Forced folds and fractures: An introduction

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Buckle folds and forced folds

A considerable body of work exists in the geological literature dealing with the formation of buckle folds, (i.e. folds formed by compression either parallel or at a low angle to the layering or fabric of the rock) and a summary of much of this is presented in Price & Cosgrove 1990. In addition, fractures associated with these folds have been reported and discussed extensively for many decades, (e.g. Stearns 1964). This in part reflects the fact that the formation of folds and their associated fracture patterns frequently plays an important role in controlling the migration and concentration of fluids within the crust and thus has important implications regarding the disposition of water, hydrocarbons and zones of mineralization.

However, there are many mechanisms other than buckling operating in the crust which can give rise to folds. One of the most important is that of 'forced folding' defined by Stearns (1978) as 'folding in which the final overall shape and trend [of the fold] are dominated by the shape of some forcing member below' and these folds and their associated fracture patterns have received relatively little attention in the literature. The present volume is an attempt to redress this imbalance.

Unlike buckle folds, which are only generated during layer parallel compression, forced folds can be formed in any tectonic environment and are equally common in extensional and compressional regimes. The dominant mechanism operation during forced folding is 'bending', defined as the flexuring of a layer or surface by a compression acting at a high angle to the layering. The two mechanisms of folding mentioned above, i.e. buckling and bending, can be considered as two end members of a complete spectrum. Many folds generated in nature, for example the folds formed in the cover sequence as a result of thrusting in the basement, will involve significant components of compression both parallel to and normal to the layering.

Like buckle folds forced folds can control fluid flow and host economically interesting fluid and mineral accumulations and it is therefore important to understand how they form and the pattern and timing of their associated fractures.

Clearly, in order to predict the role that fractures have in controlling fluid movement within and around folds of any type it is important to understand the timing of their formation. Although the intimate relationship between the geometry of folds and their associated fracture patterns strongly suggests that the same stress fields generated both structures, there is considerable uncertainty regarding the timing of fracture formation. Some fractures, for example those filled with vein material, probably formed at the same time as folding. Others however, may have formed much later during the exhumation of the rock, as a result of a decrease in confining pressure and the release of the residual stress locked into the rock at the time of folding.

This volume

The first paper (**Cosgrove & Ameen**) is written as an introduction to the volume and deals with the definitions of and the similarities and differences between buckle folds and forced folds. It focuses specifically on the three dimensional geometry, the spatial organization and the fracture patterns that characterize the two types of folds. The aim of this brief study is to establish the criteria that can be used to differentiate between buckle and forced folds and to determine if these features can be used in regions of poor exposure or in areas where it is necessary to rely on seismic data, to indicate the type of folding that has occurred. The study draws on field observations, analogue models and the consideration of conceptual models of folds. The formation of forced folds in three tectonic regimes is considered. These are the regimes of compressional tectonics (where thrusts or early normal faults reactivated as reverse faults, cause folding of the overlying strata), extensional tectonics (where normal fault movement is responsible for folding) and strike-slip tectonics.

The association of fractures and folding is examined and a comparison made between fracture patterns associated with buckle folds and those linked to forced folding in both extensional

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and compressional environments. In addition the larger-scale fractures that form in the cover rocks above normal and reverse dip-slip faults are described and the effect that various amounts of strike-slip motion on these faults would have on the resulting fracture pattern discussed.

The remaining 14 papers are grouped into four sections entitled 'Numerical analysis & field study of fractures associated with compactional forced folds', 'Forced folding in extensional environments', 'Forced folding in compressional & strike-slip environments', and 'Temporal & spatial relationships between forced folds and buckle folds, crustal-scale folds & fold/fracture relationships.' The first section contains three papers. The first two describe the use of numerical analyses to investigate the formation of fractures in forced folds, one a monocline in the Navajo formation in Utah and the other a compaction fold formed in Upper Cretaceous coal seams deformed during diagenesis by differential compaction around relatively competent sand lenses. The third paper describes large-scale compaction folding in the Tertiary rocks of the North Sea and shows how the associated fracturing has initiated the development of large, sandstone dykes.

The second section contains four papers the first two of which consider the formation of forced folds as a result of normal faulting associated with the formation of the Rhine graben and Maritime Basin of Nova Scotia respectively. The third paper looks at forced folding around a resurgent caldera in Ischia, Italy and the forth examines relatively small-scale folding associated with normal faulting in the Gulf of Mexico.

The third section contains four papers related to forced folding in compressional and strike-slip regimes. The first paper describes an experimental study, the remaining three field studies in compressive and strike-slip tectonic environments.

The final section contains three papers. The first considers the temporal and spatial relationships between forced folds and buckle folds using the Zagros Mountains as an illustration. The second paper deals with the formation of crustal-scale folds in the Bohemian massive of the Czech Republic and the final paper presents a method of determining areas of maximum strain on a folded surface and argues that these regions are likely to be the most highly fractured.

Section 1

The first paper in this group is by **Cooke *et al.*** who combine numerical modelling and field work in order to understand the distribution of fractures in the East Kaibab monocline in Utah, a forced fold in the dune bedded sandstones of the Navajo formation. Two types of joint clusters were documented. One which occurred in the hinge region of the forced fold and which is parallel to the hinge and at right angles to the bedding and the other which occurs on the steep limb of the monocline which is parallel to the hinge but oblique to the bedding. Based on these field observations and numerical modelling the authors conclude that the fold parallel and bedding perpendicular joint clusters form by curvature related stresses within the outer arc of the fold and the fold parallel but bedding oblique fractures formed as a result of interbed slip. The fold curvature and therefore the related joint clusters, relate directly to the shape and amount of displacement of the forcing member which generated the fold and the bedding plane slip and the related joint clusters, relate to the intrinsic mechanical properties (the mechanical anisotropy) of the folded unit. The authors clearly demonstrate that the fracture pattern within a forced fold is not controlled solely by the forcing member but is also sensitive to the material properties of the folded unit.

The second paper (**Laubach *et al.***) also combines detailed field observations with numerical modelling in an attempt to account for the distribution of fractures and the variation of fracture type around a forced fold. These folds, which occur in the Upper Cretaceous Mesaverde Group in SW Wyoming, are compaction folds formed in coal seams during burial and diagenesis. The folds form as a result of differential compaction of the coals and the interbedded sand lenses. Like many coals, these coal seams typically contain sub-vertical, open mode fractures (cleat). However, closely spaced normal faults abruptly substitute for open mode fractures in coal beneath some sandstone lenses that have blunt terminations. Finite element modelling of coal deformation shows that shear stress is augmented in coal layers below abruptly tapering edges of sandstone lenses favouring fault development, whereas under gradually tapering lenses shear stresses are not sufficiently enhanced to cause a shift in fracture style. The authors point out that the normal faults formed in the coal have little or no porosity and that the coal that contains them is likely to have low permeability compared to coal having typical, generally porous, open mode fractures. Thus the local change in fracture style may affect both regional and local gas and water flow within the coal.

The third paper in this group (**Cosgrove & Hillier**) also describes the formation of compactional folds during diagenesis. These folds occur in the Eocene of the Outer Moray Firth in the North Sea as a result of differential compaction of mudstones over similar aged sand-rich, deep-marine channel/fan complexes. The study of cores shows that there has been considerable remobilization and redistribution of the sand both within the sand units and out into the surrounding mudstones as small sand dykes. However, in addition to these relatively small injections it is clear from the seismic sections through the structure that sand remobilization has taken place on a larger scale than previously thought. Large dykes almost half a kilometre long and up to eight metres wide emanate from the periphery of the sand lenses and cross-cut the overlying mudsones at an angle of about 60. The authors argue that the positioning of these large-scale dykes was controlled by the stress regime within the flexed overburden which resulted in outer arc fracturing adjacent to the overpressured sand body. These fractures provide ideal sites for sand injection and the proposed process is analogous to that operating during the formation of the peripheral dykes observed at the margin of many igneous intrusions, specifically laccoliths (Pollard & Johnson 1973).

Section 2

The second group of papers all relate to the formation of forced folds in extensional settings, i.e. in association with normal faults. The first paper by **Maurin & Niviere** discusses extensional forced folding associated with the formation of the Rhine Graben. In this example there is an intimate relationship between movement on the basement fault that generated the forced folding and the deposition of some of the cover rocks in which the forced folds occur. The cover sediments lie on the Variscan basement and comprises a pre-rift sequence of Triassic and Jurassic rocks which contains an important Upper Liasic gypsiferous marl. A major unconformity separates these rocks from the overlying Palaeogene syn-rift sequence. Seismic sections show that the main basement graben-bounding fault to the west is a straight fault dipping 60° to the east. However, within the cover rocks the normal fault links with the sub-horizontal decollement horizon represented by the gypsiférous marls and the resulting geometry is listric. Continued extension on the fault generated a classic roll-over fold in the sediments above the decollement and a typical forced fold in those below. The response of the various sedimentary units to extension was controlled by their rheology. The brittle carbonates of the Dogger extended by the formation of numerous small-scale normal faults whereas the ductile sediments of the Priabonian deformed in a completely ductile manner.

The formation of a forced fold in cover rocks above a basement normal fault requires considerable thinning of the resulting monoclinal limb. However, some forced folds formed in extensional settings show no such thinning and in order for such folds to occur it is a geometric requirement that decoupling occurs between the basement and the cover. In the second paper in this group, **Keller & Lynch** describe an example of extensional forced folding from the Maritimes Basin of Nova Scotia, Eastern Canada, where seismic images and field work indicate that no significant thinning of the limb has occurred. The authors are able to demonstrate that a major detachment horizon has developed in a Visean evaporite sequence near the base of the cover rocks. A variety of kinematic indicators are developed along this horizon including a stretching lineation, a principal schistosity plane and secondary shear planes and intrafolial to upright asymmetric folds. The authors are able to demonstrate that the regionally extensive weak evaporitic layer was remarkably effective in transferring displacement between the normal fault and the décollement horizon in the cover sequence and that the mechanical decoupling of the strata above the detachment can be shown in the Horst block 70 km away from the basement fault.

In the third paper in this group relating to extensional forced folding, **Tibaldi & Vezzoli** describe late Quaternary monoclinal folding associated with caldera resurgence on the island of Ischia, Italy. The present level of erosion is such as to enable the various elements of the peripheral monocline (the gently inclined and subvertical limb) to be seen as well as the resurgent block and the peripheral normal faults that define it. They note that the forced folding occurred with the aid of at least one main detachment horizon localized within the pyroclastic succession and argue that the piston-like uplift of a fault bounded block with the generation of forced folds in the overlying volcanoclastic sediments is a viable alternative model of caldera resurgence to that of the classical doming model which is characterized by no peripheral faults, a rounded dome shape in plan view, beds continuous across the dome and the formation of a longitudinal apical graben.

The final paper in this section on forced folding in extensional regimes relates to small-scale folding associated with normal growth faults formed as a result of the Mississippi delta tectonics in the Gulf of Mexico. Using high-resolution 3D seismic images, **Mansfield & Cartwright** mapped numerous examples of low amplitude stratal folds in both the footwalls and hangingwalls of these faults. The folds do not generally have the geometry of classical drag folds and the authors explore the possibility that these deflections might occur in regions of fault overlap or linkage. Although their origin remains unclear, they are recognized as a fundamental characteristic of all large growth faults in this part of the Gulf of Mexico.

Section 3

The third section of this volume is related to forced folding associated with compressional and strike-slip regimes. In compressional forced folding the strata above the basement faults undergo some layer parallel shortening during the formation of the forced fold and there is therefore the possibility that the resulting structure will have elements of both forced folding and buckling. Indeed there is a complete spectrum between these two end member folds and most natural examples involve both processes. In the first paper in this section **Couples & Lewis** use rock and rock analogue models to investigate the influence of interlayer slip on the geometry and strain distribution within a forced fold. A variety of 'overburdens' were selected ranging from a simple homogeneous, isotropic single layer to well laminated multilayers and their response to identical basement block movements was recorded. It was observed that in the experiments where interlayer slip was possible the resulting forced fold was more localized than in the experiments with an unlayered overburden. In addition as the number of layers was increased so the fold became progressively more localized. However, as the number of layers increased a point was reached when not all the potential slip planes were activated during folding. The authors comment on this selective amplification of layer parallel slip and plan to investigate the phenomenon in a later publication.

Although the results of these proposed studies are not yet available and **Couples & Lewis** decline to comment on the reason for the activation of some rather than all potential slip planes during folding, it is clear to the present author that the system is one in which two competing mechanisms are operating. If a finely laminated layer is considered there are two possible end member behaviours the layer could adopt during folding. The first is to ignore the layering and to fold as a homogeneous, isotropic layer. This would maximize the bending stresses and minimize the frictional resistance to interlayer slip. The resulting strain distribution would be that of a tangential longitudinal strain fold (Ramsay 1967). The second type of behaviour is for all the potential slip surfaces to be activated during folding. This would maximize the resistance to folding resulting from the frictional resistance to slip between the laminations but would minimize the resistance resulting from bending stresses. The resulting strain distribution would be that of a flexural flow fold (Ramsay 1967). In practice neither of these two end members occurs and some compromize between the two develops. It is to be expected that more and more layer interfaces will slip as the fold develops in an attempt to reduce the build up of bending stresses. At each stage in the evolution of the fold a balance between the two processes will be achieved where the sum of the bending resistance and resistance to interlayer-slip is a minimum. The relative contribution of the two processes to folding at each stage in fold development will be determined by the mechanical properties of the interface (i.e. the coefficient of sliding friction or some related parameter) and the material properties of the layer (in an elastic model the Young's modulus).

In the second paper in this section **Wicks *et al.*** examine the jointing in the Lower Cretaceous Fall River Formation, a unit cropping out in South Dakota and Wyoming, and explore the relationship between these fractures and a number of forced folds which occur in the area. These folds are associated with the Larimide compression which was active during the Palaeocene and which reactivated an easterly dipping master thrust in the upper crust. The resulting uplift produced numerous monoclines and anticlines. The authors are able to demonstrate convincingly that the joint sets they examined are in no way related to the regional Larimide compressive stress or the local extensional effects associated with the resulting forced folds. They conclude on the basis of fracture type, orientation and regional distribution that the jointing predated the forced folding and probably formed in the late Early Cretaceous.

In the third paper in this section **Teper** describes the effect of basement faulting on cover rocks when the faulting is predominantly strike-slip. The area studied is the NE margin of the Upper Silesian Coal Basin in southern Poland. Here, Carboniferous molasse was deposited on a pre-Devonian crystalline basement block defined by first-order crustal boundary zones and subdivided into smaller segments by deep seated second order fractures. Many of these faults where reactivated as strike-slip faults during the Variscan compression. Experimental work and field observations (Oliver 1987; Richard 1990; 1991, Richard *et al.* 1991) have demonstrated that pure strike-slip motion on basement faults only produces buckle folds in the cover sequence and that these folds form in en echelon arrays above the faults. Their spatial organization provides an excellent kinematic indicator which declares the sense of motion on the underlying basement fault and the author was able to exploit such folds arrays in the cover rock to determine the first-order movements on the faults during the Variscan deformation. However, because of the effects of releasing and constraining bends along the basement faults, elements of vertical movement occurred along the fault which resulted in the associated cover structures being a combination of both buckle and forced folds. The author shows that the profile geometry of many of the folds in the study area are incompatible with them being pure buckles and points out that pure strike-slip tectonics is just one example in the transtensional–transpressional continuum of tectonic environments (Hartland 1971). Thus, in all environments other than that of pure strike-slip along a perfectly planar fault, varying amounts of vertical motion are to be expected along the faults during their formation and reactivation. He argues therefore that folds with elements of both buckles and forced folds are likely to occur in the cover rocks above a basement fault even when a region is dominated by strike-slip tectonics. This interplay between basement strike-slip faulting, buckle folding and forced folding is further discussed by **Cosgrove & Ameen** in this volume.

The fourth paper in this section tackles the difficult problem of differentiating between buckle and forced folds currently initiating and amplifying in a cover affected by compression. The region studied includes the Yakima fold belt which is made up of a series of asymmetric, E–W trending anticlines separated by broader, open synclines and which formed and are forming in the thick, otherwise horizontal sequence of the Columbia River Basalts Washington State. The authors (**Watkinson & Hooper**) note that the folds have been growing progressively over the last 17 Ma in response to the regional N–S compression. The study reveals that some of the pre-basalt flow structures in the underlying 'basement', specifically those that lie in an E–W or NW–SE direction, have been reactivated and that as a result a variety of styles of deformation have developed in the basalts including faulting, block uplift and flexure.

Despite detailed structural field work which enabled the fold style to be quantified and the fracture and strain distribution around the folds to be determined, the authors did not find the style of fold deformation sufficiently characteristic or distinct enough to be able to distinguish between basement controlled forced folds and buckle folds.

The final paper in this section by **Sattazadeh *et al.*** considers the possible temporal and spatial relationships between faults, forced folds and buckle folds in a particular tectonic setting. The setting chosen is the Zagros fold/thrust belt situated at the junction of the Saudi Arabian and Central Iranian plate. In the Zagros region the rheological profile of the cover sequence is dominated by the thick basal Hormuz salt, which allows the decoupling of the deformation in the basement and cover, and a second evaporite-rich horizon at the base of the Miocene. The authors conclude that the type of folding is controlled primarily by the rheological profile of the cover, the reactivation of basement faults (wrench faults and the reverse dip-slip reactivation of normal faults) and the generation of new faults (thrusts) in the cover rocks.

Dip-slip reactivation of basement normal faults forms forced folds in the overlying Hormuz salt series. The resulting displacements of the more competent units above the salt results in the initiation of important thrusts in the cover. The growth of these thrusts generates large-scale fault-bend folds. Hybrid folds involving elements of both forced folds and buckle folds form above many of the major strike-slip basement fault zones including the Kazarun and Minab lineaments. These are transpressional faults along which considerable horizontal and vertical displacements have occurred. The resulting folds in the cover overlying the Minab fault zone have the en echelon spatial organization of buckle folds formed above a strike-slip basement fault and the characteristic large aspect ratio (hinge length/half wavelength ratio) geometry of forced folds formed over a linear basement scarps. Clearly, these various types of folds, i.e. forced, hybrid and pure buckle folds, can be produced synchronously at different sites along a convergent plate boundary.

Section 4

The final section of the volume contains two papers. The first by **Stípská *et al.*** considers the formation of the extremely large-scale folds formed in the mid and upper crust and now exposed along the eastern margin of the

Bohemian massif in the Czech Republic. The authors conclude on the basis of detailed field study and petrological work that the large-scale folds are the result of a complex process which began with the eastward obduction of thrust slices onto the eastern (Brunovistulian) continent and the associated westward underthrusting of the continental margin at a transpressional margin. The authors use PT data in combination with thermal modelling to estimate the rheological evolution of this thrust stack during exhumation and show that when the stack had risen to a depth of about 15 km it encountered an autochthonous granite which acted as a relatively rigid block which inhibited further thrusting. The nappe pile, which represented a mechanical multilayer, continued to deform by folding. By considering the relative rheologies of the different nappe units and their thicknesses the authors conclude that despite the large wavelength (approximately 40 km), folding was by the process of buckling rather than bending.

The final paper by **Lisle & Robinson** focuses specifically on the relationship between folding and fracturing. They propose that the geometries and densities of fractures associated with fold structures can be predicted by assuming that the strains accommodated by fractures mimic the bulk strain induced in the strata during folding. The authors examine, from a theoretical standpoint, the distribution of bedding plane strain expected in folds formed by the various fold mechanisms. The relationship between the state of bedding plane strain (which it is argued will be directly related to fracture density) and fold surface geometry is found to vary according to different fold types, which can be distinguished from each other on the basis of their curvature properties.

The first type are *developable* fold surfaces and these have a Gausian curvature equal to zero. Fold mechanisms which are dominated by the mechanical strength of the layering, such as buckling, produce fold surfaces of this type and it is possible to estimate the bedding plane strains of such folds directly from the geometrical features of the folded layer. The authors illustrate this using flexural slip and neutral surface folds.

The other main class of folds has *non-developable* surfaces, which have non-zero Gaussian curvature. Folded surfaces with this form arise predominantly from mechanisms which involve the passive deflection of the layering in response to displacement gradients originating outside the layer, e.g. forced folds. Although the geometry of these surfaces implies the presence of bedding plane strain, in contrast to the buckle folds discussed above, this strain cannot be quantified from the geometry alone and requires additional information of the displacement patterns.

The papers presented in this volume have one principal aim in common; namely to examine the major similarities and differences between forced folds and buckle folds in order that these differences can be used to recognize the type of folds (and therefore the expected fracture pattern) that are present in regions of poor exposure or where the geologist has to rely on seismic images. It is hoped that a clearer understanding of the differences between the two fold types (their 3D geometry, spatial organization, fracture patterns etc.) and the realization that they represent the two end members of a complete range of fold types will provide a useful predictive tool for Earth scientists concerned with the detailed geometry of fold structures and with assessing their possible role in controlling fluid migration and concentration within the crust.

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