1).

According to West (1960), the Purbeck Beds have attracted great geological interest since a long time ago. This author summarized a long list of pioneer studies focused on the remarkable and varied fossil content, on the implications for basin subdivision, and on the limestone breccia (the Broken Beds) that crop out around several localities of southern Dorset (Fig. 2a), where the different lithofacies within the Purbeck Formation and their regional correlation were described in detail by West (1975), who also showed the close spatial relationship between the Broken Beds and the layers of replaced evaporite (Fig. 2a-b). Particular attention has always been paid to the West Lulworth area, for several reasons that include the excellent exposure of the Purbeck rocks along the Fossil Forest cliff (Fig. 1), where the Broken Beds occur above a replaced evaporite layer levels
displaying mushroom structures that have been interpreted as remnants of a Jurassic fossil forest (e.g. West 1975, House 1993).

Afterwards, many geologists have continued to study southern England and have driven efforts to understand the overall structural evolution of the Wessex Basin (e.g. Stoneley 1982), the extensional controls played on its sedimentation (e.g. Chadwick 1986, Ruffel 1992), its thermal and mechanical development (Karner et al. 1987), and on detailed aspects of its subsequent tectonic inversion (e.g. Underhill & Paterson 1998) that took place as a result of compression due to propagation of intraplate stresses in the Upper Tertiary, within the framework of the collision of Europe and Africa, during the

Orogeny (e.g. Anderton et al.. 1979, Lake & Karner 1987, Ziegler 1989). As a whole, these researchers combined subsurface geology and geophysical data, including gravimetry, aeromagnetic, seismic and bore hole data available at each particular time, with the surface geology, including the knowledge on the general geometry of the regional faults and folds obtained by several other authors, such as W.J. Arkell (between 1936 and 1947), M.R. House (since 1960), and M.S. Ameen & J.S. Cosgrove (between 1990 and 1991) - summary in House (1993), and Underhill & Paterson (1998). Adopting a different kind of approach, Ramsay (1992) drove his attention to systematic structural studies of small-scale structures affecting dolostones and intercalated organic shales in a particular outcrop of the Kimmeridge bay (between Worbarrow Tout and St. Alban's Head-Fig. 2a), and the results allowed him to argue for caution on the indiscriminate application of the general theory for propagation of thrust faults to any example seen in the field.

This paper is based on the results of a detailed structural study carried out in Purbeck Beds of the Fossil Forest cliff (Fig. la). The detailed description of the structures allows to characterize a zone of deformation generated by the progressive westwards displacement of a slice of rocks situated between two layer-parallel detachments that display different sense of movement. These results are combined with the vast inventory of data on the lithostratigraphy of the Purbeck Beds across southern Dorset published by West (1960, 1975), in order to show possible implications for the geology of southern England. The slip of a slice leading to a deformed wedge within non deformed Purbeck Beds resulted in several vertically juxtaposed structural

that place that part of southern England as a field type area inside which processes of crustal deformation, as recognized in recent

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literature, can be studied at smaller scales.

THE PURBECK BEDS AND STRUCTURAL LEVELS IN THE FOSSIL FOREST CLIFF The Purbeck Beds crop out in a ~ 400 m-long and ~ 30-35 m-high cliff that is part of the southern slope of the Bindon Hill, to the east of Lulworth Cove (Fig. 1) and terminates against the sea. (Fig. 3a-b). A set of stairs allows access to a natural

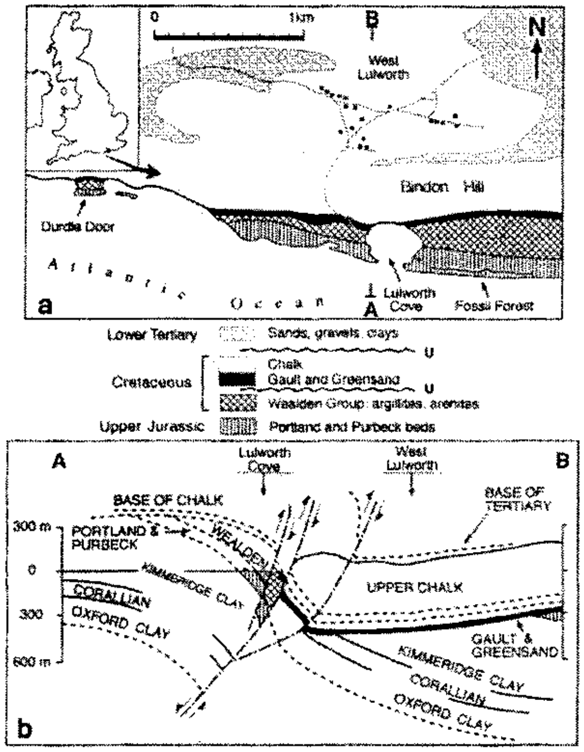


Figure 1 a-b : Simplified geology of the surroundings of West Lulworth, in southern England (inset), highlighting the site of the Fossil Forest outcrop, to the east of Lulworth Cove (a), A simplified cross section across the Lulworth Cove and West Lulworth is shown in (b). Combining data in House (1993) and in Underbill & Paterson (1998).

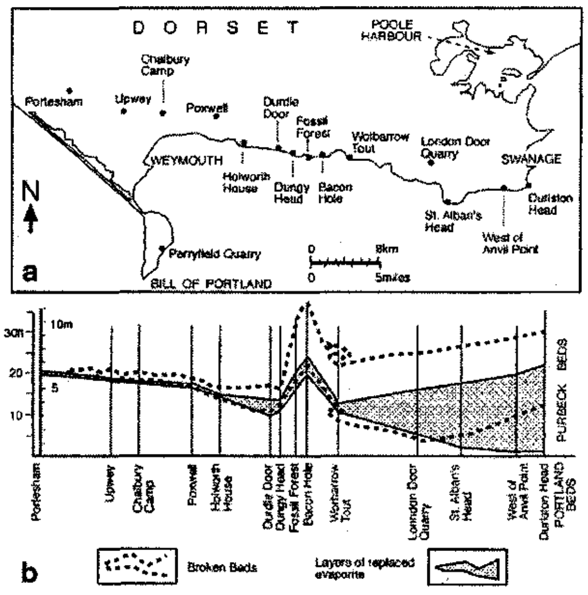


Figure 2 a-b : Distribution of the Broken Beds and evaporite layers in the Purbeck Formation across southern England, adapted from West (1975). (a) - Map of southern Dorset showing various localities where a well-established regional correlation of lithofacies has been demonstrated within the Purbeck Beds, (b) Cross section to show the regional continuity of the Broken Beds and the layers of replaced evaporite, from Upwey to Durlston Head. The lower section of the Broken Beds includes the evaporite layers, and the lower limit of the latter occurs about 1-2 m below the lower limit of the former, in most of the localities.

break in the topography, in other words a few meters wide sub-horizontal step along which one may walk comfortably parallel to the cliff and observe in detail the cm- to m-scale tectonic structures that occur in a ~10 m-thick slice of rocks that form the deformed zone (Fig. 3b-c).

The best accessible part of the cliff, situated between the sub-horizontal step and the highest visible and non deformed layers (arrow in Fig. 3c), is exactly that one enclosing a 20 m-high column of rocks inside which four juxtaposed structural levels (termed L2-L5) can be characterized (Fig. 4), situated above non deformed limestones (level LI), and below non deformed limestones and calcarenites with few and thin intercalated layers of shale (level L6). The structural levels and their contact are physically continuous, allowing careful observation throughout the outcrop. The mesoscopic folds and faults denounced soon after a quick look at the entrance of the outcrop (Fig. 3c) place strong influence on the geologists' mind and are fundamental for deciphering the structural evolution of that piece of crust, but this is only possible after detailed study of many other structures that can be seen everywhere in the outcrop. The structures documented by the photographs were observed along the ca. 300m west-east length of the outcrop, starting at the access stairs.

Structural levels L1 and L2 Structural level L1 consists of a sequence of well-laminated limestone where bedding is defined by the vertical sequence of cm-thick layers. Tabular cross-bedding also can be observed. These rocks dip to the north and form the base of the outcrop above sea level (Fig. 3b). They show only very little or none internal deformation. The I m-thick structural level L2 comprises brown calcareous marls that enclose several tens (hundreds?) of pillow-like structures and are overlain by layers of white evaporite, brown to green calcareous shale and a lens of bluish gray chert (Fig. 4), all deformed around several tens of typical mushrooms.

The pillows occur beside each other and are 3-D structures like true oblate ellipsoids with = 1 m greater axis in ellipses of bedding-parallel sections, as well as a bedding-perpendicular minor axis generally no longer than 10 cm (Fig. 5a). These structures are bound by cm-thick zones where the rock acquires a yellowish brown color and an internal foliation. The mushrooms remain salient as domes or diapirs on the sub-horizontal step of the cliff (Fig. 5b) and commonly display an empty central tube that is 50-60 cm-tall, perpendicularly to bedding, and a sub-circular geometry with diameter around 1 m, in bedding-parallel sections. The structures within level L2 are described in detail in a companion paper.

Structural level L3 This is a ~0.5 m-thick level comprising cm-dm thick layers of evaporite with intercalation of calcareous shale and chert, and presenting abundant evidence of small-scale extension and contraction structures found adjacent in vertically juxtaposed layers or in a single layer, as well as evidence of viscous flow and bedding-parallel foliation (Fig. 6).

Extension structures are ductile (and brittle), cm-dm scale boudinage and domino- and listric-style normal faults trending to the north and dipping to the west, about 60°-45° for the domino faults (as in Fig. 6a) or much less for some listric faults. Contraction structures are cm-dm scale folds of varied style (asymmetric, double hinge) and some associated northerly-striking thrust faults that generally dip = 30°, both verging either to the east or to the west, as those in Figure 6b-c. The folds develop no axial plane foliation and their axes trend to northerly directions, whereas the plunge is commonly shallow, accompanying the dip of the layers. However, sub-recumbent, cm-scale folds locally affect a foliation sub-parallel to bedding within thin evaporite layers.

The extension and contraction structures are seen very close to each other (Fig. 6) affecting respectively layers in vertical juxtaposition (Fig. 6a-b) or affecting adjacent parts of the same layer (Fig. 6c-d). Whatever is the case, these structures do not affect each other and the layers in which they are observed are confined within other layers showing no deformation, at least in the areas nearby. These facts, coupled with the extreme thinning of faulted blocks and erosion of the borders of layers of evaporite (arrows I and 2 in Fig. 6a) with incorporation of mm-cm size fragments in the intercalated layers of calcareous shale (Fig. 6d), plus the lack of axial plane foliation in the folds, and finally the sub-recumbent folds affecting a foliation sub-parallel to bedding (Fig. 6e) altogether make a definitive evidence for a contemporaneous origin under a progressive deformation, as a

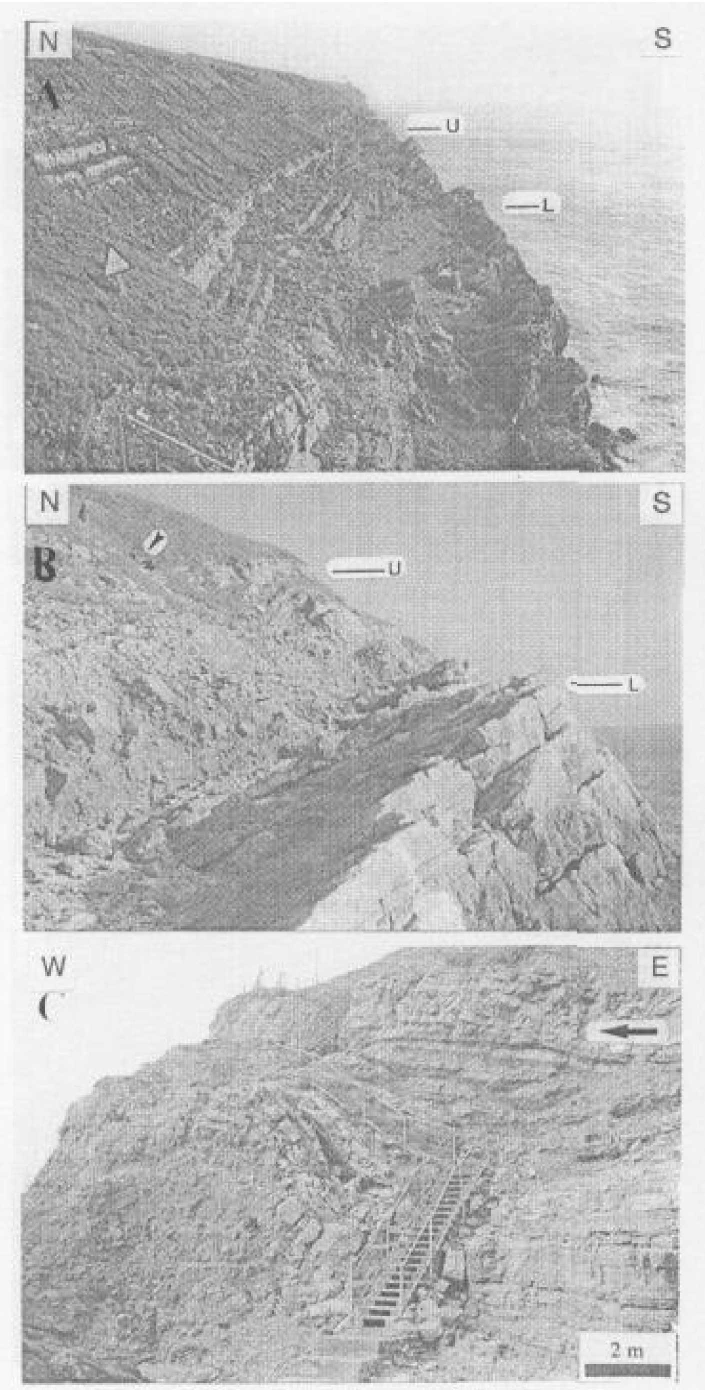


Figure 3 a-c : Overview of the Fossil Forest outcrop looking to the east from its entrance (a). The whole outcrop is nearly 400 m-long and about 30-35 in-high above sea-level (to the right). The upper and lower limits (U and L) of the deformation zone are indicated. A more detailed view of this zone (b) shows the packet of layers dipping to the north, having the Broken Beds in between. The arrow points to two people coming down the slope. The deformation zone also includes meter-scale folds and contraction faults, as those seen around the stairs to access the outcrop (c), right below undisturbed layers of limestone and intervening shale (arrow).

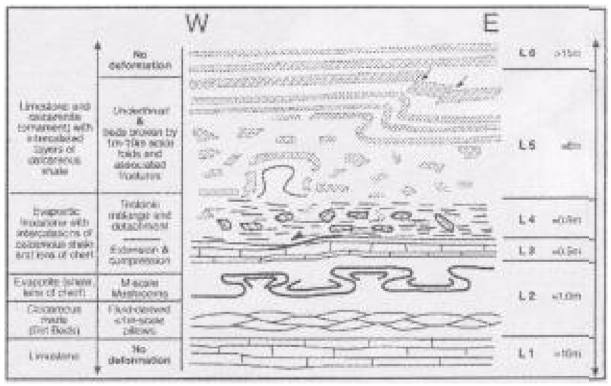


Figure 4 *: Out-of-scale diagram to summarize the main features of each of the six structural levels in the Fossil Forest outcrop - LI to L6 shown in the column to the right. The columns to the left shows the vertical succession of Purbeck rock types in the outcrop and the typical features for each level, respectively.*

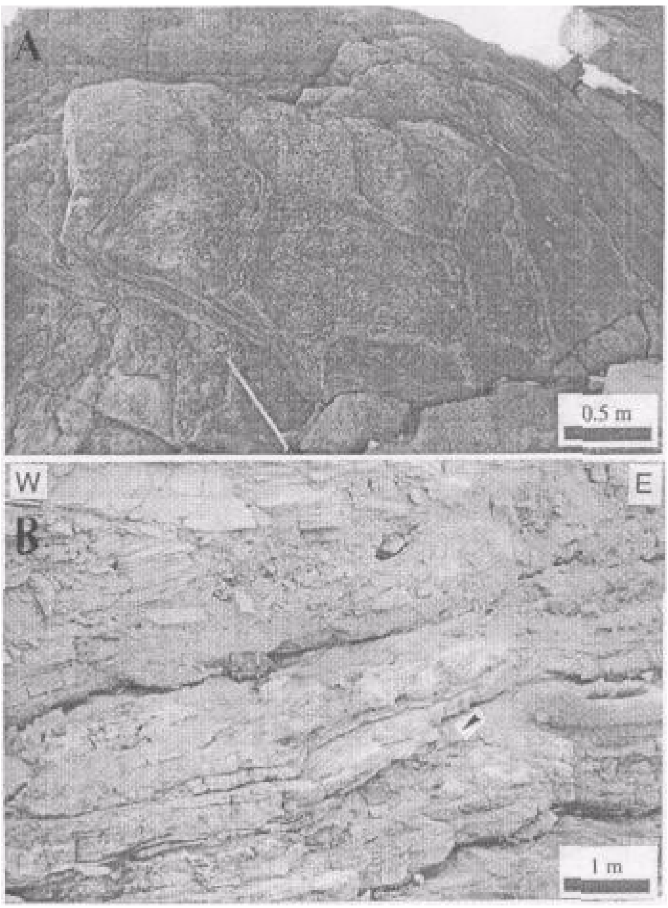
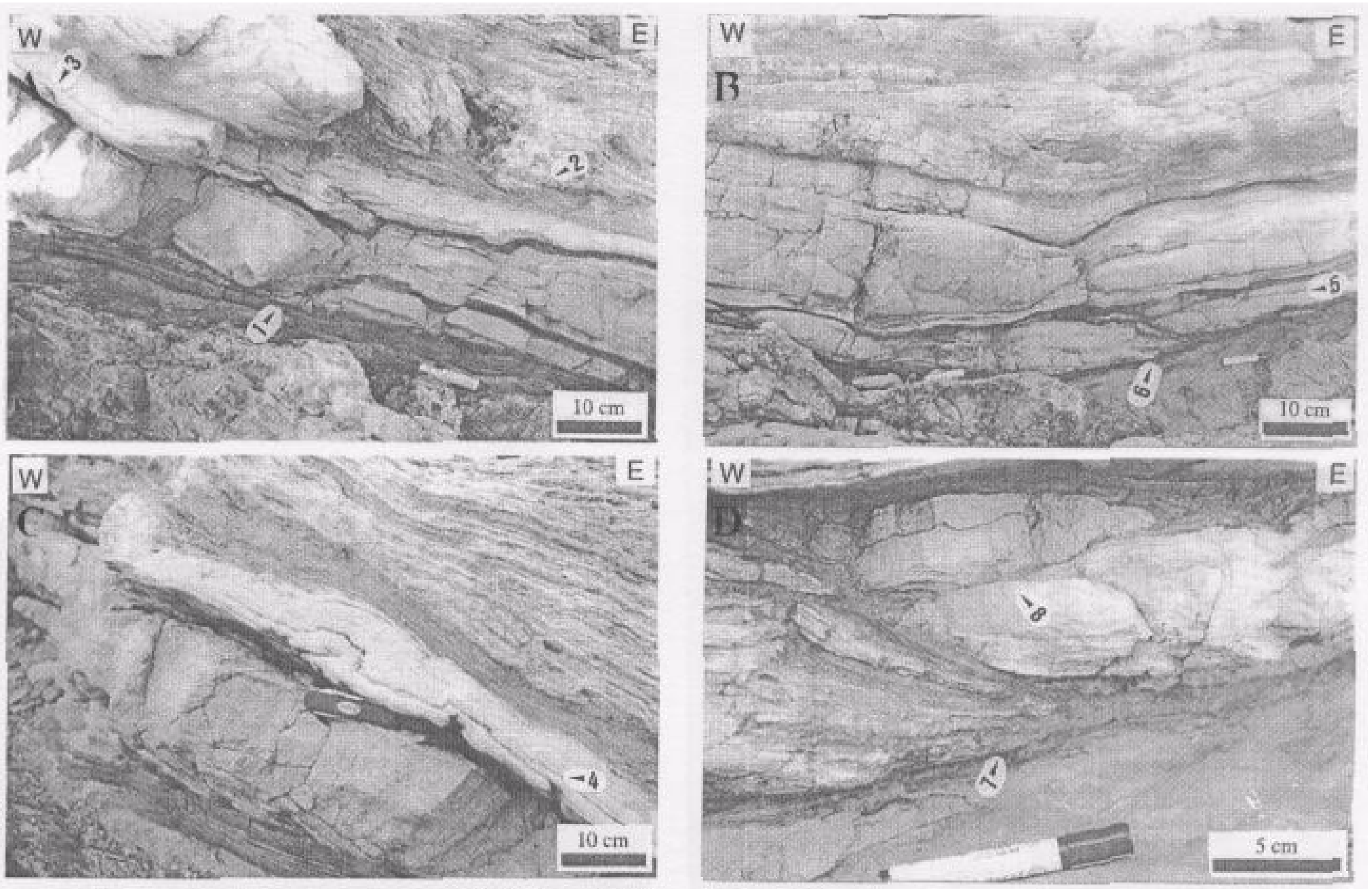


Figure 5 a-b *: The meter-scale pillow-like features that occur at the base of structural level L2 (a) affect only the ~ 30 cm-thick layer of brown carbonate marls that underlay the evaporite layers enclosing the mushrooms and overlies the non deformed limestone of L1. (b) View of the typical features of levels L3-L5 right above the levels of the I m-scale mushrooms (one is seen to the right). The arrow points to a lens of chert that is commonly associated to the mushrooms. The continuous layers of evaporitic limestone above the arrow contain cm-din scale extension and contraction structures typical of level L3. Upwards, these rocks are progressively involved in the tectonic melange (LA) - the level where the bag lies (center). The Broken Beds of level L5 are right above. Note the continuity of the structural levels.*

consequence of differential ductile How of the matter leading to intra- and inter-layer slip and shearing. In addition, the extension structures point always to ductile flow driven to westerly directions.

Structural level L4 This ~0.8 m-thick level is a typical tectonic melange consisting of abundant din-size fragments of cvaporite layers and some remnants of these layers, all immersed in a matrix consisting of shale with cm-mm scale fragments of evaporite (Fig. 7a).

The evaporite layers at the bottom of this level experienced a more intense erosion of the borders than that observed in the layers of level L3, because of a stronger ductile flow that resulted in remnants of the layers separated from each other (bottom of Fig. 7a). The intensification of the flow led to a top-down to the west extension that is clearly evidenced by a west-trending and shallowly plunging striae lineation observed on the surface of evaporite layers (Fig. 7 b-c), as well as by the clockwise rotation of rock fragments and the bedding-



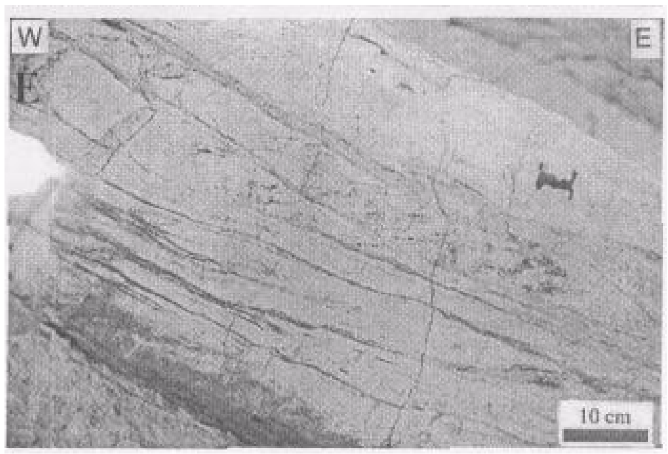


Figure 6 a-d : Extension and contraction structures due to viscous flow in level L3. (a) The 10 cm-scale domino-style normal faults affect two evaporite layers (above the white pen) and also the thin intercalated layer of brown calcareous shale. The normal faults merge in a basal detachment right above two other layers of extremely well-laminated and non deformed calcareous shale that overly grayish-blue chert. The lower la\er affected by the faults almost disappears because of intense thinning due to viscous flow (arrow I). More intense flow in the calcareous shale led to erosion of the evaporite layers along their contacts (arrow 2). The continuous layer of evaporite (arrow 3) is not affected by the normal faults, (b) Instead, it exhibits cm-scale folds and thrusts (arrow 4) the same structures of arrow 3 in (a). Note the erosion of the nun-thick evaporite layer, right above arrow 4 and along all the contact, (c) Boudinage and ductile thinning (center) coeval to thrust and folds in a single layer: arrow 5 shows a layer that has been extremely thinned to the west (around the red knife), and arrow 6 shows the area detailed in the next picture, (d) Arrow 7 shows the same point as arrow 6: note that fragments of the layer are still preserved, making evident the process of erosion by ductile flow. Arrow 8 points to a place of the same layer shown by arrow 5 in (a). Note that the din-scale E-verging folds and thrust are adjacent to the thinned area of the same layer (in the upper left corner) (e) Isoclinal folds affecting a bedding-parallel foliation in layer of evaporite.

parallel banding locally developed within the matrix (Fig. 7d). This kinematics is entirely compatible with the normal faults observed within level L3 (Fig. 6a-b) and also with a system of northerly trending, west-dipping listric normal faults that displace shale and evaporite layers for about one meter, and cross-cut the long limb of folds in basal layers of level L5 (Fig. 8a-b).

Structural level L5 This is a ~8 m-thick structural level where some layers of evaporite (at the lower part) and limestone / calcarenite (at the upper part) are preserved within a thick and typical limestone breccia containing an impressive amount of = 1 m-size fragments of layers disposed chaotically in a matrix of shale / argillite - the Broken Beds of West (1960, 1975).

The layers that are still continuous are affected by 1-10 m-scale folds that resulted in intense fracturing around the fold hinges and contributed substantially for the breccia to form (e.g. Fig. 8b-c). The folds are generally asymmetric and may be directly associated to contraction faults (Fig. 8d). Their axial planes commonly trend to northerly directions and dip as much as 40-60° either to the west or to the east, and their axes plunge at shallow angles, almost always to northerly directions. A major contraction fault affects the limestone layers at the upper part of the larger syncline in the outcrop, the one seen at the entrance of the outcrop (Fig. 3c). The fault (Fig. 9a) consists of a sharp truncation of the limestone beds along a north trending plane that dips ~30°-40° to the east and was generated by the movement of the footwall to the west under the fault plane (undcrsthrust). Thie is demonstrated by the fact that the hangingwall underlies the bottom of structural level L6, where the non deformed layers are at their original position (thick arrow in Fig. 3c), therefore it could not have been pushed up and to the east, as in a conventional upthrust. The fault also implies that a detachment was established above the footwall and stretching to the east along the layer of dark brown shale that occurs at the bottom of level L6. Other folds and normal faults (listric and planar) are observable in part of the layers situated right above the main syncline and below the contraction fault: east-verging asymmetric folds and listric normal faults affect the same layer below the area marked by cross (Fig. 9b-c), whereas a layer-parallel fracture and an east-dipping planar normal fault affect layers of limestone and shale to the east of the cross (Fig. 9d).

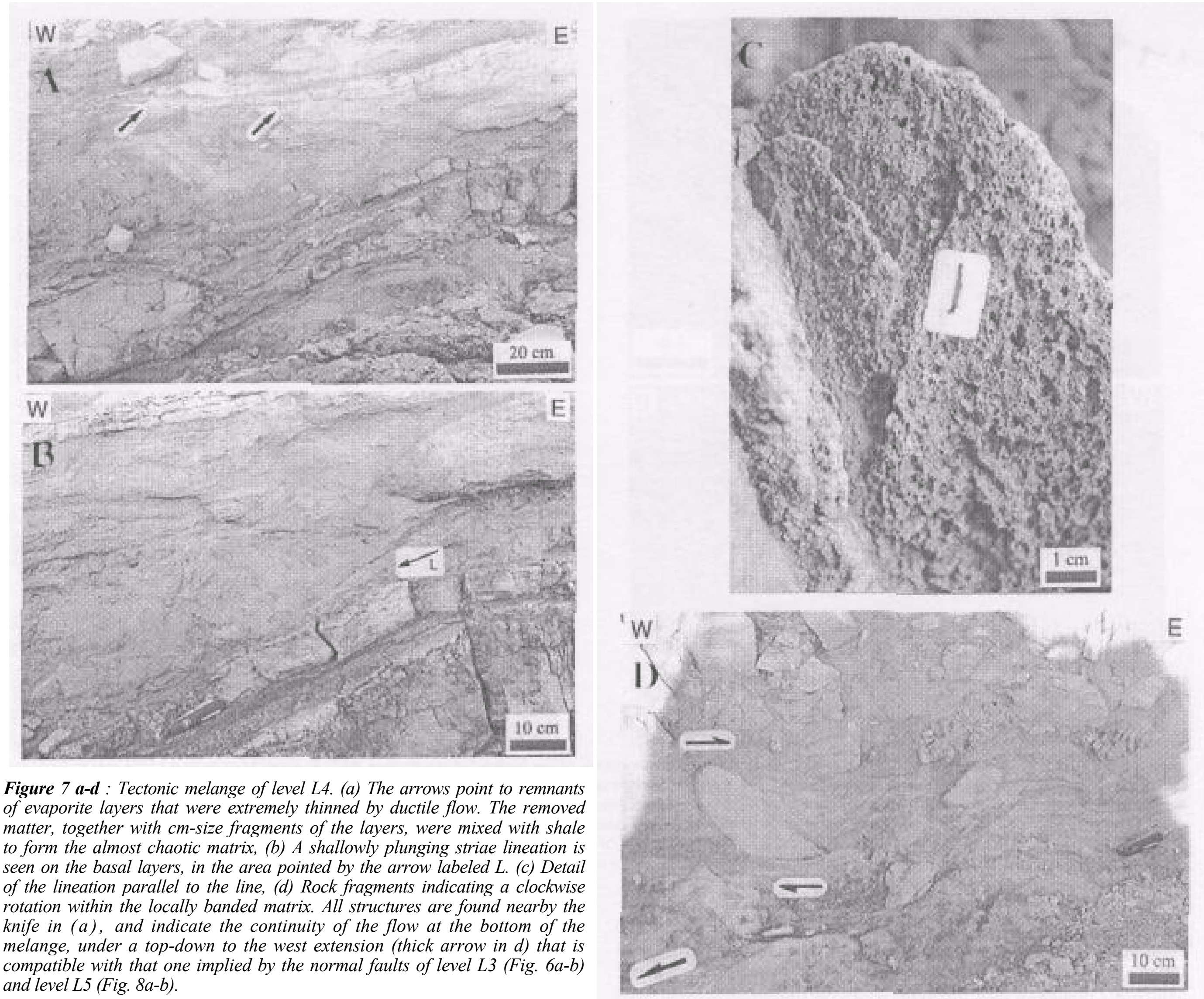


Figure 7 a-d : *Tectonic melange of level L4. (a) The arrows point to remnants of evaporite layers that were extremely thinned by ductile flow. The removed matter, together with cm-size fragments of the layers, were mixed with shale to form the almost chaotic matrix, (b) A shallowly plunging striae lineation is seen on the basal layers, in the area pointed by the arrow labeled L. (c) Detail of the lineation parallel to the line, (d) Rock fragments indicating a clockwise rotation within the locally banded matrix. All structures are found nearby the knife in (a), and indicate the continuity of the flow at the bottom of the melange, under a top-down to the west extension (thick arrow in d) that is compatible with that one implied by the normal faults of level L3 (Fig. 6a-b) and level L5 (Fig. 8a-b).*

Structural level L6 Structural level L6 consists of a sequence of non deformed and well-laminated limestone, where bedding is defined by the juxtaposition of dm-thick layers forming a more massive set at the center of the column, with intercalation of brown shale layers that are ~20 cm-thick at the bottom of the level and much thinner at the top (Fig. 9a). The limestone layer at the bottom of this level lies above the lubricant shale that allowed displacement of the rocks below.

A WEDGE OF HIGHLY DEFORMED ROCKS WITHIN THE PURBECK BEDS As well as in structural level L3, contraction and extension structures observed within level L5 (see *1 to *5 in Fig. 10) do not cut across each other, although they respectively affect close areas of layers in vertical juxtaposition, or affect adjacent parts of a single layer. Again, these structures may be all interpreted as contemporaneous and generated when a wedge of rocks moved to the west in order to form the anticline-syncline pair of folds at the entrance of the outcrop (* 1). The small folds and listric normal faults seen at the bottom of level 5 (*2) are in fact in continuity of the lower layers affected by the major anticline-syncline pair of folds (*1). This constitute the single cross-cut relationship in the whole outcrop, but still fit in the same evolution.

The slip of a ~10 m-thick wedge of Purbeck Beds to the west, above a basal extensional detachment, was established as a consequence of the intense westwards viscous flow within the evaporite layers (level L3). Such slip explains the melange of level L4 and requires another detachment somewhere above, as it was actually established along the layer of shale at the interface between levels L5 and L6. The larger anticline-syncline pair (*1 in Fig. 10) developed because the basal layers of level L5 moved to the west and below to themselves (underthrust), whereas the other contraction and extension structures observed in the area above the syncline (*5) are required to form simultaneously in order to accommodate this kind of down-sucking of the matter to the west. The listric normal faults cutting the limb of the larger folds (*2) indicate further movement, top-down to the west, along the basal detachment, and record an extension required for balancing shortening. The existence of both east- and west- verging folds and thrusts may be attributed to intra- and inter-layers differential flow, either in the case of level L3, or in the layers of limestone and of calcareous shale / argillite, in the case of level L5 (see areas marked by *2, *3 and *4, Fig. 10). The fact that the axes of the folds in levels L3 and L5 generally mimic the dip of the layers does not mean a control on the plunge by the dip of the beds, as is discussed together with the origin of the Broken Beds - next section. The relationship between the structural level L2 with the basal detachment, and the role of this detachment on the origin of the mushrooms and pillows (Fig. 4) are treated in a companion paper.

DISCUSSION Origin of the Broken Beds House (1993) refers to four different possible origins for the Lulworth Broken Beds: (1) - Penecontemporaneous structures caused by collapse of overlying beds, following either solution of evaporites or decay of vegetation; (2) - Penecontemporaneous brecciation resulting from contemporary faulting associated with a pre-Mid-Createceous growth fault along the axis of the foresyncline of the Purbeck fold; (3) - Brecciation resulting from tectonic accommodation of the rather incompetent Purbeck Beds in relation to the more competent Portland beds and Chalk during the main Mid-Tertiary folding; and (4) - Tectonic evaporation breccias in which tectonically fragmented blocks and early calcitised evaporites set in an evaporite matrix were later calcitised - referring to West (1975).

On the basis of the structures reported in detail in here, the Broken Beds are clearly tectonic structures due to fracturing associated to

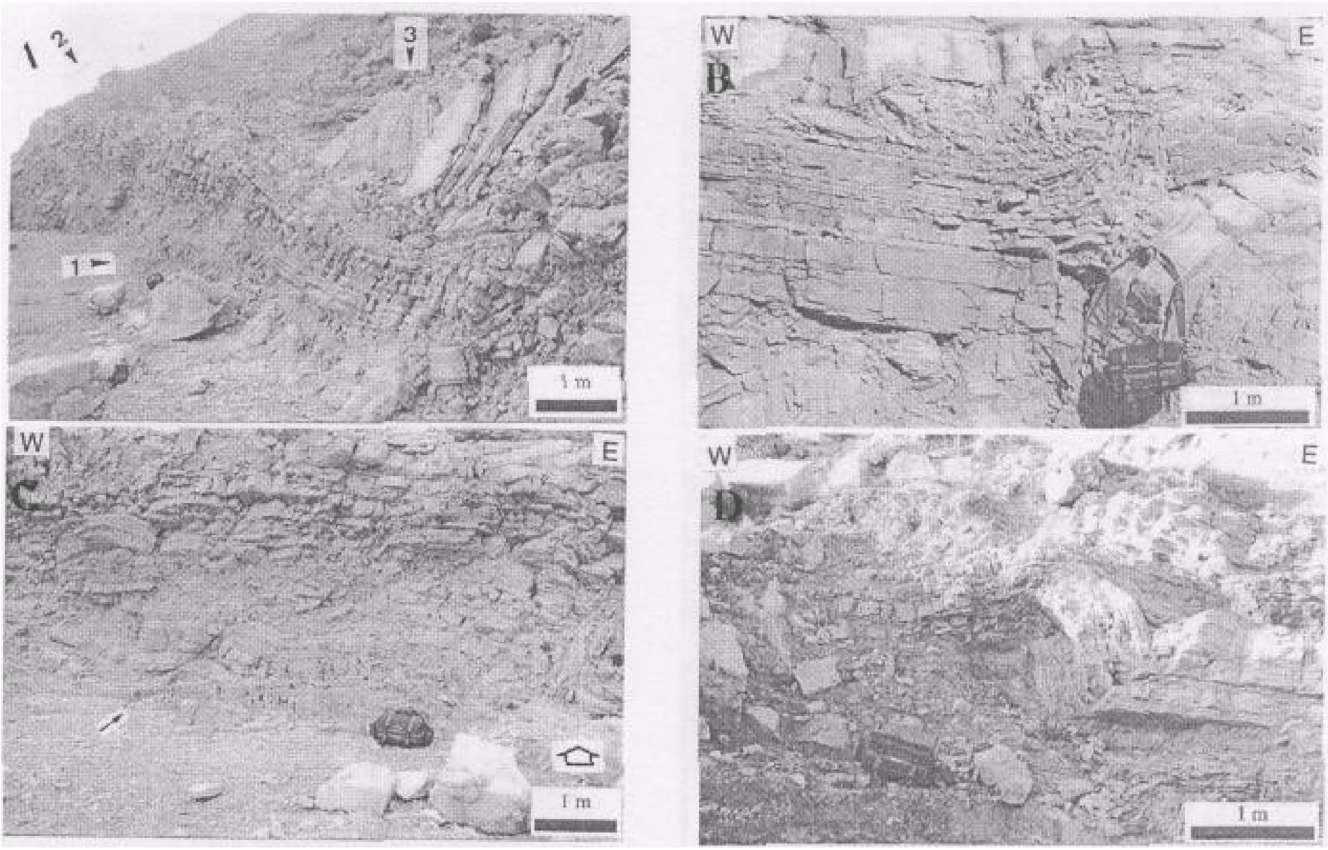


***Figure** 8 **a-d** : Structures within level L5. (a) A looking-to-lhe-west photograph of the bottom of the Broken Beds to show (arrow 1) a place where folds and listric normal faults affect the evaporite layers. See detail in the next picture and, for reference, note the blue bag and the white blocks nearby. For location (arrow 2) points to the entrance of the outcrop just 40 in away, at the background. Arrow 3 points to south-dipping layers witli remnants of a fold hinge (top of the layers). Scale is far the foreground, (b) E-verging anticline-syncline pair of asymmetric folds (large arrow to the right) with the long limb cross-cut by extensional listric faults (small arrow) compatible with a top-down to the west extensional detachment along the interface L3 /L4. Rock fragments munding about the hinge zone of the folds (lower right corner of the picture) are also a common feature in other parts of the outcrop, where the folds vergence is either to the west (c) or to the east (d).*

inter-layer slip and folding of evaporite and limestone layers, under conditions of more brittle deformation than those observed in the thinner evaporite layers of structural level L3. The original layers of evaporite / limestone now incorporated in the limestone breccia must have experienced fracturing in order to accommodate flow within intercalated layers of calcareous shale / argillites (the main content of the matrix), during displacement of the wedge earlier in breccia-forming process. However, this kind of differential behavior no longer can be directly observed in most of level L5, although it is very well recorded at many places of levels L3 and L4 (some examples are in Figs. 6a-b-c, 7a). Nevertheless, it may be deduced to have taken place in level L5 by considering the occurrence of folded layers of limestone intercalated to layers of the authentic breccia - Figure 8c is just one example. Such intercalation of layers displaying different deformation pattern cannot be explained by layer-parallel compression acting across the entire height of level L5. Just in contrary, it requires that inter-layer slip took place within ~ lm-thick layered sequences (limestone and beds of shale / argillite, let's say sequence **A**) that gave origin to the breccia, as well as within = Im-thick sequences of layers of limestone with much less or none intercalation of shale / argillite (let's say sequence **B**) that enclose the folds and fractures (Fig. 8c). Starting the process, a faster How within less competent shale / argillite layers drove the intercalated limestone layers (within sequence A) into initial brittle fracturing. Differential slip between sequences **A** and **B** drove the limestone layers with no significant intercalation of shale / argillite (sequence **B**) into shortening by development of an initial buckle of small amplitude / wavelength ratio. Further slip within sequence **A** led to formation of a matrix of shale / argillite and to a complete disorganization of the rock fragments - the breccia - whereas the limestone layers of sequence **B** underwent additional shortening that led to the folds and fractures around the fold hinges (Fig. 8c).

The structures described in this paper also indicate that, overall, the evaporite / limestone layers within level L5 responded more rigidly to deformation than those in level L3 and L2. The initial flow within the layers of level L3 increased even more the conditions for a ductile flow in the layers closer to the detachment (L3 / L4), whereas the layers of level L5 remained almost as cold as before the wedge started to move, not only due to the greater distance, but also due to their loss of physical cohesion (fracturing and breccia formation). As discussed in a companion paper, loss of cohesion may have been a key factor for heat to propagate downwards into level L2, rather than upwards into level L5, in order to dissipate further heat generated by the progressive displacement of the wedge.

West (1975) quotes an additional explanation provided by S.E. Hollingworth, in 1938, for slip to start: anhydrite and gypsum that were probably present underwent chemical transformation, so that hydration of anhydrite formed gypsum which underwent subsequent solution. Therefore a preliminary plane of weakness allowed the tectonic forces to act along certain evaporite layers. Actually, West (1975) reports that these minerals have been found in equivalent beds elsewhere in southern England, whereas himself (West 1960) described celestine (another sulphate mineral), in calcitised evaporite beds of Durlston Head (the far east in Fig. 2a).

Timing for wedge deformation and tilting of Purbeck Beds The displacement and deformation of the wedge should have preceded in time the formation of the Purbeck monocline, because the orientation of the small-scale structures in the wedge - west trending lineation, northerly trending fold axes, and fault planes dipping to easterly and westerly directions - is in flagrant contrast with that expected if deformation of the wedge was due to slide of relatively incompetent layers to the north, as a consequence of the tilting of the Purbeck Beds. The tectonic inversion resulted in regional folds whose axes trend east-west and associated thrust faults, the majority dipping either to the south or to the north (Fig. 1b).

Furthermore, as the Fossil Forest outcrop is just at the middle of a 35-40 km-long regional section (Fig. 2) along which West (1975) demonstrated the continuity of the Broken Beds and the evaporite layers and highlighted their close association, the lower limit of the evaporites being situated almost always above the lower limit of the

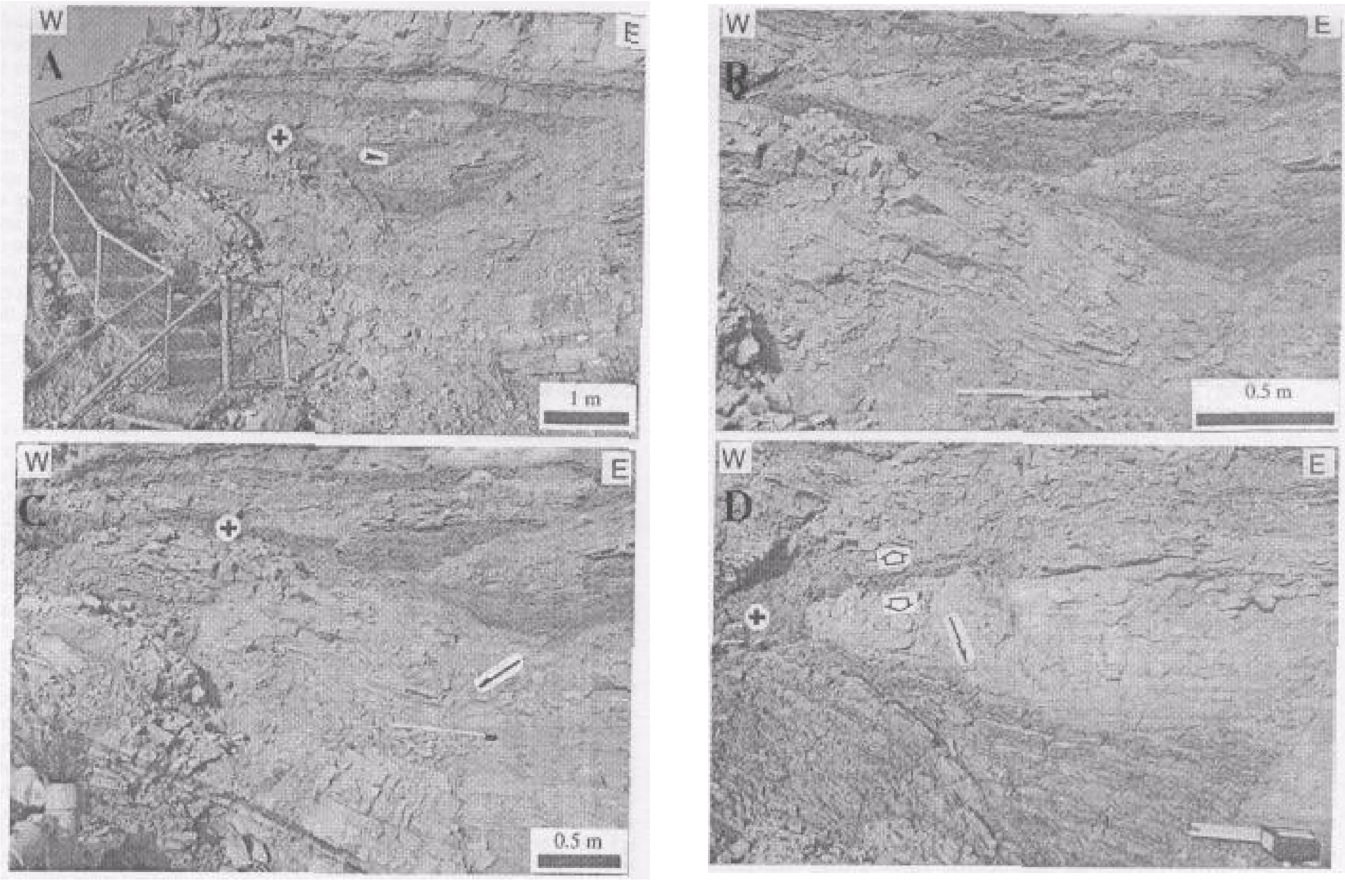


Figure 9 a-d : Undenhrust and associated structures in the Broken Beds, (a) Photograph of the entrance of the outcrop (the stairs allow localization in Fig 3c) highlighting the contraction.fault due to underthrust of the layers to the west (arrow). The cross is a reference for location of the next pictures (b) Photograph of the central part of (a) to show in more detail east-verging folds and also a west-dipping normal fault (parallel and to the right of the arrow) both affecting the same limestone layer (the one below the area marked by the cross), (c) A more detailed view of(b) to show the normal fault that displaces the limestone layers (right above the scale bar). The.fault surface is concave upward and merges into bedding, almost along the metre-lomg tape, (d) More detail of pictures in (a) and (b): a layer-parallel.fracture indicates that a sub-vertical opening (large arrows) propagated progressively from the west and was filled by the shale The thin arrow is parallel and lies to the right of the trace of an east-dipping, high-angle normal fault. This is part of a conjugate pair of faults that join in the shale at the lower central part of the picture. The trace of the west-dipping conjugate fault is also shown, but the displacement of the layers is barely seen For scale the yellow tape at the right corner of the picture is 10 cm-long.

Broken Beds, it is quite reasonable to think that: (**1**) - A deformed wedge may also exist across that area, and keeps characteristics similar to the one described in this paper; and (**2**) - If so, the evaporite detachment is part of a tectonic event of regional extent within the Wessex Basin.

Although the absolute age for evolution of the deformed wedge remains unknown, in a study of the Broken Beds in a cliff nearby Durlston Head (Fig. 2), West (1960) deduced a tectonic origin associated to substantial faulting and folding due to small tectonic stresses acting along the evaporite layers, and argued that this process took place slightly earlier in the ultimate event that tilted the Purbeck Beds to the north. West (1960) also described northward thickening of the Broken Beds, and north-dipping normal faults that cut the breccia, as evidence for further sliding to the north, during or slightly after tilting of the Purbeck Beds. This possibility is also strongly suggested at the Fossil Forest by layers of evaporite that locally dip steeply to the south and are enclosed within beds that dip to the north, as in the rest of the outcrop (Fig. 8a). That geometry suggests that the south dipping layers are part of the northern overturned limb of an asymmetric, m-scale and north-verging anticline, the hinge of which is barely preserved (Fig. 8a, arrow 3) and stretches east-west for about 6-8 meters. The south dipping layers are also fractured around the suggested fold hinge, indicating that the small slip to the north also contributed for further chaos within the Broken Beds.

A field example of crustal deformation The six structural levels described in this paper place the Fossil Forest outcrop as a smaller scale type area displaying key ingredients recognized in the most up-to-date literature for crustal deformation, such as: 1) Vertical partition of strain among layers of different stratigraphic levels; 2) A wedge of rocks moving and get deformed within basal and roof detachments with different sense of kinematics, implying in a kind of crustal excision; and 3) Different patterns of strain are a consequence of inter- and intra-layer slip at different rates, within the wedge. Furthermore, the outcrop highlights the role of inter- and intra-layer slip on the development of contemporaneous extension and

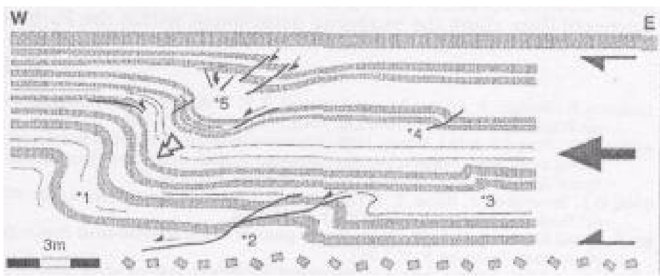


Figure 10 *: Schematic W-E vertical section (the scale is approximated) to show the main structures within structural level L5, including those in the upper part of the larger anticline-syncline pair at the entrance of the outcrop. For simplicity, the Broken Beds are not represented. Locality marked by *I stands for Fig. 3c; *2 for Fig. 8b; *3 for Fig. 8c; *4 for Fig. 8d; and locality marked by *5 stands for Fig. 9a-d. The thickest black arrow indicates the displacement of the ~1O m-thick wedge of sediments above a top-down to the west e.\tensional detachment along which the melange of L4 developed (bottom). As a consequence of this displacement, an upper detachment developed along a layer of shale (the bottom of level L6) and the basal layers moved to the west underneath themselves, giving rise to the major synciine-anticline pair (* 1) by underthrust. Thus, the layers around the area marked by *5 were sucked down and entered into the bay formed by the major syncline (white arrow), leading to the contraction and extension structures observed in the surroundings of*5.*

contraction structures, found very close to each other, in a single layer or respectively affecting superposed layers. Actually, on the base of seismic reflection data and theoretical computation it has been shown (Reston 1987, Yin 1989, Blundell et al. 1989, Blundell 1990) that the ductile-brittle deformation of the upper crust is a consequence of sub-horizontal ductile flow within the lower crust. Since then, geological theory has increasingly recognized partition in the deformation according to juxtaposed structural levels that display different styles of structures and heterogeneous strain, and the importance of differential slip for tectonics and erogenic processes (e.g. Carreras & Capella 1994, Odea & Lister 1995, Axen et al. 1998).

In fact, slices of the intermediary-lower crust may move sub-horizontally towards a zone of subduction, during continental collision, leading to crustal shortening at upper levels and raising mountain belts by overall underthrusting, such as initially proposed for the European Alps (Hsu 1989), and now recognized by Epard & Escher (1996) and Escher & Beaumont (1997). Sub-horizontal flow leads to crustal wedges bound by lower and upper detachments displaying sense of relative movement different from each other (as in Fig. 10) and may also lead to a concentration 'of matter in a certain depth, helping the ascent of deep crustal material that forms the core of metamorphic complexes (Block & Royden 1990). Such wedges are in fact required to exist because km-scale sections of crust have been excised to allow crustal attenuation associated to rapid uplift of deeper materials even from the upper mantle (e.g. Argles et al. 1999). Furthermore, as the metamorphic complex ascents in the crust, the progressive ductile deformation within its core leads to folding of the sub-horizontal high-T fabrics, with axis parallel to the stretching lineation, and keeping pace with brittle deformation of the rocks that make the colder cover of the core complex, according to normal faults that indicate crustal stretching in the same direction (Fletcher & Bartley 1994). Similarly, but at much higher levels and in a different tectonic setting, detailed structural studies of generally flat-lying Neoproterozoic (meta)sediments that cover continental areas adjacent to Pan-African / Brasiliano collision belts, in central and northeastern Brazil, have allowed D'el-Rey Silva & Pereira (1995) to demonstrate a systematic partition of strain among vertically juxtaposed less and more competent layers, so that ductile flow within fine-grained siliciclastics (basically meta argillites) develops contraction structures indicative of slip towards the root of the adjacent belts, whereas the overlying and more competent layers (metasiltstones, metasandstones) record normal faults indicative of extension in a direction parallel to the flow in the layers of finer material.

If the wedge moving between two detachments at West Lulworth is just the record of an event of more regional extent, as suggest the Broken Beds-evaporite spatial relationship across a larger area (Fig. 2), then a question naturally arises: why an east-west earlier flow along the basal detachment, if the inversion of the Wessex Basin resulted in north-south compression soon after?. The answer may be simple: the westward flow along the evaporite detachment within the Purbeck Beds may well be just the upper expression of similar movements along intra-crustal detachments that Ziegler (1989) predicted to have existed at deeper parts of the crust, for Cenozoic tectonic inversion to take place. If so, the vertical juxtaposition of strain that Gomez et al.(1998) described for the Atlas mountains of Morocco may have taken place during the tectonic inversion of the Wessex Basin: these two areas are situated respectively to the south and to the north of the same zone of convergent collision between Europe and Africa, and both their tectonics relate to Cenozoic transpression, according to Gomez et al. (1998) for the Atlas, and to Lake & Karner (1987) and Ziegler (1989) for southern England. Then, the orthogonal partition of strain is plausible, because an east-west ductile flow along any deeper crustal detachment may have easily induced parallel movement along the very weak evaporite layers situated above, slightly before the continuity of the flow at the deeper level could propagate north-south stress across the entire crust above, leading to contraction and uplift of sedimentary basins and their basement.

CONCLUSIONS The Forest Fossil cliff, at Lulworth Cove, southern England, may be considered a type area for understanding processes of crustal deformation, as it displays: (1) A ~ 10 m-thick wedge of higly deformed rocks comprising four vertically juxtaposed structural levels (L2-L5) situated above undeformed limestone (LI) and below undeformed limestone with minor shale / argillite intercalations (L6), all within the north-dipping Purbeck Beds; (2) The structural levels record different deformation patterns and heterogeneous strain. Strain partitioning results from sub-horizontal movement of the wedge along a weaker, top-down to the west detachment established on evaporites, and below another one established on shales, leading to a kind of crustal excision; (3) The detachments display different sense of movement, and are required for decoupling the wedge from levels LI and L6; and (4) - Deformation is controlled by differential flow at varied gradients, due to inter- and intra-layer slip capable to develop contemporaneous extension and contraction structures that are found very close to each other, in a single layer or respectively affecting superposed layers. Structural level L5 encloses a remarkable evaporite / limestone breccia formed by inter-layer flow and associated folding with intense fracturing around the hinges. As the breccia occurs in close spatial relationship with evaporite layers, across a 35-40 km segment of the coast of southern England, these events may be part of east-west flow and wedge decoupling above a regional detachment, possibly earlier in the Alpine tectonic inversion of the Wessex Basin, that lately resulted in north-south compression and uplift of basin and its basement. The east-west and north-south movements may be part of a vertical partition of strain during the transpression-related inversion of the basin and intra-crustal detachments that are required at deeper levels.

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