J. Univ. Kuwait (Sci.) 7, 1980

Incipient metamorphic fabrics in the Carboniferous rocks of the South Wales Coalfield

F. I. KHALAF

Kuwait Institute for Scientific Research, Kuwait

ABSTRACT

Detailed petrographic studies on carbonate and terrigenous rocks of Carboniferous age in the South Wales Coalfield have revealed the modification of their fabrics in the western, incipiently metamorphosed part of the coalfield (the anthracite area). Aggrading and degrading recrystallisation and lattice deformation are the main effects of incipient metamorphism in carbonate rocks. In terrigenous rocks, reaction of the matrix with framework grains, deformation of argillaceous rock fragments, and development of deformed fibrous quartz veinlets are the main fabric modifications. These incipient metamorphic fabrics are controlled to some extent by the lithology of the different carbonate and terrigenous rock types. There is a significant relation between fabric modification of the rocks studied and the variation of the fixed carbon ratio of the associated coal seams. The development of the incipient metamorphic fabrics increases progressively towards the western and northwestern parts of the coalfield (the anthracite area). Modification of fabric is first observed in some carbonate rocks in areas where coal seams have more than 80% fixed carbon and reaches its maximum development, in both carbonate and terrigenous rocks, in northwestern areas where the fixed carbon ratio is 92·5%.

INTRODUCTION

REGIONAL SETTING

The South Wales Coalfield (Great Britain) is an oval-shaped region with a total area of about 750 sq. miles (Fig. 1). All the rocks recorded in the coalfield are Carboniferous in age and divided into three main series, the Carboniferous Limestone Series (Lower Carboniferous), the Millstone Grit, and the Coal Measures Series (Upper Carboniferous). The Carboniferous Limestone Series consists mainly of carbonate rocks with some terrigenous rocks, whilst the whole sequence of the Millstone Grit and the Coal Measures Series is composed of terrigenous rocks.

The South Wales Coalfield is a major synclinal depression containing a number of flexures, and several major faults cross the basin cutting through the structures. The majority of these structures have resulted from the Variscan orogeny which took place during late Carboniferous and Permian times. The main faults trend east-northeast and are commonly associated with the compression belts of the western region of the coalfield. Three main fault zones of this trend have affected the coalfield, namely

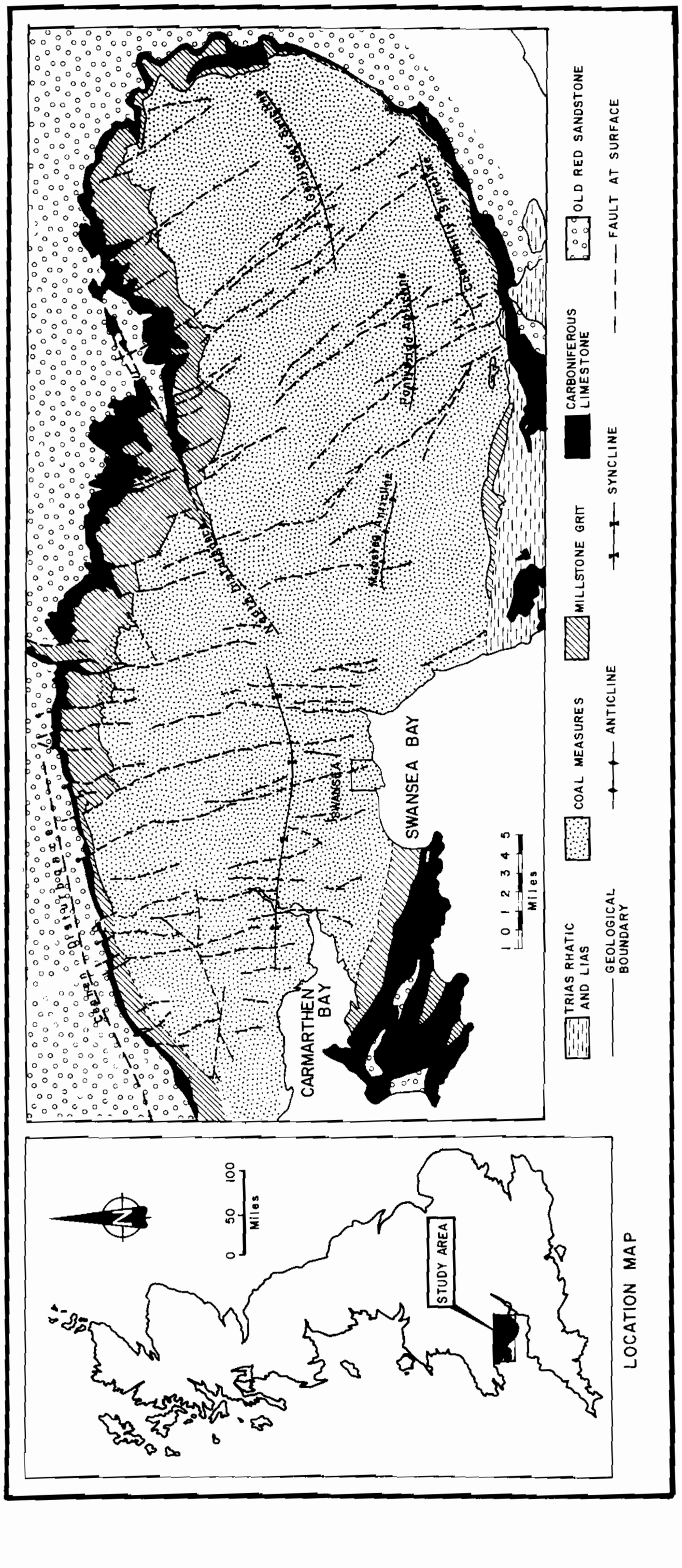

Fig. 1. Geological map of the South Wales Coalfield.

Neath, Tawe and Cennen disturbance (Fig. 1). Most of the faults along the Neath and Tawe belts appear to be major wrench faults of sinistral displacement, while those along the Cennen belt are of more complex history with appreciable thrusting. The trend of these belts suggests that they are inherited from Caledonian fractures in the precarboniferous rocks (Owen 1971).

The majority of the South Wales coals range from medium volatile (bituminous) coals to anthracites, with the exception of a few high volatile coals confined to the southern and eastern margins of the coalfield. One of the main characteristics of these coals is the regional or lateral variation of their rank from east to west (Fig. 2). Three main coal types are recognised in the coalfield: bituminous coals in the southern and eastern regions, low volatile steam coal at the northern and middle parts of the central region, and the anthracites in the northwestern region (Adams 1967; George 1970). The reason for this variation in coal rank and the origin of the anthracites has been a subject of study over the past 60 years and several theories have been proposed to explain the phenomena (Strahan & Pollard 1915; Fuchs 1946; Trotter 1948; Davies & Bloxam 1974).

Since these investigations have only partly documented the problem without giving a satisfactory explanation, a series of studies was carried out on the diagenetic changes and degree of metamorphism of the Carboniferous rocks of the coalfield in an attempt to determine the thermal history of this basin, and consequently to explain the above mentioned regional variations (Khalaf 1974; Gill *et al.* 1977).

THE CONCEPT OF INCIPIENT METAMORPHISM

One of the most problematic subjects facing both sedimentary and metamorphic petrologists is the definition of the transitional stage between diagenesis and regional metamorphism of sediments. This stage has been studied mostly in the terrigenous rocks by many petroleum geologists and clay mineralogists. Most of these studies were aimed at an understanding of the alteration stages of the organic matter, particularly the processes of coalification and generation, maturation and destruction of hydrocarbons. These processes are clearly related to post-diagenetic conditions and to the temperatures and pressures that have affected the host rocks.

The alteration of clay minerals (Burst 1959) and organic matter (Staplin 1969) has been shown to be a sensitive indicator of the transition zone between diagenesis and metamorphism in terrigenous rocks and to a lesser extent in carbonates. Dunoyer de Segonzac (1970) has reviewed the structural and chemical variation of clay minerals during diagenesis and low grade metamorphism. He used certain characteristics of illite for the definition of the intermediate stage between deep diagenesis and metamorphism. He used the term *anchizone* for this stage. Weaver (1960) and Kubler (1964) first defined this intermediate stage and used the term *anchimetamorphic* zone. Landes (1967) has termed this stage *eometamorphism*. Kossovskaya and Shutov (1970) summarized some of the Russian work on the alteration of terrigenous rocks during deep burial. Logvinenko (1957) has used the terms *epigenesis* and *metagenesis* and Koplan (1971) used the term *catagenesis* for this intermediate stage.

Khalaf (1974) in his study on the Carboniferous rocks of the South Wales Coalfield has used the term incipient metamorphism to indicate a very early stage of metamorphism where regional changes of fabric and mineralogy of the rock are not obvious. He used illite sharpness ratio, vitrinite reflectivity percentage and the degree

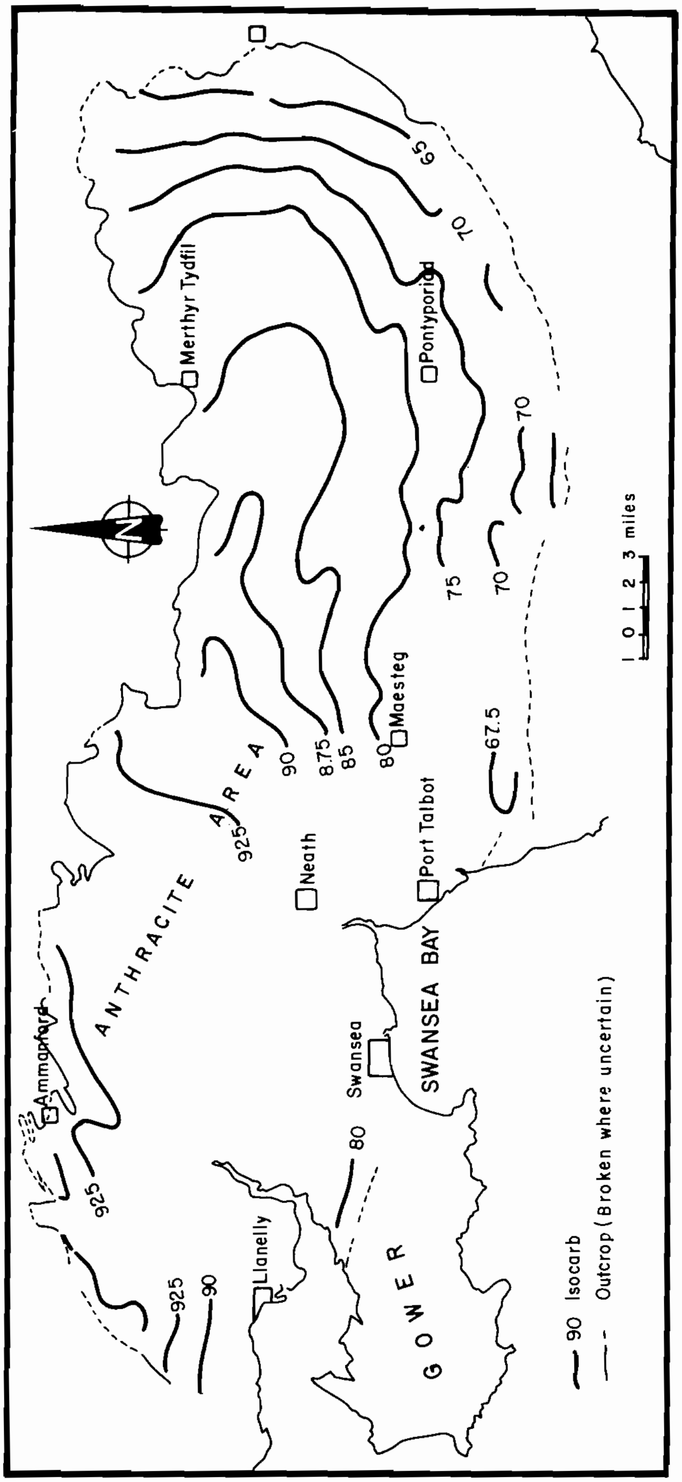

Fig. 2. Isocarb map of the South Wales Coalfield (after Mohafez 1966), based on 9 ft seam, dry and ash-free.

of carbonisation of spores and pollen grains as indicators for this zone. Using these indicators, Khalaf (1974) was able to identify three stages of incipient metamorphism in the rocks of the South Wales Coalfield, namely zone (I) early stage of incipient metamorphism, zone (II) middle stage of incipient metamorphism and zone (III) late stage of incipient metamorphism.

On the basis of illite crystallinity, zone (I) of South Wales is correlated with the unmetamorphosed rocks of Weaver (1960) and Kubler (1968), while zones (II) and (III) are correlated with the anchimetamorphic zone of Kubler (1968) and the incipient to weak metamorphic zone of Weaver (1960). Zones (I), (II), and (III) of South Wales could be correlated with the early stage, middle stage, and late stage of catagenesis, respectively (Koplan 1971). On the basis of the colour variation of spores and pollen grains, zones (I), (II), and (III) of South Wales could be correlated with the zone of slight thermal alteration, the zone of moderate thermal alteration and the zone of strong to severe thermal alteration of the thermal zones recognised by Staplin (1969) in the Paleozoic rocks of British Columbia. These correlations were clearly defined by Khalaf (1974).

As yet, little has been published on the fabric changes that can occur in carbonate rocks within the incipient metamorphic stage. Wardlaw (1962) described fabric alterations in some Irish carbonates that had been deformed. Brown (1972) described fabric alteration in incipiently metamorphosed mud-supported carbonate rocks in parts of the central Appalachians. He found that recrystallisation had caused an increase in the grain size of the matrix.

The present paper outlines the results of a reconnaissance petrographic study of the incipiently metamorphosed Carboniferous rocks from the South Wales Coalfield. It describes the various fabrics that developed in the carbonates and terrigenous rocks and which could be used for the recognition of the incipient metamorphic zone. It is worth mentioning that the fabrics described here occur only in the rocks of the western area of the South Wales Coalfield which had been subjected to incipient metamorphism as indicated by the degrees of illite crystallinity and vitrinite reflectivity (Khalaf 1974). The regional distribution of the recrystallised fabrics is clear evidence of their origin due to incipient metamorphism. However, it is possible that some of these fabrics can originate also by processes other than metamorphism.

FABRIC MODIFICATIONS OF CARBONATE ROCKS

Petrographic studies on the carbonate rocks in the northwestern area of the South Wales Coalfield have revealed the modification of their original and diagenetic fabrics by recrystallisation and lattice deformation of calcite and dolomite crystals.

A. RECRYSTALLIZATION

Definition

The definition of the recrystallization process was the subject of controversy between many carbonate petrologists. Folk (1965) has reviewed most of these ideas, and introduced the term 'neomorphism' to include two processes, namely inversion and recrystallisation. The first embodies all of the polymorphic transformations, such as transformation of aragonite to low-Mg calcite, and high-Mg calcite to low-Mg calcite. He defined the recrystallisation as a process by which original calcite is replaced by calcite of different grain size, morphology and orientation. Bathurst (1958) attempted to explain some of the coarser recrystallisation fabrics found in rocks by analogy with processes which take place during the annealing of work-hardened metals. Later, in 1964, he showed that the analogy was in error as it dealt with rocks showing no metamorphism. Folk (1965) pointed out that the process occurring in metals should have little in common with those taking place in porous, fluid-saturated carbonates, which are initially composed of metastable minerals such as aragonite and high-Mg calcite. This suggestion of Folk is relevant only in the early stages of diagenesis, because eventually carbonate sediments may lose their effective porosity and most of their interstitial fluids, and become mono-mineralic rocks composed essentially of low-Mg calcite. Wardlaw (1962) has defined recrystallisation as the replacement of physically unstable grains by grains of the same mineral which are less strained or more stable.

Voll (1960) suggested that the free energy of deformation is the main driving force of recrystallisation. Griggs *et al.* (1960) in their detailed experimental work on annealing recrystallisation in calcite crystals and aggregates have shown that single crystals and aggregates of calcite recrystallise when annealed at high temperature. They suggested that the driving force for recrystallisation is the internal strain of energy of crystals and/or the grain boundary energy. There is a critical temperature below which recrystallisation does not occur, and this critical temperature is thought to be dependent on the difference in free energy between the initial and recrystallised states. They also concluded that an increase in strain prior to annealing decreases the critical temperature. The critical temperature for annealing crystallisation was dependent on the grain size and was lower for the smaller grain sizes. They found that Solenhofen Limestones recrystallised at 800°C without prior strain.

In the present study, recrystallisation is defined as the process which takes place in rock, commonly after complete lithification which results in the transformation of the original rock fabric to a newly formed fabric which is stable under new conditions of temperature and pressure.

Recognition of recrystallised calcite

One of the most difficult problems in the identification of the incipiently metamorphosed carbonate rocks is the distinction between the diagenetic sparry cement and the recrystallised pseudosparry calcite. The recognition of the recrystallised calcite in the rocks studied was based mainly on Stauffer's criteria (1962), summarised below:
—Irregular grain size of crystal mosaic.
—Truncation of crystal mosaic of previously existing structures, such as laminae of oolites on fossil structures.
—Ghosts of allochems in crystal mosaic.
—Embayments of calcite crystals which may have plane sides, into microcrystalline calcite of allochems.
—Curved serrated or interlocking intergranular boundaries between crystals.

Besides the above-mentioned criteria, there are others that would suggest that a crystal mosaic is recrystallised calcite. These are:

—Loosely packed allochems.
—Poorly sorted allochems.
—Angular allochems.

—Gradational boundaries between calcite mosaic and microcrystalline calcite.
—Calcite crystal size never smaller than 4 μm and generally larger than 7 μm.
—Irregular patches of crystal mosaic in micro-crystalline calcite in the middle of coarser calcite mosaic.

Recrystallisation fabrics

Two types of recrystallisation fabrics have been recognized in the incipiently metamorphosed carbonate rocks of the Carboniferous Limestone Series of the South Wales Coalfield, namely aggrading recrystallisation fabrics and degrading recrystallisation fabrics.

1. Aggrading recrystallisation fabrics

This process is described in detail by Folk (1965). Bathurst (1958) has used the term 'grain growth' for aggrading recrystallisation fabric. He defined this process as 'a dry solid state process', referring to the stage of annealing that follows the completion of primary recrystallisation, when a selected few of the new unstrained crystals continue to grow at the expense of their neighbours. The term 'pseudospar' has been introduced by Folk (1965) to cover the sparry calcite formed by neomorphism which is inversion or recrystallisation in the solid state in the presence of hybrid films. In the present study, the term pseudospar will be used to indicate sparry calcite formed by recrystallisation only. In the carbonate rocks of the Carboniferous Limestone Series in the anthracite area of South Wales, aggrading recrystallisation has been recognised to affect the micrite matrix, the allochems, and the calcite cement filling fractures.

(a) Aggrading recrystallisation of micrite matrix. Biomicrites, especially the foraminiferal biomicrites, are the rocks most susceptible to recrystallisation. They are generally formed of fine-grained allochems floating in a groundmass consisting of pseudospar mosaic (Figs 3 and 4). Remnant micrite patches are frequently present in the pseudosparite groundmass. Pseudosparry calcite crystals are commonly ill-sorted and have irregular boundaries. They range in size from 10 to 150 μm (Fig. 5). It was found that increase in the grade of incipient metamorphism is manifested in the micrite matrix by increase in the crystal size and the sorting of the pseudosparry calcite crystals. Micrite in the micrite envelopes of shell fragments and algal grains is found to be resistant to recrystallisation. In the poorly sorted oolitic biosparites, it was found that micrite patches have been completely recrystallised to pseudospar mosaic. Pseudosparry calcite crystals commonly display lamellar twinning.

(b) Aggrading recrystallisation of the allochems. This fabric is well developed in some biomicrites and poorly sorted oosparites, in which some of the allochems have partially or completely recrystallized. In some foraminiferal biomicrites where the micrite matrix is almost completely recrystallised, complete recrystallisation of foraminiferal tests has been recognised (Fig. 6). The original shape of recrystallised foraminiferal tests are preserved as ghosts floating in coarsely crystalline pseudosparite mosaic.

In case of the poorly sorted oolitic biosparites, the micrite or microsparite forming the oolites has been partially or completely recrystallised to pseudosparry calcite mosaic, while their original shape is preserved as ghosts. Pseudosparry calcite crystals range in size from 10 μm to 85 μm. In the case of superficial oolite, which consists of a

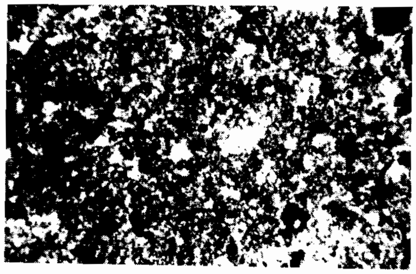

Fig. 3 300 μm

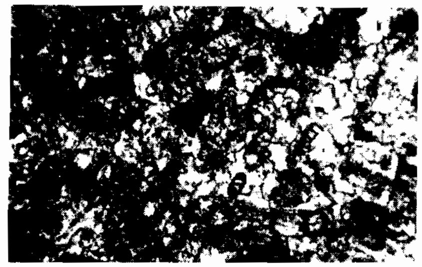

Fig. 4 300 μm

Fig. 5 300 μm

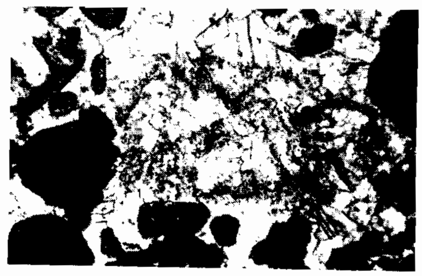

Fig. 6 300 μm

Fig. 7 300 μm

Fig. 8 300 μm

Fig. 3. Aggrading recrystallisation of micrite.

Fig. 4. Advanced stage of aggrading recrystallisation of micrite.

Fig. 5. Completely recrystallised matrix in a biomicrite rock. Note the curved boundaries between the adjacent pseudospar crystals.

Fig. 6. Ghost of a foraminiferal test in a completely recrystallised matrix in a biomicrite.

Fig. 7. Partially recrystallised oolite in an oolitic limestone. Note ghost of the original oolite in the pseudospar.

Fig. 8. Almost complete recrystallisation of an oolite.

coarse-grained crinoidal debris covered by a thin micritic shell about 100 μm thick, the latter has been partially recrystallised to a mosaic of bladed calcite crystals (Fig. 7). In the case of the nucleus-free oolite, the whole oolite has been recrystallised to a mosaic of ill-sorted equigranular pseudosparite crystals. The original shape of the completely recrystallised oolites is commonly preserved as ghosts (Fig. 8).

(c) Aggrading recrystallisation of fracture-filling cement. In some micritic rocks the fracture-filling cement, which usually consists of a mosaic of equicrystalline sparry crystals, has been recrystallised to a mosaic of pseudosparry calcite crystals with irregular boundaries (Fig. 9). The fractures have an irregular boundary due to the outward growth of the pseudosparite replacing the groundmass micrite.

2. Degrading recrystallisation fabrics

This fabric is developed by the recrystallisation of large strained calcite crystals into a number of small unstrained calcite crystals, so that the original single crystal calcite grain is replaced by a polycrystalline aggregate of calcite grains.

Attention was drawn to textures of this type by Voll (1960) who recorded that in low temperature recrystallisation of limestone, even after light straining, numerous nuclei have been formed within the coarse-grained calcite crystals. Wardlaw (1962) has described this process in the Irish Carboniferous limestones. He suggests that this could be due to minor chemical reaction, for which the energies of reaction are the driving force for the recrystallisation. Orme & Brown (1963) introduced the term 'grain diminution' to describe the *in situ* replacement of a deformed crystal by cryptocrystalline unstrained crystals of the same mineral. This concept was reviewed by Bathurst (1971) and he used the term primary crystallisation for such a process.

(a) Degrading recrystallisation of the crinoidal fragments. Degrading recrystallisation is a common feature among the crinoidal biomicrites and crinoidal biosparites of the anthracite area of the South Wales Coalfield. In these rocks, degrading recrystallisation mainly affects the crinoidal fragments and their syntaxial calcite overgrowths. The following fabrics have been recognised:

(i) Partial or complete recrystallisation of the crystalline debris to a pseudosparry calcite mosaic. Pseudosparry crystals have characteristic irregular boundaries and are of about 55 μm in average size. Cleavage traces of the original calcite crystal are preserved within the pseudosparite mosaic (Figs 10 and 11).

(ii) In some biosparite, recrystallisation is confined to the syntaxial overgrowths which have been partially replaced by a mosaic of pseudosparry calcite crystals (Figs 12 and 13).

(b) Degrading recrystallisation of the fracture-filling cement. This fabric is remarkably well displayed in the calcite veins located in the northwestern coalfield. These calcite veins usually consist of a mosaic of very coarse calcite crystals, which reach up to 2 cm in diameter. In thin section it is evident that these calcite crystals have been recrystallised. Newly formed unstrained crystals of about 130 μm in average size are present as aggregates, and have usually developed adjacent to the twin lamellae of the host crystal (Fig. 14). While twin lamellae are frequently present in the strained host crystal, the newly formed crystals are almost untwinned, which is an indication of the absence of strain. Strained host crystals commonly have well developed thick twin lamellae.

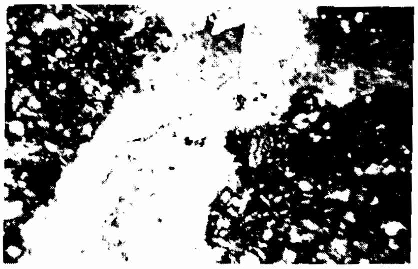

Fig. 9 — 300 µm

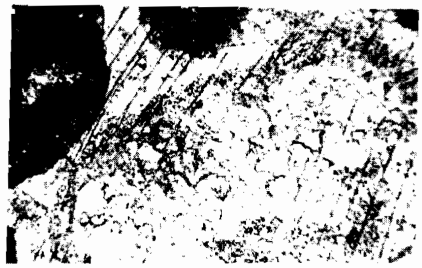

Fig. 10 — 500 µm

Fig. 11 — 500 µm

Fig. 12 — 500 µm

Fig. 13 — 500 µm

Fig. 14 — 250 µm

Fig. 9. Recrystallised sparry calcite veinlet.

Fig. 10. Degrading recrystallisation represented by microcrystalline crinoid fragment. Note that recrystallisation is confined to the crinoid fragment and that it does not affect the calcite overgrowth.

Fig. 11. Partial degrading recrystallisation of a crinoid fragment.

Fig. 12. Degrading recrystallisation of syntaxial calcite cement near the contact with the crinoid fragment.

Fig. 13. Degrading recrystallisation of syntaxial calcite cement.

Fig. 14. Degrading recrystallisation of a coarsely crystalline calcite infilling fractures.

Incipient recrystallisation of these twin lamellae is demonstrated by the development of newly formed fine crystals within the twin lamellae. This gives the twin lamellae the appearance of having been corroded by the calcite groundmass (Fig. 15).

These fabrics have been described by Griggs *et al.* (1960) in their experimental work and they found that they developed in single calcite crystals strained at low temperature and annealed at 800°C.

B. DEFORMATIONAL FABRICS

These fabrics are very common in the carbonate rocks outcropping in the anthracite area and are represented by: (1) undulose extinction, (2) distortion of twin lamellae, and (3) deformed calcite veinlets.

1. Undulose extinction

Undulose extinction of the deformed crystal is a product of the dislocation of the lattice boundaries (Voll 1960). This is observed in the unrecrystallised strained crystals, e.g. coarse-grained dolomite crystals in the porphyrotopic dolomites outcropping in the western area of the coalfield. These crystals are also characterised by curved cleavage traces (Figs 16 and 17). This is the only deformation texture observed in the dolomites. In some partially dolomitised biomicrites, curved dolomite crystals have been dedolomitised and the deformed lattice has been inherited by the newly formed calcite (Fig. 18).

In some incipiently metamorphosed crinoidal biomicrites, the crinoidal ossicles show signs of lattice dislocations. This is displayed by the presence of adjacent disoriented bands, which can be clearly seen between crossed nicols as radially arranged bands (Fig. 19). This fabric is commonly seen in the horizontal section of the crinoidal ossicles.

2. Bending of twin lamellae and the cleavage traces

This fabric is commonly seen in the large deformed calcite crystals forming the crinoidal debris as well as in the intergranular calcite cement. The curved twin lamellae have been fractured and displaced in some cases (Fig. 20). In the recrystallised biomicrites it is often found that the cleavage traces of some pseudosparry calcite crystals are curved (Fig. 21). The same feature has also been seen in the deformed crinoid ossicles and their overgrowths.

3. Deformed calcite veinlets

Deformed veinlets of calcite which fill fractures occur in the carbonate rocks of the anthracite area. It is suggested that sparry calcite formed during early stages of diagenesis. The present deformation fabrics could have been developed by the action of compressional movements which affected the western area of the South Wales Coalfield. The following fabrics of deformed calcite veinlets have been recognised: (i) deformed calcite veinlets in coal fragments present in packed biomicrite, (ii) deformed calcite veinlets in completely chertified micrite, and (iii) deformed calcite veinlets developed in stylolite seams in dolomicrite.

Fig. 15 — 250 μm

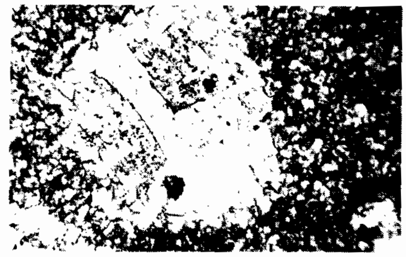

Fig. 16 — 300 μm

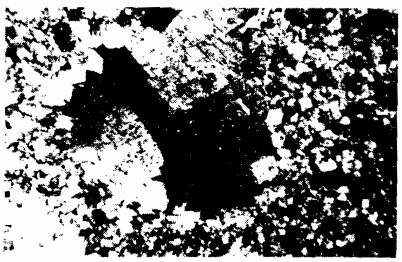

Fig. 17 — 300 μm

Fig. 18 — 300 μm

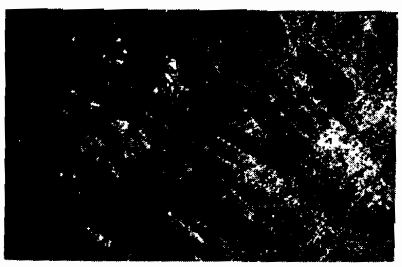

Fig. 19 — 500 μm

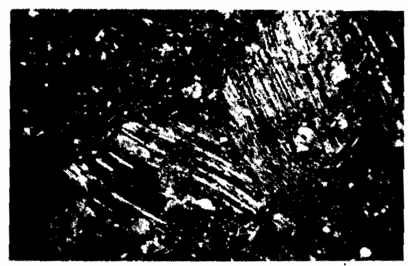

Fig. 20 — 300 μm

Fig. 15. Broad twin lamellae in a deformed coarsely crystalline calcite crystal. Note the corrosion of the twin lamellae by the calcite in the groundmass.

Fig. 16. Deformed dolomite crystals. Note curved damage planes and brush extinction.

Fig. 17. The same as Fig. 16 but between crossed nicols.

Fig. 18. Deformation fabric represented by wavy extinction displayed by calcitised dolomite crystal.

Fig. 19. Deformed crinoid ossicle.

Fig. 20. Deformed calcite crystals in a biomicrite. Note curved twin lamellae.

(i) *Deformed calcite veinlets in coal fragments*
This fabric has been noticed in the incipiently metamorphosed packed biomicrites. Calcite veinlets are present filling fractures in coal fragments trapped and deformed between the skeletal debris forming the packed biomicrites. Each calcite veinlet consists of bundles of calcite fibres which extend from wall to wall transversely, and many are of sigmoidal shape (Figs 22 and 23). Fine pieces of the coal material detached from the fracture wall are often seen floating in the fibrous calcite mass. Some of these pieces are included by more than one fibre. The fibrous structure is more commonly expressed by optical extinction shadows than by physical grain boundaries.

(ii) *Deformed calcite veinlets in silicified limestones*
Deformed fibrous calcite veinlets have been identified in the chert nodules in the Lower Limestone Shales of the Gower Peninsula. These nodules commonly consist of completely silicified micrite or biomicrite. Calcite veinlets about 2 mm thick are usually horizontal to sub-horizontal and are characterised by sharp boundaries. These calcite veinlets consist of sigmoidal calcite fibres extending from wall to wall transversely and are uniform in shape but vary in width (Figs 24 and 25). Optical study has revealed that groups of adjacent fibres are almost in lattice continuity with one another.

(iii) *Deformed calcite veinlets in dolomite*
In the dolomicrites of the Main Limestones, outcropping in the northern part of the South Wales Coalfield, very thin fibrous calcite veinlets are present within the organic matter concentrated on the stylolites (Fig. 26). These stylolite seams reach up to 3 mm in thickness and are commonly fractured. Fractures are filled with fibrous calcite similar to that previously described.

INCIPIENT METAMORPHIC FABRICS OF THE TERRIGENOUS ROCKS

Kossovskaya & Shutov (1958) in their study of the terrigenous rocks of the Veikloyansk geosyncline, Mesozoic deposits in the eastern part of the Russian platform, have distinguished three zones in the transitional stages between diagenesis and metamorphism. These are: (i) zone of unaltered clay cement which is characterised by recrystallisation of clays, hydromicatisation of kaolinite, and complete disappearance of montmorillonite, (ii) zone of quartzite-like structure with hydromica–chlorite cement, and (iii) zone of spine-like structure characterised by the perpendicular orientation of chlorite and muscovite lamellae penetrating into the composite regenerated grains of quartz and feldspar.

In the following section, characteristic fabrics of the incipiently metamorphosed Coal Measure rocks of the South Wales Coalfield will be discussed.

The terrigenous rocks of the South Wales Coalfield are found to be less susceptible to incipient metamorphism, with respect to their fabric modification. Three main fabrics are recognised in these rocks: (1) reaction of clayey matrix with framework grains, (2) deformed rock fragments, and (3) deformed fibrous quartz veinlets. All these fabrics occur in sandstone and siltstone rock types and it was difficult to notice any modification in the fabrics of the argillaceous rocks.

Fig. 21 — 250 μm

Fig. 22 — 500 μm

Fig. 23 — 250 μm

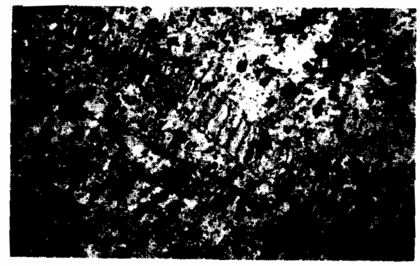

Fig. 24 — 500 μm

Fig. 25 — 500 μm

Fig. 26 — 250 μm

Fig. 21. Deformed pseudospar crystal.

Fig. 22. Fibrous calcite veinlet developed in hydraulic fractures in a coal streak.

Fig. 23. Sigmoidal shape of the calcite fibres.

Fig. 24. Fibrous calcite veinlet in a silicified biomicrite.

Fig. 25. The same as Fig. 24 but between crossed nicols.

Fig. 26. Fibrous calcite veinlet developed in an organic-rich stylolitic seam.

A. REACTION OF CLAYEY MATRIX WITH FRAMEWORK GRAINS

In the sandstones and siltstones of the anthracite area, a reaction between the clay matrix minerals and the quartz grain has been noticed. Clay minerals in these rocks are composed mainly of well crystalline illite and chlorite (Gill *et al.* 1977) which are usually arranged perpendicular to the quartz grain boundaries forming a texture similar to the spine-like structure which is characteristic of zone (iv) of Kossovskaya & Shutov (1958). It seems that the recrystallised clay minerals have corroded the quartz grains which are characterised by hazy outlines (Fig. 27).

B. DEFORMED ROCK FRAGMENTS

The difference between the fabric of the argillaceous rock fragments in the litharenites of the eastern part and that of the western part (anthracite area) of the South Wales Coalfield is very clear. In the anthracite area, the argillaceous rock fragments in the litharenites are completely deformed and have lost their original shape and internal fabric because they have been transformed to a clayey 'pseudomatrix' (Fig. 28). Commonly, in these rocks a reaction rim at the contact between argillaceous rock fragments and quartz grains has been developed. These reaction rims consist of newly formed clay minerals, which are arranged normal to the quartz grain surfaces.

C. DEFORMED FIBROUS QUARTZ VEINLETS

Fibrous quartz veinlets have been noticed occasionally in the quartzarenites of the anthracite area. They are very similar in their mode of occurrence and texture to those described in the carbonate rocks. Fibrous quartz veinlets are usually developed along horizontal weak planes, such as contact between coal streaks and the quartzitic groundmass, and they consist of quartz fibres extending transversely from wall to wall (Figs 29 and 30). Some of the fibres are bent and curved. Between crossed nicols, each group of bundles basically has an optical continuity, but the lattice of each individual fibre is slightly dislocated from the lattice of the adjacent fibre. The mechanism by which the fibrous quartz veinlets have been developed is probably similar to that responsible for the formation of the formerly described fibrous calcite veinlets.

OCCURRENCES OF THE INCIPIENT METAMORPHIC FABRICS

The development of the above-mentioned incipient metamorphic fabrics in both carbonate and terrigenous rocks is found to be mutually related to their grade of metamorphism as disclosed from the fixed carbon percentage of the associated coal seams.

In the carbonate rocks, the modification is gradual and it is difficult to draw a border-line between incipiently metamorphosed and unmetamorphosed rocks. However, it is obvious that incipient metamorphic fabrics are prominent in the area to the west of the coalfield where the associated coal seams have a fixed carbon of more than 80%. The following evidence confirms this concept:

(i) There is no indication of fabric modification in the limestones of the southern and eastern outcrops of the coalfield.

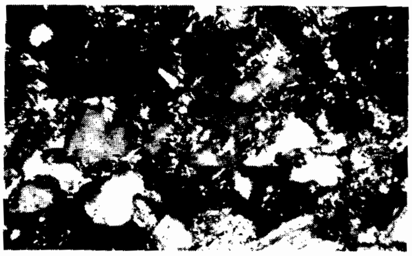

Fig. 27 175 μm

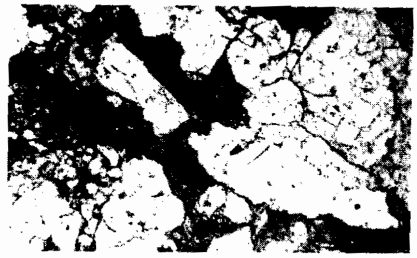

Fig. 28 400 μm

Fig. 29 175 μm

Fig. 30 175 μm

Fig. 27. Incipient metamorphic fabric of sandstone. Note the development of micaceous minerals and the reaction between the matrix and the quartz grains.

Fig. 28. Argillaceous rock fragment squeezed between the rigid quartz and feldspar grains.

Fig. 29. Fibrous quartz veinlet in a sandstone.

Fig. 30. Same as Fig. 29.

(ii) In the central part of the northern outcrop (from Brynmawr in the east to Penwyllt in the west) recrystallisation has affected only the micrite matrix of the biomicrites, and no more fabric modifications have been noticed.

(iii) In the western outcrops (anthracite area) recrystallisation has affected most of the rocks, the matrix and the allochems. Also, deformational fabrics in both calcite and dolomite crystals have been observed only in the rocks of this area.

In the terrigenous rocks, fabric modifications are found to have occurred in the anthracite area with fixed carbon of about 92·5%. The following remarks indicate the mutual relation between the fabric modification in these rocks and coal rank:

(i) The degree of deformation of the argillaceous rock fragments in the litharenites is clearly increased towards the anthracite area. While it was very difficult to recognise the original fabrics of these fragments in the litharenites of the western outcrops, they are slightly deformed in the litharenites of the eastern part of the coalfield.

(ii) The matrix clay minerals develop a spine-like structure and are progressively coarser in size westwards.

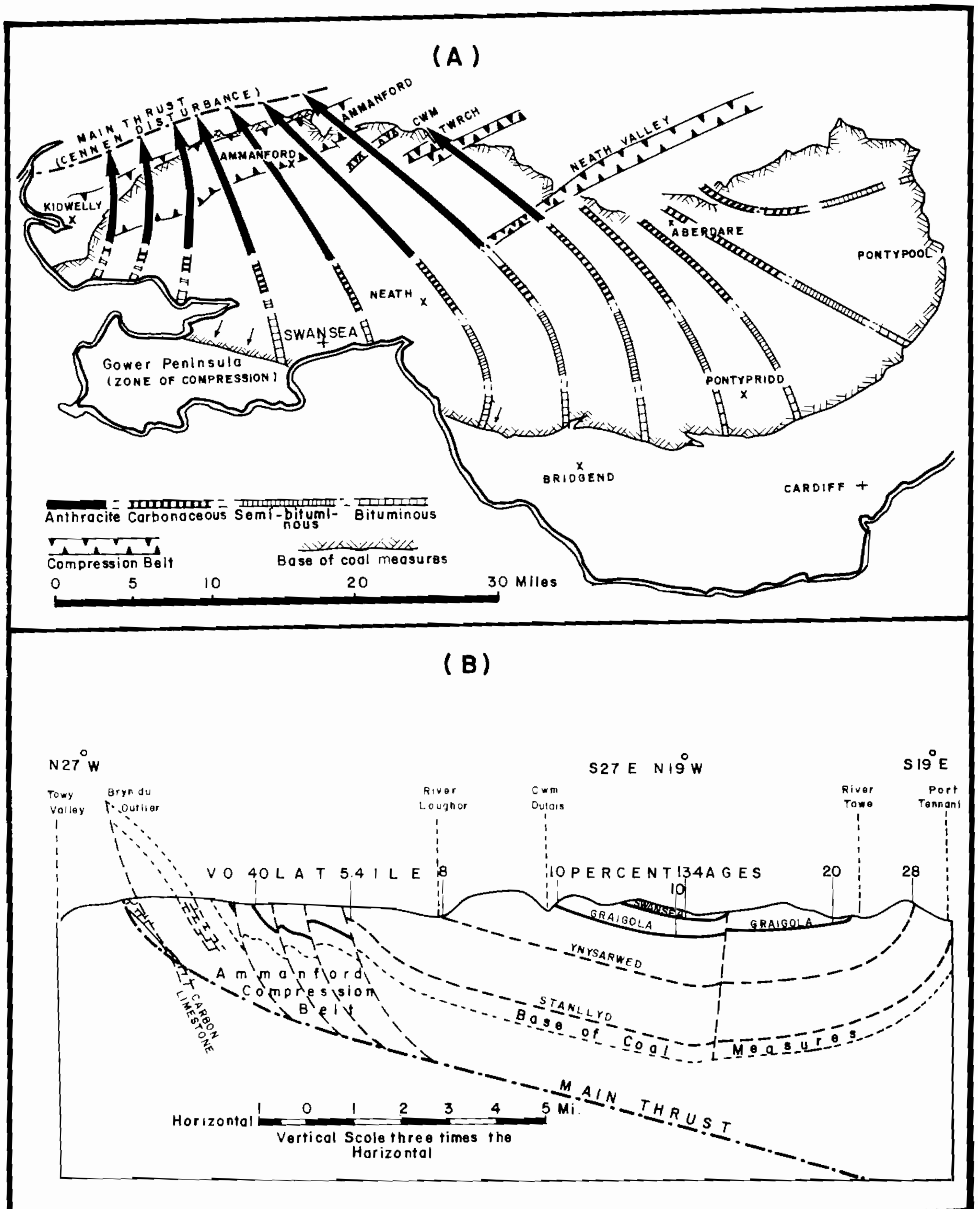

Fig. 31. Map (A) and cross section (B) of the South Wales Coalfield, showing the relationship between the main thrust and devolatilisation (after Trotter 1948).

(iii) The recrystallised clays have commonly reacted with the framework grains in the anthracite area. Also, fibrous quartz veinlets are observed only in this area.

Generally speaking, although the above mentioned petrographic study has shown a clear lateral variation of the fabric modification in the South Wales Coalfield, there is no indication of vertical variation in these fabrics with increase in depth.

Khalaf (1974) in his comprehensive study on the incipient metamorphism of the Carboniferous rocks of South Wales Coalfield, has concluded that the metamorphism of the Carboniferous rocks follows the same pattern as the coal seam metamorphism or carbonisation. Therefore, the causes of the coal metamorphism could generally be considered to be the causes of the incipient metamorphism of the associated rocks.

Trotter (1948) argued that devolatilisation and the corresponding increase of rank from gas coals to anthracite were the products of shearing stress with incidental friction heat created by a major thrust (the Careg Cennen disturbance, Fig. 31). He further suggested that the rank of a coal seam is then a function of its distance from the thrust plane. However, the absence of any indication that the incipient metamorphic textures increase with depth suggests that the metamorphism is not related to frictional heat from a thrust zone at depth. Consequently it seems more likely that the deformational and recrystallisation fabrics demonstrated by the Carboniferous rocks in the western area of the South Wales Coalfield could be attributed to the effect of the greater differential compressive stress, possibly accompanied by a slight increase in temperature which affected the western part of the coalfield more than the eastern part.

CONCLUSIONS

(1) Detailed petrographic studies on both the carbonate and terrigenous rocks in the South Wales Coalfield have revealed the modification of their fabrics in the western part of the coalfield (the anthracite area).

(2) In carbonate rocks, the main effects of incipient metamorphism are recrystallisation and lattice deformation. Two main recrystallisation fabrics have been recorded: (i) aggrading recrystallisation leading to increase in the micrite crystal size and the development of pseudospar crystals, and (ii) degrading recrystallisation responsible for the replacement of the strained large crystals by a mosaic of finely crystalline pseudospar crystals. Deformational fabrics are common in the anthracite area where the following three fabrics are recognised: (i) undulose extinction of calcite and dolomite crystals, (ii) bending of twin lamellae and cleavages in calcite and dolomite, and (iii) development of deformed fibrous calcite veinlets.

(3) In terrigenous rocks, three main incipient metamorphic fabrics have been noticed in the anthracite area: (i) reaction of the clayey matrix with quartzitic framework grains, (ii) deformation of the argillaceous rock fragments and the development of pseudomatrix in the lithic arenites, and (iii) development of deformed fibrous quartz veinlets.

(4) The fabric modifications have been controlled to some extent by the lithology of the incipient metamorphosed rocks. The carbonate rocks are generally more affected by incipient metamorphism than the terrigenous ones. In the case of the carbonate rock types, micrites are the most susceptible to recrystallisation, while dolomites are the most resistant to modification. In the terrigenous rocks, all the fabric modifications are confined to the sandstone and siltstone rock types only without affecting the argillaceous ones.

(5) There is a mutual relation between fabric modification in both carbonate and terrigenous rocks and the coal rank. The development of incipient metamorphic fabrics increases progressively towards the western and northwestern parts of the coalfield (the anthracite area). The fabric modifications in carbonate rocks are prominent in areas of more than 80% fixed carbon, while those in the terrigenous rocks are confined to areas of 92·5% fixed carbon. On the other hand, incipient metamorphic

fabrics in both the carbonate and terrigenous rocks are not recorded in the southern and eastern parts of the coalfield. In the central part, the only fabric modification noticed is the initial effect of recrystallisation on the micrite matrix of some biomicrites. (6) Fabric modifications in the carbonate and terrigenous rocks in the South Wales Coalfield are mainly lateral, and there is no indication of vertical variation with increase in depth. Consequently, it does not seem likely that the devolatilisation of the coals and the incipient metamorphism of the associated sediments are related to frictional heat from an underlying thrust zone as suggested by Trotter (1948). It is concluded that the recrystallisation was due to greater strain in the crystals of the rocks in the west because these rocks have suffered greater compressional stress.

REFERENCES

Adams, H.F. 1967. The seams of South Wales Coalfield. Institute of Mining Engineers, London, 38 pp.

Bathurst, R.G.C. 1958. Diagenetic fabrics in some British Dinantian Limestones. Liverpool Manchester Geol. J. **2:** 11–36.

Bathurst, R.G.C. 1964. Diagenesis and paleoecology: a survey. In. **Imbrie, J. & Newell, N.B. (Eds).** Approaches to paleoecology, pp. 319–44. Wiley, New York.

Bathurst, R.G.C. 1971. Carbonate sediments and their diagenesis. Development in Sedimentology **12,** 620 pp. Elsevier, Amsterdam.

Brown, P.R. 1972. Incipient metamorphic fabrics in some mud-supported carbonate rocks. J. Sedim. Petrol. **42:** 841–7.

Burst, J.F. 1959. Post diagenetic clay mineral environmental relationship in the Gulf Coast, Eocene. Clays and Clay Minerals **6:** 327–41.

Davies, M.M. & Bloxam, T.W. 1974. The geochemistry of some South Wales coals. In: **Owen, T.R. (Ed).** The Upper Palaeozoic and Post Palaeozoic Rocks of South Wales, pp. 225–67. University of Wales Press, Cardiff.

Dunoyer de Segonzac, G. 1970. The transformation of clay minerals during diagenesis and low-grade metamorphism. Sedimentology **15:** 281–348.

Folk, R.L. 1965. Some aspects of recrystallization in ancient limestones. In: **Pary, L.C. & Murray, R.C. (Eds)** Dolomitization and limestone diagenesis. Soc. Econ. Paleont. Mineral., Spec. Pub. No. **13:** 14–48.

Fuchs, W. 1946. Origin of coal and change of rank in coalfields. Fuel Sci. Pract. **25:** 132–4.

George, T.N. 1970. British regional geology; South Wales. Institute of Geological Sciences, London, 152 pp.

Gill, W.D., Khalaf, F.I. & Massoud, M.S. 1977. Clay minerals as an index of the degree of metamorphism of the carbonate and terrigenous rocks in the South Wales Coalfield. Sedimentology **24:** 675–91.

Griggs, D.T., Paterson, M.S. & Heard, H.C. 1960. Annealing recrystallization in calcite crystals and aggregates. In: **Griggs, D.T. & Handin, J. (Eds).** Rock deformation. Geol. Soc. Am., Mem. No. **79:** 21–37.

Khalaf, F.I. 1974. Diagenesis and incipient metamorphism of the Carboniferous rocks in the South Wales Coalfield. Ph.D. Thesis, University of London, 548 pp.

Koplan, M. Ye. 1971. Criteria for determining zones of catagenesis in terrigenous sediments. Int. Geol. Rev. **13:** 1363–70.

Kossovskaya, A.G. & Shutov, V.D. 1958. Zonality in the structure of carbonate and terrigenous deposits in platform and geosynclinal regions. Ecol. Geol. Helv. **51:** 656–66.

Kossovskaya, A.G. & Shutov, V.D. 1970. Main aspects of the epigenesis problem. Sedimentology **15:** 11–40.

Kubler, B. 1964. Les argiles, indicateurs de métamorphisme. Rev. Inst. Franc. Pétrole **19:** 1093–112.

Kubler, B. 1968. Evaluation quantitative du métamorphisme par la cristallinité de l'illite. Bull. Centre Rech. Pau-S.N.P.A. **2:** 385–97.

Landes, K.D. 1967. Eometamorphism and oil and gas in time and space. Bull. Am. Assoc. Petrol. Geol. **51:** 828–41.

Logvinenko, N.V. 1957. Late diagenesis (epigenesis) of the Donetz Carbonaceous rocks. USSR Izvestiya Ser. Geol. No. 7.

Mohafez, S. 1966. The carbon ratio theory applied to British Isles. M.Sc. Thesis, University of London, 110 pp.

Orme, G.R. & Brown, W.W.M. 1963. Diagenetic fabrics in the Avonian Limestones of Derbyshire and North Wales. Proc. Yorks. Geol. Soc. **34:** 51–66.

Owen, T.R. 1971. The relationship of Carboniferous sedimentation to structure in South Wales. Compte Rendu de Congrés Intern. Strat. Geol. Carbonif. **3:** 1305–16.

Staplin, F.L. 1969. Sedimentary organic matter, organic metamorphism and oil and gas occurrence. Bull. Canad. Petrol. Geol. **17:** 47–66.

Stauffer, K.W. 1962. Quantitative petrographic study of Paleozoic carbonate rocks, Caballo Mountain, New Mexico. J. Sedim. Petrol. **32:** 357–96.

Strahan, A. & Pollard, W. 1915. The coals of South Wales with special reference to the origin of anthracite. Mem. Geol. Surv. U.K., 91 pp.

Trotter, F.M. 1948. The devolatilization of coal seams in South Wales. J. Geol. Soc. Lond. **104:** 387–437.

Voll, G. 1960. New work on petrofabrics. Liverpool Manchester Geol. J. **2:** 503–67.

Wardlaw, N.C. 1962. Aspects of diagenesis in some Irish Carboniferous Limestones. J. Sedim. Petrol. **32:** 776–80.

Weaver, C.E. 1960. Possible uses of clay minerals in the search for oil. Bull. Am. Assoc. Petrol. Geol. **44:** 1505–18.

(Received 1 May 1979)

خصائص النسيج الصخري الناجم عن التحول البدائي لصخور العصر الكربوني من منطقة حقل فحم جنوب ويلز

فكري خلف
معهد الكويت للأبحاث العلمية ، الكويت

خلاصة

دلت الدراسات البتروجرافية للصخور الجيرية والرملية من العصر الكربوني في منطقة حقل فحم جنوب ويلز على تغير نسيجها الصخري في المنطقة الغربية التي تتواجد بها طبقات فحمية من رتبة الانثراسيت . ولقد تبيّـن أن تغير نسيج الصخور الجيرية المتأثرة بالتحول البدائي نتج أساسا عن عمليات إعادة التبلور الازديادي والتدهوري والتواء الهياكل البلورية لمعدني الكالسيت والدولوميت . أما في الصخور الرملية فينعكس هذا التغير في وجود هالة تحيط بالحبيبات المعدنية نتيجة لتفاعلها مع المعادن الطينية الموجودة في المادة اللاحمة لهذه الصخور ، واعادة تشكيل الحبيبات الرملية المكونة من فتات بعض الصخور الطينية ، وكذلك التواء بلورات الكوارتز المكونة لبعض العروق الصخرية . ومن الجدير بالذكر أن هذه الأنسجة الصخرية تعتمد في وجودها إلى حد كبير على نوعية الصخور الجيرية والرملية .

وقد اتضح من هذه الدراسة وجود علاقة بين تواجد هذه الأنسجة الصخرية في الصخور المختلفة ونسبة الكربون الثابت في طبقات الفحم المتواجدة معها . كما تبيّـن أن درجة التحول البدائي تزداد في اتجاه الغرب وتظهر بوضوح في أماكن تواجد طبقات الانثراسيت . وتكمن أهمية هذه الدراسة في امكانية استخدام ظاهرة وجود بعض الأنسجة الصخرية في تحديد مراحل عمليات تحول الصخور الرسوبية وما بها من مواد عضوية ، الأمر الذي يساعد إلى حد كبير في تفسير وجود الرواسب البترولية السائلة والغازية وشبه الصلبة .