<u>The Carboniferous evolution of the Central Coalfield</u> <u>Basin, Midland Valley of Scotland: implications for</u> <u>basin formation and the regional tectonic setting.</u>

Thesis submitted for the degree of Doctor of Philosophy

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The Carboniferous evolution of the Central Coalfield Basin, Midland Valley of Scotland: implications for basin formation and the regional tectonic setting.

By Matthew David Hooper

Abstract

The Midland Valley of Scotland was a major Carboniferous depocentre containing volumetrically significant intrusive and extrusive magmatic suites. The area has long been a target for economic activity providing large datasets and a wellconstrained stratigraphy. This study assesses the sedimentological and structural development of the Central Coalfield Basin, one of four important Carboniferous basins within the Midland Valley. A tectonostratigraphic framework for the Central Coalfield is established by an integrated analysis and interpretation of 2D reflection seismic profiles, borehole and well data and sedimentological studies. Based on this research, the wider implications for the regional tectonic setting and general concepts of basin formation are also examined. The Midland Valley has a distinctive Carboniferous sedimentary fill. Temporal and spatial facies changes are minimal; depocentres were dominated by shallowmarine, deltaic and alluvial environments and no Carboniferous alluvial fans are recorded along basin margins. Therefore deposition appeared to have kept pace with accommodation generation. In contrast, deep marine Dinantian and Namurian sediments are preserved in the basins of central and northern England reflecting underfilled depocentres and in the Northumberland Basin. Accommodation was generated by the syn-depositional evolution of the NNE-SSW orientated Clackmannan-Falkirk-Stane Syncline supplemented by local fault generated accommodation. Syncline growth occurred during the mid- and late-Viséan, while during the Namurian regional subsidence was accompanied by slower syncline growth and periodic fault movement. During the Westphalian folding occurred across the Midland Valley post-dating the majority of deposition. The largest, intrabasinal fault-bounded structure recognised is the 25-km-long, ENE-trending Forth graben in the northern Central Coalfield. E-W orientated faults offset syndepositional Carboniferous folds and faults and are therefore interpreted as Late Westphalian to Early Permian. The occurrence, orientation and timing of major fold and fault systems in the Central Coalfield are consistent with dextral strike-slip movement along the Southern Upland and Highland Boundary faults. This dextral motion generated ENE-WSW directed compression and NNW-SSE extension resulting in NNE- orientated folds and the fault orientations recognised. The synclinal depocentres and groups of faults observed in the other coalfield basins of the Midland Valley also have orientations and syndepositional histories consistent with this dextral transtensional model.

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Introduction

The British Carboniferous coalfields and their stratigraphy are amongst the most intensely studied in the world with numerous detailed and regional accounts from all branches of the Earth sciences. The coalfields of the Midland Valley of Scotland (MVS) (Fig 1.1.1) have been exploited for coal, coal-bed methane, hydrocarbons, ironstones, limestones, building materials and water. Many of these industries have long since vanished or are in decline, yet the extraction of coal bed methane is viewed as a new potential. All of these resources have provided vast geological datasets which are used in this study to understand the tectonic evolution and depositional setting of the Central Coalfield of the MVS.

The MVS is one of the major Carboniferous depocentres in the UK and is the furthest north of the major onshore UK Carboniferous basins. The MVS is distinctly different from other onshore depocentres in the UK. It has the largest volume of Carboniferous igneous material of any of the basins. There is also an absence of goniatites in the MVS and the sedimentary deposits have no major lateral changes in facies compared to the Carboniferous basins of England.

The MVS formed as an isolated basin between the Caledonian Mountains to the north and the Southern Uplands to the south separating it from comtemporaneous basins developed to the south and north - the Northumberland Trough and Solway Basin and Moray Firth Basin respectively. Sedimentation may have extended across Southern Uplands Block during some periods of the Late Carboniferous, linking the MVS with the Northumberland Trough and the MVS (Cameron & Stephenson 1985).



Fig 1.1.1 Simplified geological map of the MVS, reproduced from the 1:625000 Geological Map of the United Kingdom North-Solid Edition showing the location of the main MVS depocentres and volcanic rocks. Insert Onshore UK Carboniferous basins.

The MVS is flanked, to the north, by the Dalradian metamorphic rocks of the Scottish Highlands and, to the south, by the Ordovician to Silurian deposits of the Southern Uplands (Cameron & Stephenson, 1985). The principal bounding structures to the MVS are the Highland Boundary fault and the Southern Upland fault. These faults are believed to be Caledonian in origin (Anderton *et al.* 1979).

The ENE-trending 90-km-wide Midland Valley of Scotland MVS (Fig. 1.1.1) extends for some 300 km along strike across southern Scotland (Browne & Monro, 1989), and contains Silurian, Ordovician and Devonian deposits beneath the Carboniferous. The four Carboniferous basins within the MVS are: 1. the Ayrshire Coalfield in the west; 2. the Central Coalfield; 3. the Midlothian-Fife Coalfield in the east and; 4. the small Douglas Coalfield (Fig. 1.1.1). The coalfields are bounded by faults and volcanic provinces that separate the Carboniferous fill into these four distinct depocentres (Francis 1991a; Bluck 2000) (Fig. 1.1.1).

1.2 Tectonic Evolution of the Carboniferous of NW Europe

The tectonic evolution of Carboniferous basins in the UK and Ireland was controlled by the oblique (dextral) collision between Gondwana and Laurussia during the Variscan Orogen (Warr, 2000). The most widely accepted model for the generation of the Pennine and Northumberland-Solway Basins involves a Dinantian rifting event as a result of N-S extension (Maynard *et al.* 1997; Fig. 1.2.1 A-D) and (Leeder 1982), they along with (Leeder & McMahon, 1988, Fraser and Gawthorpe, 1990) considered reactivation of NE- and NW-trending Caledonian structures to be important. Extension in this broadly back-arc setting is suggested to be a result of lithospheric stretching as the Theic oceanic plate underwent northward-directed subduction along the southern margin of Armorica Fig. 1.2.1 Palaeogeographic reconstructions illustrating the assembly of the crust upon which the Northwest European Carboniferous Basins formed from Maynard *et al.* (1997). A. mid Viséan 334 Ma; B. Late Viséan 320 Ma; C. late Namurian 314 Ma; and D. Westphalian A/B 312 Ma.







(Warr, 2000).

Other models propose that Carboniferous basins in England formed as pull-apart basins caused by motion along major zones of strike-slip movement (Dewey, 1982; Coward, 1993). Belt (1969) and Dewey (1982) both proposed that the final collision and development of the Variscan orogeny developed in dextral megashear. Coward (1993), however, invokes Late Devonian-Early Carboniferous expulsion of a 'North Sea-Baltic Block', bound to the south by a dextral shear system (in the East Midlands-Southern North Sea area) and to the north by a sinistral NE-trending shear system (e.g. the Great Glen fault), in which it is suggested that movement along these shear systems created NW-SE extension and generated pull-apart basins. By the late Carboniferous, the 'North Sea-Baltic Block' was driven solely dextral strike-slip movement in northern Britain and caused basin inversion (Coward, 1993).

Five main fault trends are recognised within the coalfields of the MVS; NW-SE, NE-SW, ENE-WSW, WNW-ESE and E-W. Major folds are also recognised in the central and eastern MVS with axes generally orientated NNE-SSW. This structural complexity has been explained by several contrasting models for tectonic evolution (e.g. Leeder 1982; Dewey 1982; Read 1988; Gibbs 1989 and Coward 1993). These models can be summarised into a dextral megashear model, a model involving back-arc extension generated by northward subduction of the Rheic Ocean and a model involving sinistral displacement followed by dextral displacement along major faults.

3

1.3 Stratigraphy of the Midland Valley

The stratigraphical framework used in this study is based upon the stratigraphy of Cameron and Stephenson (1985) with updates from Francis (1991a); Browne *et al.* (1999) and Read *et al.* (2003).

The Carboniferous deposits in the MVS are divided into four groups; 1. the Inverclyde Group; 2. the Strathclyde Group; 3. the Clackmannan Group; and 4. the Coal Measures group (Fig. 1.3.1). In the Central Coalfield these groups are sub-divided into thirteen formations (Fig. 1.3.1). The formations of the MVS as defined by Browne *et al.* (1999) are correlated based upon their ability to be mapped, and are commonly placed at either the base or top of a basin-wide marine unit, commonly a limestone. These thirteen Carboniferous formations overlie some 1-2 km of Upper Old Red Sandstone, deposited in the late Devonian-Tournaisian.

The age constraints of these formations in the MVS are defined from Ar^{39}/Ar^{40} dating of contemporaneous magmatic phases (Monaghan and Pringle in press), and from biostratigraphy.

During this study the standard BGS stratigraphic correlations were used in the Central Coalfield and across the MVS to identify the succession, and were justified by cross-checking both with BGS solid 1:10,000 and 1:50,000 geology maps, and with opencast coal mine operators, who used both the BGS standard stratigraphic correlations and their own systems. Where probable formation boundaries were encountered, samples of limestone thought to be such were collected to be examined by BGS palaeontologist Dr M. Dean, who identified the fossil assemblage as either indicative of a limestone formation boundary or not. A

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	West Lothian								tion	5	tion		West Lothian Oil-Shale	Formation	Gullane at	Arthur's Se Volcanic Formatio			
Midland Valley	Fife	I Measures		al Measures	I Measures		ormation		estone Format	Coal Formatio	estone Format	Pathhead	Sandy Craig Formation	Pittenweem Formation	Anstruther Formation	Fife Ness Formation	one Formation	ormation	od Formation
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Figure 1.3.1 Figure 1.3.1 Lithostratigraphical and chronostratigraphical divisions of the Carboniferous in the Midland Valley and Scottish Borders. Adapted and Jpdated from Francis 1991), Browne (1999) and Read *et al.* (2003). Radiometric dates are from Menning *et al.* (2000). Regional correlation formation; Lst, Limestone; CC, Castlecary; TH, Top Hosie; MB, Marine Band. reassessment of the biostratigraphy used in correlating stratigraphy was beyond the remit of this study.

1.4 Climatic setting and general fill of the Midland Valley of

Scotland

During late Devonian-Tournaisian time the MVS formed part of the Laurussia continent (Ziegler 1982) and lay four degrees south of the equator in a semi-arid climatic zone (Cameron and Stephenson 1985). During the Carboniferous the MVS moved northward into a more tropical climatic zone (Cameron and Stephenson 1985) and by the early Silesian, lay close to the equator at the southern margin of the Laurussian continent (Ziegler, 1990). It continued to move northward, lying eight degrees north of the equator by the end-Carboniferous to early-Permian the climate again becoming increasingly arid.

The late Devonian-Tournaisian succession consists of an overall fining package of predominantly alluvial sediment. This is believed to be conformably overlain by the 2-3 km thick succession of Dinantian strata (Fig. 1.3.1) comprising fluvial, deltaic, lacustrine and shallow-marine deposits.

Contemporaneously, extensive alkaline basic lavas were extruded between the coalfield depocentres in the western part of the MVS (Francis 1991b; Figs. 1.1.1, 1.4.1). These igneous rocks are referred to throughout this thesis but have not been examined in detail as part of this study. Smaller restricted volcanic centres were also extruded in the eastern MVS during the Carboniferous, (Figs. 1.1.1; 1.4.1; Francis 1991b Cameron & Stephenson 1985; Browne *et al.* 1999). On the western side of the Central Coalfield the voluminous (*c.*100 km²)

Monaghan and Pringle (1996). Stratigraphical Birrenswark and Kelso Stevenson (1985) and updates from Francis (1991b) compared to stratigraphy is based igneous rocks from Chadwick *et al.* (1995). ranges for magmatic phases based upon upon Cameron and Gradstein and Ogg Carboniferous age new Ar/Ar ages by constraints on the the timescale of (in press), The Kersehopefoot, Glencartholm, Figure 1.4.1



Clyde Plateau Volcanic Formation (Figs 1.1.1 and 1.4.1) is present as a series of faulted blocks. 40 Ar/ 39 Ar dates (Monaghan and Pringle, in press) for the Clyde Plateau Volcanic Formation give an age range for the formation between 335.4 ± 2 to 329.1 ± 1.4 Ma.

The Bathgate Hills Volcanic Formation (Fig 1.1.1 and 1.4.1) is located in the central MVS, forming the eastern margin to the Central Coalfield and part of the complex western margin to the Midlothian-Fife Coalfield, and is interbedded with sedimentary rocks of the Upper Viséan and Lower Namurian.

The Garleton Hills Volcanic Formation (Fig 1.4.1) is located in the eastern MVS in East Lothian, between the Lammermuir fault and the D'Arcy Cousland Anticline (Fig 1.4.2). This has been dated between 342.4 ± 1.1 and 342.1 ± 1.3 Ma (Monaghan and Pringle, in press) and volcanic activity around the Clyde Plateau continued until the mid-Viséan whereas the Bathgate Hills Volcanic Formation and the volcanics in the eastern MVS continued to be active into the Westphalian (Monaghan & Pringle, in press).

Late Carboniferous to Early Permian sills, vent intrusions and dolerite plugs are present across the MVS and these have an age range of *c*. 298 to 292 Ma (Monaghan and Pringle, in press).

The Late Dinantian to Early Namurian succession (Fig. 1.4.1) consists mainly of shallow-marine carbonates, mudstones, sandstones and fluvio-deltaic successions (Chapter 2; Browne *et al.* 1999). Similar deposits are present in other Carboniferous basins in the UK during this time, for example the Northumberland Trough, where the sedimentation rate was able to keep pace with the rate of subsidence and managed to maintain a more or less stable base level (Fraser and Gawthorpe 2003).





Periodic marine transgressions occurred throughout the Carboniferous and marine sedimentation was most extensive during the Namurian (Cameron and Stephenson 1985), the late Namurian was dominated by fluvial sedimentation (Browne *et al.* 1999). Read (1988) interpreted this change in sedimentary style to be a result of a major base sea-level fall.

The overlying Westphalian succession (Fig. 1.4.1) mainly comprises deltaic and floodplain deposits whose environments are similar to other Carboniferous basins (Fraser & Gawthorpe 1990: 2003; Browne *et al.* 1999; Kelling 1988).

The Highlands of Scotland, remnants of the Grampian Mountains, were the predominant source area for MVS Carboniferous sediment. Smaller volumes of sediment were derived from the Fennoscandia and the Greenland shield to the north-east and northwest respectively (Morton & Whitham, 2002).

1.5 Proposed models of Carboniferous basin development applied

to the Midland Valley of Scotland

The wide variety of data sources and the knowledge of other contemporaneous basins across Northern Europe and North America has led to several contrasting models for the development of the MVS during Carboniferous times these are detailed in the following sections.

1.5.1 N-S Crustal stretching

Leeder (1982) adopted and adapted the McKenzie (1978) model for the formation of Devonian and Carboniferous basins of NW Europe. N-S crustal stretching generated the Northumberland Trough, Solway, Pennine and MVS basins in a back-arc setting. Further south, southern Britain and Brittany underwent northward-verging thrust fault deformation as a result of the closure of the Rheno-Hercynian back-arc seaway. Leeder (1976; 1982) and Leeder and McMahon (1988) proposed that the N-S tension resulted in shear within the MVS, reactivating NE and NW Caledonian structures. An early extensional phase was then replaced by thermal subsidence during the Namurian-Westphalian. The model rejects strike-slip development of the MVS on the basis of lack of evidence. Leeder (1982) proposes that accommodation was generated by N-S extension producing new syn-sedimentary E-W faults and reactivation on the NE- and NWstriking Caledonide structures as pull-apart faults with little or no strike-slip motion. Stedman (1988) also proposed N-S extension, using studies of borehole samples in the Ayrshire Coalfield to find a heavy mineral assemblage similar to the heavy minerals from the Loch Doon Granite, owing to the proximity of the source and sink this 1988 study proposed no lateral movement along the Southern Upland fault.

1.5.2 Dextral strike-slip

Dewey (1982) suggested that a subduction zone to the south of Britain had a lateral escape structure on the overriding block that would have produced an anticlockwise rotation. The rotational displacement was taken up by a zone of dextral strike-slip motion which would have played the dominant role in the development of the Devonian-Carboniferous of Northern Britain. This zone would have connected to a further recognised zone of dextral transform faulting in the Canadian Maritimes and linked the northern Appalachians to Western Europe. Dextral motion during the Carboniferous along these major structures is proposed to have produced the graben and half-graben tectonics of NW Europe.

Read (1988) developed this model to explain the evolution of the MVS,

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and proposes polyphase subsidence history is linked to dextral strike-slip motion superimposed on dominant regional thermal subsidence; evidence being drawn from field exposures and strain ellipse analysis of the orientations of faults within the MVS. Read (1988) and Rippon *et al.* (1996) also interpret the volcanic structures of Bo' ness and Clyde Plateau lavas as areas'of minimal subsidence that also acted as a barrier to sedimentary transport.

1.5.3 Sinistral followed by dextral strike-slip motion

The pre-Carboniferous evolution of the Midland Valley was examined by Phillips *et al.* (1987) who proposed that sinistral strike-slip tectonism controlled the early development of the Midland Valley terrain along reactivated Caledonian NE-SW structures producing basins reflecting a NE-SW fault system. Coward (1993) also suggested that the Devonian and Carboniferous basins of NW Europe, including the MVS, formed as a result of sinistral movement along NE-trending faults during a period of continental escape where the UK-North Sea-Baltica Block moved away from the Acadian indentor of the North American-Greenland Block and Western Europe Block. The sinistral movement between the blocks facilitated the growth of pull-apart basins. Any resulting signature of sinistral movement has subsequently been overprinted by dextral strike-slip movement caused by the closure of the Ural Ocean. It is suggested that this movement overprinted the UK, producing basin inversion and N-S fold axis generation during the Late Carboniferous.

Rippon *et al.* (1996) also proposed a model of sinistral strike-slip movement along NE-trending basin bounding faults: the Highland Boundary fault and Southern Upland fault. The authors also proposed that E-W tension caused extension during early Dinantian to Lower Namurian times. Sinistral movement was overprinted by dextral strike-slip movement associated with initial E-W compression, followed by N-S extension later in the Late Carboniferous.

1.6 Objectives of this study

As a result of these contrasting proposed models the aim of this project is to unravel the structural evolution of the Central Coalfield of the MVS (Fig. 1.1.1) and the wider implications for the evolution of the whole MVS. This study aims to answer a number of fundamental questions:

- What were the major structures during Carboniferous sedimentation in the Central Coalfield of the MVS and when were these active?
- Did the variously orientated faults in the Central MVS control accommodation during sedimentation?
- What does the orientation of structures within the central MVS tell us about the wider controls on accommodation generation?
- What are the controls on temporal and spatial variation in subsidence within and between individual depocentres?

The consideration of these questions will have wider implications both for the evolution of Carboniferous basins (e.g. the Maritimes Basin, eastern Canada) and for conceptual models of basins in general.

1.7 Techniques

This unique study of the MVS makes use of previously unpublished reflection seismic data (Appendix 1) to understand the broad evolution of the MVS. This project integrates British Geological Survey (BGS) map data, paper borehole records and well data (Appendix 2) archived by the BGS and field locality information with the reflection seismic data. Combining these diverse datasets links surface geology with the subsurface. The stratigraphical and geographical location of the data resources used in this study are illustrated on Fig. 1.7.1.

Field data from across the MVS depocentres (Fig. 1.7.1) was predominantly collected during the summer months of 2000 and 2001 and also in periodic visits throughout the project (Appendix 3). Twenty-seven field localities have been studied, of which twenty-three were or are opencast coal mines and four are natural sections. Data collected included detailed logged sections and photomosaics. Company data, for example mine plan data, was also acquired from a number of opencast sites.

The interpretation of the large reflection seismic dataset located internally within the central area of the MVS (Fig. 1.7.1) was the most important aspect of this project. Seventy-eight reflection seismic lines from the central MVS have been interpreted, the majority of which were obtained under licence from the United Kingdom Onshore Geophysical Library (UKOGL). Others were obtained from the DTI and BGS archives. The seismic dataset was collected by several companies- Saxon Oil PLC, Tricentrol Oil Corporation Ltd., Teredo Oils Ltd., Berkeley Resources Ltd., Enterprise Oil and Horizon Exploration Ltd. This is the

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Valley and Scottish Borders. Stratigraphic table adapted and updated from Cameron and Stevenson (1985); Francis (1991); Browne (1999) and Read *et al.* (2003). No seismic data has been available in the Douglas and Ayrshire Coalfields and the offshore seismic in the Midlothian-Fife Coalfield has been interpreted by Ritchie *et al.* (in press); Underhill *et al.* (in prep.).

first study to examine the complete dataset.

The interpretation of the reflection seismic data utilising the borehole and well dataset to identify formations has enabled a spatial and temporal framework of deposition in the MVS to be established. The seismic data allows faults and structures active during the Carboniferous to be distinguished from later structures that would have influenced deposition. Aspects of these published models can therefore be tested and developed.

1.8 Thesis Layout

This first chapter provides a brief discussion on the main objectives and techniques utilised during this study and includes a review of the general stratigraphy and tectonic setting of the UK Carboniferous basins. Chapter 2 deals with the facies and facies associations of the MVS derived from measured sedimentary logs in the Central, Ayrshire, Douglas and Midlothian Coalfields. Integrating the sedimentary logs with borehole records has enabled palaeogeographic reconstructions to be produced. Chapter 3 contains discussions on the methodology of seismic interpretation. Chapter 4 contains seismic interpretations from the Central Coalfield, with selected lines illustrating key features in the tectonic development of the Central Coalfield. A model of the tectonic evolution for the central MVS is established from the seismic interpretation in this chapter. Chapter 5 deals with the analysis of borehole data in the central MVS from the interpretation of isopach formation maps, in terms of the tectonic model established in chapter 4. Chapter 6 examines the tectonostratigraphic development of the western and eastern MVS, i.e. comparing the documented structures in these areas to those defined from the central MVS and therefore to the model established in this study. Chapter 7 discusses the evolution
of the central MVS and draws some generic results for Carboniferous basins.

Chapter 8 contains the conclusions to this study and proposed future work.

Chapter 2

Carboniferous sedimentology of the Midland Valley of Scotland

2.1 Introduction

The sediments of the MVS were predominantly deposited in shallow marine or terrestrial environments (Francis 1993; Browne and Monro, 1989; Read, 1989a; Read, 1989b; Read, 1988; Browne *et al.* 1987a and b; Cameron and Stephenson, 1985; Kirk, 1983; Read *et al.* 1971). This chapter details the evolution of depositional environments of the Namurian and Westphalian (Fig 2.1.1).

The sedimentary facies described in this study are derived from the few good natural exposures and twenty-three opencast coal workings within the Limestone Coal Formation, Upper Limestone Formation, Passage Formation and Coal Measures. Facies descriptions are also derived from borehole records (Fig. 2.2.1) that penetrate the Carboniferous succession. Four main depositional environments are interpreted from the facies associations, 'shallow marine', 'marginal marine', 'fluvial-deltaic' and 'alluvial floodplain'. The sedimentary facies presented here are similar to those described from Carboniferous successions elsewhere in the MVS and the British Isles (Fielding *et al.* 1988; Guion *et al.* 1995). The presence of many opencast sites provides a unique opportunity for a detailed, 3-D facies study of strata.



Fig 2.1.1 Simplified geological map of the MVS, reproduced from the 1:625000 Geological Map of the United Kingdom North-Solid Edition with the locations of fieldwork studies (white circles) undertaken in this work.

Regional	horizons (MVS)			Base Lower	Measures	No.3 MB		-Plean Lst -Calmy Lst	Orchard Lst	Black Metals Marine Band		-Hurlet Lst	Raeburn	Lower Carb. Volcanics	•				
Solway- Cheviot						,		Stainmore- Group -			Liddesdale Group			Upper	Upper Border Group Volcanic Beds Middle Border Group			Lower Border Group	
	East Lothian	Measures	Il Measures									Aberlady Formation		Formation	Catternic Volcanic Formation				
Midland Valley	West Lothian						-	noi		ч	ion		West Lothian Oil-Shale Formation		Gullane eat	Arthur's So Volcanio Formatio		l	
	Fife			Measures	-	ormation			L	estone Forma	Coal Formatic	stone Formati	Pathhead Formation	Sandy Craig Formation	Pittenweem Formation	Anstruther Formation	Fife Ness Formation ne Formation	ormation	od Formation
	Ayrshire & Central	Upper Coa	Middle Cos	Lower Coa	Passage F		Upper Lim		Limestone	Lower Lime	Lawmuir FM	ZEW Z	Clyde Plateau	Formation		Clyde Sandsto	Ballagan F Kinnesswo	Kinnesswo	
	Group	səjn: Bal	up Clackmannan Group				Strathclyde Group Bathgate Gro				Group Inverciyde		9 Ənuj						
Minenore	Sone	IX X	VIII NIII	SS	Æ	KV	so	TK		NC	_	Ľ√	^		TC			>cm	
Stage		Bolsovian	Duckmantian	Landsettian	Yeadonian- Chokierian		Arnsbergian	Pendleian		Brigantian		Asbian <			Holkerian & Arundian		- university		
Dadiametria	Dates	308	- 311	- 313.5	- 316.5		320	020	- 324		- 326.5		- 331				-342.5		354
Series		Mestphalian ∩ অ ⊲		Namurian							nsəsi	٨		U	eisie	unoj			
w	eyste Sub-	nsisəlið						Dinaîtian											

Fig. 2.2.1 Lithostratigraphical and chronostratigraphical divisions of the Carboniferous in the Midland Valley and Scottish Borders. Adapted and updated from Francis (1991), Browne (1999) and Read *et al.* (2003). Radiometric dates are from Menning *et al.* (2000). Regional correlation horizons in the MVS (this study). Abbreviations; FM, Formation; Lst, Limestone; CC, Castlecary; TH, Top Hosie; MB, Marine Band.

2.2 Stratigraphic and depositional framework of the MVS

The Grampian Mountains were the source of the sediment to the Carboniferous MVS (Fig. 2.1.1), with some sediment also derived from Scandinavia and Greenland (Morton and Whitham, 2002; Shell pers. comm.). The Dinantian succession comprises the Inverclyde and the Strathclyde groups and the Lower Limestone Formation at the base of the Clackmannan Group (Fig. 2.2.1). The base of the Inverclyde Group is poorly defined and is generally placed at the transition from the red, alluvial and aeolian Upper Devonian sandstones into carbonate-bearing sediment that is more typical of the Carboniferous succession (Browne and Monro, 1989, Browne et al. 1999). The lower Dinantian Inverclyde Group contains a basal succession interpreted as a high salinity lagoonal/coastalflat environment that dried out during periodic subaerial exposure and is overlain by Strathclyde Group succession of fluvial and floodplain deposits (Cameron and Stephenson, 1985; Andrews and Nabi, 1998; Browne et al. 1999; Stephenson et al. 2002). However, farther west, in the Central Coalfield, the Strathclyde Group is represented by the Clyde Plateau Lavas, a thick volcanic succession. The mid-Dinantian Strathclyde Group is subdivided into the Gullane Formation and the West Lothian Oil Shale Formation (Browne et al. 1999). The base of the group is defined by the appearance of the first coals and palaeosols. The group comprises sandstones, shales, siltstones, claystones, palaeosols and coals (Browne and Woodhall 1999). Marine horizons in the lower Strathclyde Group contain a restricted marine fauna while the upper Strathclyde Group horizons are characterised by a diverse and fully marine fauna (Wilson 1974; Wilson et al. 1989).

The base of the Upper Dinantian Lower Limestone Formation is defined at

the base of the Hurlet Limestone across the entire MVS (Browne and Woodhall 1999). This formation is dominated by sandstones, mudstones, limestones and rooted palaeosols. Limestone intervals representing marine sedimentation are more numerous (up to seven main limestones) and more aerially extensive (recognised in several basins) than the marine sediments of either the Inverclyde or the Strathclyde groups. Coal horizons are also locally more important in the Lower Limestone Formation (Fielding *et al.* 1988) compared to the Strathclyde and Inverclyde groups. Cameron *et al.* (1998) interpreted the formation to have been deposited under predominantly deltaic conditions.

The base of the Namurian (Pendleian) Limestone Coal Formation is defined at the Top Hosie Limestone (Fig. 2.2.1). The Limestone Coal Formation was the main focus for the Scottish coal industry (in addition to the Westphalian A and B Coal Measures), and companies continue to exploit the reserves in this unit. The Limestone Coal Formation varies in character across the MVS and is represented by a thin (c. 30 m) sandy succession in Ayrshire to a (550 m) thick succession of coals, sandstones, siltstones, claystones and palaeosols arranged in upward coarsening cycles, in the northern Clackmannan Syncline of the Central Coalfield (Cameron and Stephenson 1985; Cameron *et al.* 1998). Two major marine transgressions are recorded across the MVS represented by the Johnstone Shell Bed and by the fossiliferous mudstones of the Black Metals Marine Band. Thinner, condensed successions developed across topographically high areas whereas expanded sequences were deposited in the low areas. Cameron *et al.* (1998) interpreted a predominantly fluvio-deltaic depositional environment for this formation.

The Namurian (top Pendleian and Arnsbergian) Upper Limestone

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Formation is defined at the base of the Index Limestone (Browne and Monro 1989). The formation contains up to nine important marine limestone horizons and mudstone intervals (Cameron and Stephenson, 1985). The most extensive horizon is the basal Index Limestone which represents a regional marine transgression and is present in all coalfields except east central Fife. The Castlecary, Plean(s), Orchard, Lyoncross and Calmy limestones (Fig. 2.2.1) also represent important marine transgressions, but these are not as regionally extensive as the Index Limestone. The remaining five marine horizons can only be correlated within coalfields. Floodplain sediments including thin coals, shallow marine sandstones and deltaic sandstones are also common within the formation. The Upper Limestone Formation attains a maximum thickness of 590 m in the northern Clackmannan Syncline (Cameron and Stephenson, 1985).

The Namurian (Chokierian to Westphalian A) Passage Formation is defined at the top of the Castlecary Limestone or, where this limestone is absent due to erosion, on the lowermost sandstone bed of the Passage Formation (Browne and Monro 1989). The formation is dominated by single or multistorey channel sandstones largely deposited by fluvial systems, palaeosols, thin coals and claystones on extensive floodplains. The Passage Formation is thickest, at *c*.335 m, in the northern Clackmannan Syncline (Cameron and Stephenson, 1985).

The Westphalian succession is divided into the Lower, Middle and Upper Coal Measures and the base of the Coal Measures is placed at the base of the Lowstone Marine Band (Browne and Monro 1989). Thin marine horizons and many coal seams occur in the Lower and Middle Coal Measures and mudstones; sandstones, siltstones and palaeosols dominate these Westphalian strata (Browne *et al.* 1997a). In the Central Coalfield the Lower and Middle Coal Measures represent deposition on a poorly-drained floodplain traversed by small fluvial channels (Browne *et al.* 1997a). In the south-west Central Coalfield, Ayrshire and Douglas Coalfields a fluvial-deltaic environment was dominant. Occasional short-lived marine transgressions are interpreted from thin mudstones horizons that extend across the MVS. The Upper Coal Measures were deposited initially in a similar environment to the Lower and Middle Coal Measures but the climate is interpreted as having become increasingly arid from palaeosol and plant species (Cameron and Stephenson, 1985).

2.3 Facies descriptions and interpretation

Sedimentary facies are defined on the basis of physical and sedimentological characteristics; colour, grain-size, composition, texture, bedding, sedimentary structures, fossils and ichnofabrics. These characteristics distinguish one sedimentary facies from associated or adjacent facies and reflect the process of deposition and the environment. The characteristics that define a facies are produced by a number of variables that include the composition of the sediment, the process involved in deposition and reworking, either by organisms or the process of deposition. These processes may be non-specific to an environment of deposition and therefore the context of an individual facies is the defining factor that enables the depositional environment to be interpreted.

Many facies schemes exist for the Carboniferous that are similar to those facies described here (e.g. Collinson *et al.* 1977; McCabe, 1977; Cameron and Stephenson, 1985; Fielding, 1987; Fielding *et al.* 1988; Guion and Fielding, 1988; Guion *et al.* 1995; Andrews and Nabi, 1998 and Brettle, 2001).

Each facies is described (Fig 2.3.0), with photographic evidence if appropriate. Facies interpretations have been predominantly derived from the mid-Brigantian to Langsettian succession. This stratigraphic bias is a result of access to exposure (Chapter 1 Fig. 1.7.1) and the penetration of boreholes in the central MVS, and therefore, the full Carboniferous succession is not represented in this sedimentary study. Other workers have studied Viséan, Namurian and Westphalian deposits outside the Central Coalfield, for example, Shell (2002) and Browne *et al.* (1996) in the Midlothian-Fife Coalfield. The facies (sections 2.3.1-2.3.15) are described sequentially from those representing predominantly terrestrial settings to those indicative of marine environments.

2.3.1 Coal

This facies comprises coals of varying types from anthracite to cannel coals, (Fig. 2.3.1). Poorer quality coals can contain laminated siltstones, claystones and sandstone partings. The better quality coals are low in sulphur and have high calorific values (Site Operators, *pers. comms.)*. All coals have three sets of cleavage (cleat) that are developed at an early compaction stage and may represent an expression of the tectonic stress (Browne *pers. comm.*). Plant debris is abundant within the poorer quality coals, occurring in both clumps and as isolated recognisable leaf and plant fragments. Coal seam thickness is very variable. Coals with siltstone, claystone and sandstone interlayers that split the coal into leaves can attain thicknesses of 3 m. Individual coals are commonly 20-50 cm thick (e.g. the Splint, Virgin, Airdrie Blackband) but some coals have been recorded up to 5 m in thickness (e.g. the Twelve Foot and Six Foot coals). Coal seams are commonly overlain by laminated mudstone or siltstone that can contain *Lingula* or bivalves, including for example, *Sanguinolites, Dunbarella, Naiadities*,

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	Lithology	Description	Interpretation/Significa	nce
Terrestrial		Mudstone roof to coal locally with <i>Lingula</i> present Coal of varying quality from anthracitic to cannel. Coal seams are up to 3 m thick but commonly 50 cm or less. The coal seams are often split into leaves. Coal seams can be traced across coalfields but not between them	The coals of the Midland Valley formed in swamp either with a brackish or fresh water input. The coals often underlie flooding surfaces or lake deposits. Coals are also found in the bases of channels as lag deposits.	Swamp restricted marine
	Red Fe nodules (siderite FeCOs)	Structureless friable siltstone with occasional sandstone horizons. Heavily root penetrated with ironstone nodules (siderite). The siltstone is commonly pale grey or sometimes red/brown in colour	Rooted friable siltstone represents soil formation. Grey colour is interpreted as indicating a waterlogged soil Red/forown colour represents well drained soils. The occasional sandstone horizons are either minor floods as these soils formed on floodplains or small runoff channels.	Palaeosois
	Fe nodules (siderite FeCOs)	Laminated siltstome commonly dark brown in colour. Laminae occasionally undulose. Commonly contains plant material of leaves and small twigs. Ironstone nodules, probably siderite, are present in bands and individually.	Laminated siltstones represent slow accumulation of sediment. Abundant plant material, lateral & vertical facies association indicate that these deposits were formed in lakes. Undulose lamination is probably caused by differential loading and de-watering. These deposits are occasionally slumped.	Lake sediment
	Siltstone dominated Sandstone dominated 50% sandstone & siltstone	Heterolithic sandstone and siltstone commonly pale grey to brown in colour. Occasional unidirectional & climbing ripples in the sandstones. Commonly root-penetrated, removing structure, & occasionally burrowed. Contains plant debris.	Heterolithic sandstone & siltstone represent floodplain floods. Sandstones represent waxing flow, siltstones waning flow . Plant material is carried in by the flood or present from plants on the floodplain. The unit was then overgrown with flora & occasionally burrowed before the next flood.	Overbank deposits
	A 20 cm D 10-50 cm C - 10 cm	A. Trough cross-bedding, abundant plant material B. Planar cross-bedding occasionally slumped, abundant plant material C. Structureless sandstone bed with rip-up clasts along base; contains abundant plant material D. Laminated sandstone & siltstone with unidirectional & climbing ripples & dewatering structures Beds A-C commonly have erosional sharp bases	Structures interpreted to have been produced within fluvial channels. A & B represent continuous flow and often form in multi-story packages. C represents either a flash flood or a sudden channel splay.	Fluvial channels
	Tidal sandstone	Foresets with symmetrical ripples on the top surface of each foreset. Occasional shell fragment of either brachipod or bivalve. Plant debris is also present.	Foreset represent an advance of a fluvial channel during low tide. Rippled top surface of each foreset is interpreted to be where the tide rose and flooded the sandstone wave-rippling the upper surface. The unit is interpreted to be a tidal environment.	Tidal deposit
	A P Marine C Marine B Marine	 A. Bioturbated sandstone with vertical & <i>Thalassonoides</i> burrows B. Bioturbated sandstone with bivalves & brachiopods and shell fragments C. Symmetrical wave ripples in sandstone D. Foresets with bivalves and brachiopods and occasional corals E. Bedded sandstone with bivalves and brachiopods 	A & B bioturbated marine sandstones where primary sedimentary structure has been removed. Sandstone C represent marine conditions above fairweather wave base. D was formed by submarine currents or delta progradation. E formed below storm wave base in restricted bays.	These marine sands are occasionally present instea of limestones
	A B C C C C C C C C C C C C C C C C C C	A. Laminated claystone identified as marine because of the facies associated in the immediate section e.g. Between two limestones B. No lamination but contains marine fauna C. Laminated and marine fauna D. Laminated with gastropods E. Laminated contains <i>Lingula</i> ; marine because of facies association	All claystones with marine fauna or marine facies associations represent flooding surfaces. Some of these can be correlated between coalfields e.g. Black Metals Marine Band & Johnstone Shell Bed. Others can only be traced within a coalfield or locally <3 km.	Flooding surface High clastic input or restricted area e.g. Between delta lobes
Marine	A B C D E	Marine mudstone Majority of limestones have in-situ shelly upper surfaces A. Disarticulated crinoidal limestone B. Disarticulated productids shell fragments & crinoids C. Solitary corals, mainly complete bivalves & brachiopods D. Granular limestone, many shell fragments E. Complete shells and articulated crinoids Majority of limestones have in-situ shelly lower surfaces Marine mudstone	Pass vertically into limestone or marine muds. Period of little clastic deposition with faunal establishment A, B & D Storm deposit C. Deposited near to source E. In-situ limestone Period of little clastic deposition allowing fauna to grow. Occasionally sharply erosive based	Seismic reflectors Formation boundaries Maximum flooding surfaces

Figure 2.3.0 Facies descriptions and interpretations of the Carboniferous sediments of the Midland Valley, Central, Ayrshire, Douglas and Midlothian-Fife coalfields.



Figure 2.3.1 McDonald Coal occurs in two leaves separated by 10 cm palaeosol. Spireslack Opencast Coal Site, Ayrshire Coalfield, near Muirkirk (NS 74782,29116).



Figure 2.3.2 Grey palaeosol, Gasswater natural stream (burn) section, SW of Muirkirk, Ayrshire Coalfield. (NS 62901,23291).

Curvirimula and Carbonicola.

Interpretation: Mire to swamp

The environments of coal formation are difficult to distinguish from one another because an interpretation of the lateral facies relationships, and a vertical change in environment is required. Coals can be deposited in either mires, swamps and raised bogs adjacent to lakes, shallow marine bays and or terrestrial floodplain sediments (Elliott 1965; Moore 1968; McCabe 1990). Coals of limited areal extent are more likely to be formed in mires developed in isolated raised areas. Coals of greater areal extent are more likely to represent swamp environments. Therefore, coals in the MVS were predominantly formed on poorly-drained floodplains where the water table was close to the depositional surface, indicating mainly swamp conditions.

2.3.2 Grey or red claystone and siltstone with rootlets

This facies is predominantly composed of fine-grained friable, predominantly structureless, siltstone with occasional thin (<2 cm) laminated beds or lenses of sandstone. The siltstone is either pale grey or red in colour and occurs in packages between 30 cm and 2 m thick. The red and grey siltstones can pass laterally into each other within the same bed or be interbedded within a succession. Preserved rootlets or infilled root structures, of which hair-like root traces are the most common, obscure any primary sedimentological structures (Fig. 2.3.2). The rootlets show a variety of orientations; vertical, horizontal and radiating. Rootlet lengths vary from a few millimetres to tens of centimetres. The siltstone also contains abundant plant material, including leaf and stem remains preserved on parallel laminae. Siderite nodules are commonly found in the grey siltstone and occur in a variety of orientations, commonly forming around rootlets or plant material. Slickensides along arcuate fractures are also common within the siltstone.

Interpretation: Wet; Well-drained Palaeosol

The clay and silt originate from fluvial overbank floods. The abundant roots demonstrate that these floodplains were vegetated and the growth of vegetation disturbed any original depositional structure. These claystones/siltstone are palaeosols and the colour is important in determining the level of the water table. A grey colour is interpreted to be a result of the soil, being developed in poorly-drained conditions, while the red colour represents well-drained soils (Fulton, 1987; Guion *et al.* 1995). Slickenside surfaces were formed by either post-depositional compaction or the rooting process (*sensu*. Guion *et al.* 1995).

2.3.3 Heterolithic sandstone and siltstone

This facies is composed of very fine- to medium-grained, pale-grey to yellow, laminated sandstone and grey to brown siltstone that form larger centimetre-scale beds. A heterolithic unit is commonly between 0.3 and 2 m thick. The base of the facies was observed as either non-erosive, or deposited on an erosion surface with 10's cm of relief across a distance of 10's of metres. The occurrence of an erosion surface at the base of these heterolithic units may be unrelated to the deposition of the unit because the laminae have a consistent thickness across irregularities on the erosion surface. Hair-like roots are the most commonly recognised root structures in the sediment. The sandstones sometimes fine upwards to siltstone or are non-erosively, but abruptly overlain by siltstone. Transitional or abrupt bed contacts are commonly disturbed by the presence of these hair-like root systems (Fig. 2.3.3).

Interpretation: Overbank palaeosol

The heterolithic root-penetrated sandstone and siltstone facies is interpreted as overbank deposition on a flood plain. The fining upward sandstone beds are interpreted to represent river flood events when waters exceeded channel depth, broke the banks and sand and silt was deposited as the flow waned. Siltstone layers represent minor or distal floods events. Periods of non-deposition between floods allowed for plant colonisation. Therefore, heterolithic units were deposited on the floodplain after a period of non-deposition and possible subaerial exposure.

2.3.4 Laminated siltstone and minor sandstone

This facies is characterised by very friable, finely laminated siltstone above a non-erosive and occasionally gradational base. The facies reaches 1.5 to 5 m thick, and is commonly interbedded with fine-grained sandstone beds with asymmetrical and occasionally symmetrical ripples. The laminated siltstone locally coarsens up into very fine- to fine-grained sandstone (Fig. 2.3.4). The siltstone can contain plant debris in the form of compressed stems and leaves and other organic material, such as black soft carbonaceous mudstone. Fauna includes non-marine bivalves *Carbonicola, Naiadites* and gastropods that are distributed along bedding planes. Bioturbation is common but is generally too indistinct to identify an ichnogenus, although *Planolites* can been recognised in some sections. Nodules of siderite are also commonly present and can occur individually or in discontinuous bands.



Figure 2.3.3 Overbank palaeosol deposit, Viaduct OCCS, NE of Muirkirk, Ayrshire Coalfield (NS 73124,29845).



Figure 2.3.4 Lacustrine siltstone deposit abruptly overlain by fluvial sandstone, Blinkbonney OCCS, Midlothian-Fife Coalfield, NT (34883,62286).

Interpretation: Lake margin deposit

This facies represents subaqueous deposition and the presence of nonmarine bivalves suggests a freshwater lake environment. The coarsening upwards successions, from siltstone into sandstone, are interpreted as periods when lakes were filling up with sediment, probably as deltas prograded into the lake (section 2.4.3). The presence of asymmetrical ripples also suggests that the facies represents a location close to a fluvial input. The presence of symmetrical ripples indicates that lakes were of sufficient size where waves could be generated. The sandstone interbeds represent increased input from rivers or streams during or after storms. When this facies overlies the laminated siltstone marine facies (Section 2.3.14), the boundary between the facies is gradational, indicating a marine environment becoming restricted and replaced by this freshwater facies.

2.3.5 Laminated claystone and siltstone

This facies is characterised by dark brown to grey laminated claystones and/or siltstones. Units are 1-5m thick and have non-erosive bases. The laminated mudstones contain plant material and occasional centimetre-scale siderite nodules. Fossils occur along isolated layers and can include broken and whole non-marine bivalves, gastropods, fish scales and occasional plant fragments. Little bioturbation is present in the rock despite the presence of abundant fauna. However, it is common along the fossiliferous layers.

Interpretation: Lake deposits

This laminated claystone and siltstone facies with its non-marine faunal assemblage is interpreted to represent deposition from suspension in a standing body of fresh water. The absence of bioturbation in the deposit except in distinct layers is probably due to poor environmental conditions for life.

2.3.6 Laterally discontinuous sandstone bodies

This facies comprises fine- to medium-grained sandstone with a varying proportion of siltstone preserved in lens-shaped bodies (Fig. 2.3.5). The base of the facies may be associated with 2-5 cm intraclasts of coal and mudstone. The sandstone bodies can have a lens-shaped geometry that is between 5-80 m wide, predominantly perpendicular to palaeoflow, and reach up to 8 m thick. The lenses have been traced up to 60 m along palaeo-depositional dip. The pale yellow-brown sandstone contains a variety of sedimentary structures, including planar-and trough-cross bedding and soft-sediment deformation structures. Bed thicknesses within the lenses vary from thin beds near the base, 5-15 cm, to thicker beds up to 80 cm, generally present higher in the lens.

Interpretation: Fluvial channels

The elongate lens geometry and sedimentary structures within the sandbody suggests that this facies was deposited by a fluvial system. The bases of these sandstones suggest that there was rapid flow eroding and depositing before the flow settled into a steady state. The conglomeratic basal layer between the sandstone lenses represent channel lag deposits. The presence of trough and planar cross-bedding internal structures shows a variety of internal flow regimes during deposition. The deformation of the foresets is interpreted as slumping of the downstream migrating bar either caused by turbulent flow, loading or change in water volume in the channel.

2.3.7 Medium- to coarse-grained sandstone with siltstone

This facies consists of medium- to coarse-grained pale grey-dark yellow



Figure 2.3.5 Lateral and multi storey sandstone channels, Damside OCCS (NS 88582,57992).



Figure 2.3.6 Trough cross-bedded sandstone, East of Kirkcaldy, Ravenscraig Castle, beach section (NT 29120,92435).

sandstones between 10 cm and 150 cm thick containing up to 30% silt-grade material. These sandstone beds are laterally discontinuous over distances of 2-4 m and have a distinctive 3-dimensional lobate geometry. There are a variety of sedimentary structures preserved within the unit; climbing ripples are locally present at the base of the unit; these can be overlain by asymmetrical ripples while the unit tops may contain laminae. The siltstone is present either as laminae or as drapes on the individual ripple foresets, highlighting the ripple structure. Bed bases may have concave angular clasts of broken mudstone or sandstone. Abundant plant material, between 2-75 cm in length, is also present at the bed base. The top of the deposit may either have a transitional contact with overlying sediments or have polygonal, 3-5 cm deep cracks infilled with sandstone or mudstone.

Interpretation: Rapid deposition from unconfined flows

The broad lobate geometry suggests deposition from a unconfined riverderived flow i.e. a crevasse splay across the floodplain (Collinson, 1996; O'Brien and Wells, 1986). Climbing ripples in the base of the deposit suggest rapid aggradational sedimentation from waning flows. The angular intraclasts of mudstone and sandstone are interpreted floodplain-derived, rip-up clasts. The floodplain was also the source of the plant material. The rare laminae observed in the upper part of these deposits represent suspension deposition from ponded water. The polygonal cracks represent desiccated surfaces developed during subaerial emergence. The basal surface of this facies can overlie, downlap onto or erode any facies, however, it commonly has a transitional upper surface with terrestrial facies.

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2.3.8 Trough cross-bedded sandstones

Pale yellow, trough cross-bedded, fine- to medium-grained, subarkosicsubarenitic (Pettijohn *et al.* 1987) sandstones form stacked units up to 6 m thick (Fig. 2.3.6). Individual troughs are between 10 and 40 cm thick, with an apparent width of 20-50 cm and contain plant material. Each trough has an erosional contact. The bases of these trough cross-bedded sandstone units also have erosional bases with up to 2 m of local relief.

2.3.9 Planar cross-bedded sandstone

This facies consists of predominantly quartz arenite (Pettijohn *et al.* 1987), occasionally subarkosic to subarenitic pale yellow to grey planar cross-bedded sandstone. These sandstones form multistorey packages of sandstone that can reach 9 m thick and have erosional bases (Fig. 2.3.7). Foresets are between 0.5 and 1.3 m high and consist of fine- to medium-grained sandstone. The individual foresets can fine up, with coarse grains or granules occurring along the base of each foreset. Foresets are locally deformed by slumping and appear convoluted. The units contain plant material between the foresets varying from 3- 20 cm in size.

Interpretation: flow deposits

The trough cross- and planar cross-bedded sandstone facies represents deposition of sand from either a confined or unconfined flow. These flow deposits are found within a variety of other individual facies from fluvial channels (section 2.3.6) to marine sands (section 2.3.13). The deformation of the foresets was caused locally by loading or slope instability. The plant material within the sediment is drifted material and is more common where the unit is associated with terrestrial facies.



Figure 2.3.7 a & b. (a) Planar cross-bedded sandstone, Watsonhead OCCS, (NS 83573,55069) (b) Fossilised tree trunk in loose block, Climpy OCCS.



Figure 2.3.8 Tidal deposit with paired mud drapes, above the Black Metals Marine Band Dalquhandy OCCS, Douglas Coalfield, (NS 79170,33119).

2.3.10 Cross-bedded sandstone with foreset siltstone drapes and/or rippled foresets

This facies comprises fine- to medium-grained sandstone with siltstone drapes. The siltstone drapes are present on the toeset and foreset surfaces; they comprise micaeous-muddy laminae that commonly, but not always, occur in pairs up to 5 mm apart. The siltstone drapes are commonly thickest at the toe of the foreset, thinning up the face of the foreset. The siltstone drapes appear to be rhythmically spaced (Fig 2.3.8). Foresets broadly have symmetrical ripples reworking the upper surface of each foreset. Plant remains and semi-complete shell valves and fragments of either brachiopods and bivalves are common within the sandstone.

Interpretation: Tidally influenced cross-bedded sandstone

The presence of rhythmically spaced paired muddy drapes and foresets suggest either tidal processes (Nio and Yang, 1991) or regular pulsing of fluvial discharge (Brettle, 2001). In this case, siltstone drapes are interpreted to have been deposited during periods of tidal slack, while the foresets represent deposition during ebb and flood of the tide. The tidal interpretation is supported by the presence of marine fauna and by symmetrical wave ripples that were produced as the upper surfaces of the foresets were then reworked during the flood phasesof the tide. Rippled foresets also are representative of tidal deposits (Reading and Collinson, 1996).

2.3.11 Symmetrically rippled sandstone

This facies consists of well-sorted, fine- to medium-grained sandstone. The sandstone is pale yellow/opaque in colour with grey micaceous layers highlighting the symmetrical ripple laminations. The crest-to-crest wavelength is 5 to 10 cm and ripple profiles are observed to be straight with common bifurcations. The bed thickness is commonly between 10 and 40 cm thick with occasional *Skolithos* burrows and locally a rooted upper surface. The facies has a sharp flat erosional basal contact with other sandstone facies.

Interpretation: Upper (marine) shoreface above fair-weather wave base

The presence of symmetrical ripples throughout this well-sorted sandstone indicates that the sediment was deposited under conditions of constant reworking by wave action. However, there is no indication of fauna, apart from *Skolithos* burrows, which can occur in marine or brackish water deposits.

2.3.12 Parallel-bedded heterolithic sandstone

This facies is characterised by very fine- to fine sandstone with mudstone and siltstone laminae and occasional symmetrical and asymmetrical ripples. The basal contact of beds within this facies is commonly sharp and erosive with flute and tool marks. Sole structures were also observed on bedding surfaces. Laminae are laterally persistent across exposures for distances of up to 25 m. Units locally coarsen upwards and are commonly between 0.7 and 1.2 m in thickness. Sedimentary structures are in places destroyed by intense bioturbation. *Skolithos* and U-shaped *Diplocraterion* burrows are present along specific horizons or at the top of a bed (Fig. 2.3.9). Locally, within-bed slump structures were observed. Polygonal cracks are present at the top of some beds.

Interpretation: Marine sandstone deposited on delta front

This bioturbated sandstone represents deposition in restricted marine conditions. The predominantly bedded and laminated sandstone suggests that this



Figure 2.3.9 *Diplocraterion* burrows in shoreface sediments, Wester Mosshat (NS 97949,56351)..



Figure 2.3.10 *Diplocraterion* & septate burrows in shoreface sediments, Dalquhandy OCCS, (NS 78912,33827).

facies was deposited nearshore because of the presence of the occasional asymmetrical current ripples and symmetrical wave ripples. A nearshore marine setting is consistent with the presence of *Diplocraterion*, a marine trace fossil. The polygonal cracks are interpreted as desiccation during subaerial exposure.

2.3.13 Bioturbated sandstones

This facies is characterised by fine- to medium-grained pale grey to yellow sandstone (Fig. 2.3.11). The sandstone has occasional foresets up to 40 cm high, parallel and undulose laminations, but generally these have been obscured by intense bioturbation. A marine fauna is present consisting of Productid brachiopods, both whole and broken, crinoid ossicles, coral fragments, *Skolithos* and *Diplocraterion* burrows and other unidentified brachiopods and bivalves. The whole Productids and the brachiopods are parallel to bedding and articulated.

Interpretation: Lower shore-face sandstone below storm wave base

This intensely bioturbated sandstone with Productid and unidentified brachiopods indicate a fully marine environment. The intense bioturbation means that it is difficult to place the unit in an exact location in the water column. The fauna are interpreted to be in life position because of the presence of articulated shells and their orientation. The intensity of the bioturbation and the fine- to very fine-grained sandstone lithology suggests that deposition could have occurred slowly, below storm wave-base.

2.3.14 Laminated claystone and siltstone with marine fauna

This facies is characterised by dark brown to grey, laminated claystone or siltstone forming successions 3-5 m in thickness. Where this facies is interbedded with limestones it is commonly grey and calcareous. Flute and groove marks have



Figure 2.3.11 Marine sandstone, limestone equivalent, Gasswater Stream (Burn), (NS 62901,23291).



Figure 2.3.12 Laminated marine claystone, Dalquhandy OCCS, Douglas Coalfield, (NS 78912,33827).

been recorded on some of the bed bases. The laminated claystones contain organic material and occasional centimetre-scale siderite nodules. Fossil assemblages include broken and whole *Lingula*, crinoid ossicles, brachiopods, bivalves, fish scales and occasional plant fragments (Figs. 2.3.12 & 2.3.13). Little bioturbation is present in the sediment. The facies is often observed to occur in subtly coarsening-upward packages with siderite nodules occurring between each package.

Interpretation: Predominantly suspension-deposited marine sediments

The laminated claystone is interpreted to represent deposition following a marine transgression because of the fossil assemblage including broken and whole *Lingula*, crinoids and brachiopods. The deposit was formed as a result of clastic input into a marine setting below storm wave base. However, the calcareous nature of those deposits interbedded with limestones indicates that carbonate production was still occurring. The fossil assemblage present is a result of storm activity damaging reef and shallow marine environments proximal to the coast and the shell and fragments being deposited in the deeper areas. The coarsening-upwards cycles are interpreted to represent filling of the available accommodation.

2.3.15 Limestone

The majority of limestones have in-situ (but some reworked) shells at their upper and lower surfaces (Figs. 2.3.14 and 2.3.15) with five distinct types of fossil assemblage within the limestones: A. Disarticulated crinoids; B. Disarticulated productid shells, unidentified shell fragments and crinoids; C. Solitary corals (Fig 2.3.16), mainly complete bivalves and brachiopods; D. Abundant shell fragments



Figure 2.3.13 Laminated marine mudstone, MacGreggor marine band. Pittenween Harbour



Figure 2.3.14 Marine mudstone to limestone transitional boundary, (NS 73124,29845).

and occasionally whole shells within the CaCO₃ grains; E. Complete shells and articulated crinoids. The cement of these limestones is composed of fine- to medium-grained sparite. Limestones have either a sharp basal contact, if overlying the coal or terrestrial siltstone facies, or a gradational basal contact if overlying the marine mudstone facies (Fig. 2.3.14). Commonly the limestones are structureless, though they may show a slight upward fining. Individual units range between 0.1 and 1.7m in thickness. Poorly sorted grains of calcium carbonate in layers or lenses are occasionally present. The limestones are discretely bedded, structureless or massive. The limestones are either interbedded with or overlain by dark claystones (Figs. 2.3.12 & 2.3.13) or siltstones (facies 2.3.14) that often contain the same types of fossil assemblage as the associated limestone.

Interpretation

The marine limestones formed during periods of low clastic input. The presence of large amounts of broken and disarticulated material within the limestones indicate that they were redeposited during storm events. The base of the marine limestones commonly represent eustatic sea-level changes. The clay intervals that separate the limestones are interpreted to be periods of higher clastic input.

2.4 Facies Associations

The environments of deposition in the Carboniferous MVS can be analysed by grouping the facies identified in the field and boreholes into facies associations. Facies boundaries delineate lateral and vertical changes in environment of deposition. This relationship conforms to '*Walthers Law*' (Walther 1894), which states that facies in vertical contact with each other must be the product of spatially adjacent environments during deposition. A facies association comprises a set of facies that are found together in a vertical succession, without any major break in deposition.

The measured Carboniferous strata can be divided into six facies associations: (1) open marine; (2) restricted marine; (3) deltaic; (4) fluvial; (5) poorly-drained floodplain; and (6) well-drained floodplain. These facies associations were compiled from fieldwork and boreholes studied in this work (Fig. 2.4.0). The facies associations tend to be stacked in the order presented (1-6), however, not all associations locally occur in a single cycle.

2.4.1 Open marine facies association description

The lower boundary of this facies association is sharp and can be easily defined. The upper boundary to this facies association is commonly wave-rippled and can be root-penetrated or be gradational into siltstones or sandstones, and may be placed only within a zone of sediment rather than at a single horizon.

The base of the open marine facies association is marked by a generally prominent fossiliferous limestone (section 2.3.15) or laminated claystone or siltstone (section 2.3.14) that immediately overlies non-marine deposits, commonly coals or palaeosols (Fig. 2.4.1). The limestone can pass upward into laminated claystone or siltstone facies or vice versa. A siltstone typically overlies the interbedded limestone, laminated claystone and siltstone. These siltstones occur in 1 to 1.5 m coarsening-upwards cycles with isolated siderite nodules or siderite bands (Fig. 2.4.1). The siltstones contain an abundant marine assemblage, but, fossiliferous plant material is uncommon and no in-situ plant material was



Figure 2.3.15 Marine limestone, Muirkirk Stream (Burn) Ayrshire Coalfield, (NS 69069,25624).



Figure 2.3.16 *Syringopora gegiculata,* coral that grows in isolation in shallow marine shelf conditions, from Burntfoot Moor OCCS, (NS 68442,27097).

observed. Siltstone is typically overlain by a sharp-based, laminated or heterolithic sandstone (described in sections 2.3.11 to 2.3.13), interpreted to be shoreface sandstones.

Interpretation

This open marine facies association provides evidence for prolonged subaqueous deposition following a major marine transgression. The marine flooding is represented by either the fossiliferous limestone or laminated mudstones. However, sandstone is also found at a stratigraphically equivalent level to the limestone facies (2.3.14). Flooding is considered to be rapid but passive, as there is little evidence of erosion of the underlying sediment during the drowning of the floodplain. The coarsening-upward siltstones represent the reestablishment of clastic-dominated deposition and progradation of sedimentary bodies into a standing body of water. The lack of root structures, in comparison to other silt-dominated facies, suggest sufficient water depth to preclude vegetation growth. The absence of wave ripples suggests that this siltstone was deposited below storm wave base.

The overlying sharp-based symmetrically rippled sandstone with laminated marine claystone facies (2.3.14) and tidal facies (2.3.11) imply a marine rather than lacustrine setting. The association of these facies is interpreted as a shoreface. The facies association probably reflects an abrupt switching of the clastic supply system, indicating rapid progradation of sediment bodies into the standing body of water, with deposition occurring during waning flow. The presence of wave ripples at the top of the uppermost bed implies that the deposit was reworked by wave action after deposition.

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KEY to all logs

0	Siderite nodule	2-	Flute marks
	Leaf remains	V	U-shaped burrows
X	Plant stem	// N	Vertical lined burrows
X	Root structure		Fish scales
00000	Rhizocretions	W	Coral
	Cross-bedding with wave-rippled foresets	\odot	Crinoid ossicle
	Large scale trough cross-bedding		Crinoid
1 ANSAZ	Convolute bedding	(Fossil centre to siderite nodule
111111	Planar cross-bedding	ALL DE CONTRACTOR	Broken brachiopod
1112	Low angle trough cross-bedding	ALL DE CONTRACTOR	Brachiopod
	Trough cross-bedding	()	Broken bivalve
	Wave ripples		Bivalves
HHH+	Current ripple lamination	0	Lingula
ITTIM	Current ripple		Gastropods
~	Wave ripple crest		Wet Palaeosol
matthe	Climbing ripples		Dry Palaeosol
mark	Erosion surface		Sandstone
1200	Lamination		Siltstone or Claystone
D	Rip-up clast	\square	Section gap

Fig 2.4.0 Location of opencast coal sites (OCCS) and natural exposures where sections have been measured during field seasons between October 1999 and November 2002, and the key to all log sections.

2.4.2 Restricted marine facies association

The restricted marine facies association comprises interbedded siltstones and sandstones, and extends from either above the open marine, laminated mudstones and siltstones, or above the sharp-based sandstone, of the open marine facies association. The lower boundary of this silt-dominated facies association is poorly defined because it is gradational and recognition largely depends upon a change from being dominated by marine fossiliferous assemblage that dies out vertically being replaced by a drifted floral assemblage, with occasional in-situ roots. However, the facies association is easily defined where it overlies the upper sharp-based sandstone of the open marine facies. The upper surface is easily defined because there is a transition to terrestrial or fluvial sediments.

The laminated siltstones at the base of the restricted marine facies association typically occur in 1-1.2 m units with no vertical grain size changes. Isolated siderite nodules or siderite bands (Fig. 2.4.1) occur in these restricted marine siltstones. The restricted marine siltstone is typically overlain by a sharp-based sandstone. These sandstones are predominantly structureless but contain laminations, thin planar bedding, bi-directional wave ripples, current ripples, trough cross-bedding, *Diplocraterion* and vertical burrows. The top of the bed is commonly root-penetrated with desiccation cracks. These sandstones are typically overlain by palaeosols and coals.

Interpretation

The observed gradational change from abundant marine fauna assemblage to a siltstone with abundant plant material suggests that the siltstone was being deposited in an area that was becoming increasingly separated from open marine conditions. The occasional root structures in the top of the siltstone suggest that



15m-

opencast coal mine, (Douglas Coalfield NS 79226, 33906) and Spireslack opencast coal mine, (Ayrshire Coalfield NS 74782,29116). Fig. 2.4.1 Sections of logs recorded at Dalquhandy

20m

25m

6 Well-drained floodplain and 3 Deltaic facies association; 5 Poorly-drained floodplain 2 Restricted marine facies Open marine facies FS flooding surface. Abbreviations; association association 4 Fluvial

Symbols are in the key to all logs Fig. 2.4.0. The limestones palaeontologist Dr M Dean who assemblage and confirmed the are named because samples aken in this study were examined the fossil dentified by BGS imestone.

5

cloy sit vis is ms as vas gr pebble

8

Om

6 1 1 1 1 0

5m

10m

relative water depth and salinity fell to allow vegetation growth.

The change form open an open marine setting to a restricted marine setting could be the result of many factors. These range from closure of the access point to the sea, infilling of the depocentre or relative sea-level change (*sensu*. Crowley and Baum, 1991; Maynard and Leeder, 1992; Read, 1994; Flint *et al.* 1995; Hampson, 1998; Davis *et al.* 1999; Brettle, 2001; Shell, 2002).

2.4.3 Deltaic facies association

The deltaic facies association overlies the open- or restricted-marine facies association or the poorly-drained floodplain facies association. Two examples of this association (labelled 3, Fig. 2.4.2) are presented from different locations in the Ayrshire Coalfield (Fig. 2.4.0) at the same stratigraphic level and approximately 1.5 km apart. These are above the Index Limestone that forms the boundary between the Limestone Coal and Upper Limestone formations (Fig 2.4.2).

The lower boundary of this facies association is placed at a siltstone that commonly contains a marine faunal assemblage that includes brachiopods, bivalves and gastropods. The structureless or laminated siltstone coarsensupwards through sandstones with laminated heterolithic intervals of very fine sandstone and siltstone (Fig 2.4.2). Each successive sandstone bed is coarser and may be structureless or, more rarely, contain trough cross-bedding or ripple crosslamination. Beds may be cut by small channels or scours, 2-4 m in width. Convoluted layers occur and wave ripples are common throughout (Fig 2.4.2). Disarticulated marine fauna and occasional horizons with abundant drifted plant material can occur throughout. A coarse sandstones containing planar- and trough-cross bedding is present above the wave-rippled sandstones; the foresets can be paired or have symmetrical ripples on the foreset tops (Fig 2.4.2 and


Fig. 2.4.2 Sections of logs from Burntfoot Moor opencast coal site and Muirkirk natural section, both are located in the Ayrshire Coalfield (Fig. 2.4.0), approximately 1.5 km apart and describe the top of the Limestone Coal Formation and the lower part of the Upper Limestone Formation.

section 2.3.11). The boundaries between all of the beds and facies can be either gradational or sharp and erosive. The tops of the trough- and planar-cross bedded sandstones are commonly penetrated by hair root traces. This coarsening-upwards sandstones deltaic succession is overlain by a thin palaeosol or coal horizon.

Interpretation

The marine siltstone at the base of the deltaic facies association represents the prodelta which grades upwards from the local basin floor (Leeder, 1999). The coarsening-upwards succession observed represents the progradation of a delta into a standing body of water either established following a marine flooding event or the formation of a lake. Gradational boundaries between coarsening upwards siltstones and sandstones indicate continuous deposition during progradation. However, the sharp and erosive bases between other coarsening-upwards sandstone units may indicate lobe-switching or the development of crevasse splays. Those sandstone, beds that contain marine fauna, plant material, convolute beds, laminae and asymmetrical and climbing ripples (Fig 2.4.2) are interpreted to represent deposition on the delta front. This area is then incised by the small channel or scours bypassing sediment towards open water. The coarser planarand trough-cross bedded sandstones are interpreted as the main distributary channel systems on the delta tops, the symmetrical ripples on foresets (Fig 2.4.2 and section 2.3.11) indicate that these sandstones were being deposited subaqueously and were then subject to wave reworking. This facies commonly occurs above the marine facies association and below the terrestrial facies association. The root-penetrated tops of these sandstones represent emergence of the delta top through further progradation of the delta front and the change to delta plain. The overlying thin palaeosol or coal horizon represents deposition on the

36

delta plain. The deltaic facies association in both logs may represent the same delta laterally, or two separate but adjacent deltas.

2.4.4 Fluvial facies associations

The fluvial facies association extends gradationally from the top of the deltaic facies association or has an erosional base commonly eroding into floodplain sediments (Fig. 2.4.3 and sections 2.4.5 and 2.4.6). The fluvial facies association contains single and multi-storey stacked, tabular cross-stratified, lenticular bodies (sections 2.3.6 and 2.3.7) that are between 5 and 80 m wide. However, much wider associations of channels have been recorded in the MVS (Francis, 1991a; Read, 1988; Read, 1989a; Read, 1989c).

In this study these sandstone units have a very coarse basal unit that may contain rip-up clasts and erodes into the underlying unit. The individual units within the sandstone bodies fine upwards, units consisting of thinly bedded or laminated sandstones, and trough and planar cross-bedded sandstones that fine upwards (sections 2.3.7 to 2.3.9). The overall lenticular sandstone bodies (Fig. 2.3.6) also fine-upwards, to fine- or medium-grained sandstone. The lensoid units inter finger laterally with finer-grained floodplain facies associations or other lensoid sandstones (Fig. 2.3.6). The upper part of a sandstone lens tends to be planar and contain hair root (Fig. 2.4.3) and in situ *Stigmaria* root traces. Minor coals are occasionally preserved at the top of the individual channel units.

Shell, (2002) studied the petrology of comparable sandstone bodies from the Viséan of Fife. The sandstones are composed of 84-88% quartz, 5-6% feldspar (orthoclase) and 7 - 10% lithic fragments, including cherts and



Fig. 2.4.3 Part of the log through the Passage Formation, from the coastal section along the Joppa shore east of Edinburgh, in the Midlothian-Fife coalfield. The log is continuous and includes a 1 m overlap between each column. The section shows the fluvial, poorly-drained and well-drained floodplain facies associations.

metamorphic fragments and are classified as sublitharenites.

Interpretation

The sedimentary structures and the geometry of these large sandstone units are interpreted as the deposits of fluvial channels. The coarse basal unit of the lensoid sandstones represents a channel lag deposit. The presence of numerous sub-metre-scale internal erosion surfaces implies that the individual channels amalgamated to form 'multi-storey' packages of sandstones.

These large channels are exposed in the high walls of many opencast sites and along coastal sections through all formations. However, the Passage Formation is dominated by these channels (Fig. 2.4.3) and the Lower Coal Measures also has numerous channels.

2.4.5 Poorly-drained floodplain facies association

The poorly-drained floodplain facies association extends from the top of either the fluvial, deltaic or restricted marine facies association. The top of the poorly-drained facies association is commonly marked by a coal or rooted siltstone. However, this facies association is also commonly inter layered with the well-drained floodplain and fluvial facies associations as well as in erosional contact with the fluvial facies association.

The poorly-drained floodplain facies association comprises sand-rich and sand-poor packages. The sand-rich packages consist of structureless sandstone (section 2.3.7) and heterolithic sandstone and siltstone (section 2.3.3). The sandpoor deposits consist of laminated siltstones, with siderite nodules, both rooted and non-rooted and siltstones with minor sandstones (sections 2.3.4 and 2.3.5). Also present are substantial thicknesses of grey rooted siltstone (Fig. 2.4.3 and section 2.3.2). The presence of substantial coal (section 2.3.1) deposits have also been observed interlayered with these deposits. The sand-rich and sand-poor deposits are laterally equivalent to laterally discontinuous fluvial sandstones.

Interpretation

The sand-rich subgroup is interpreted as representing periods of increased lateral channel activity when flooding commonly overtopped the depositional channel levees, creating crevasse splay deposits (section 2.3.8) and finingupwards heterolithic overbank deposits (Fig. 2.4.3). The sand-poor group represents deposition in areas distant from major channels, or during periods of low channel activity. The laminated siltstones with siderite nodules represent ponded areas, bays or lake deposits on a poorly-drained floodplain. Wet palaeosols formed adjacent to the lake deposits and the presence of coals indicates swamp conditions on these poorly-drained flood plains

2.4.6 Well-drained floodplain facies association

The well-drained floodplain facies association extends from either the top of the poorly-drained floodplain or from the fluvial facies association. The base of the facies association is placed above a sharp-based erosive sandstone, while the top of the unit is commonly a red rooted siltstone. This is overlain by red, oxidised, rooted, siltstones that are interpreted as palaeosols (section 2.3.2). The siltstone is often scoured by thin (c. 10-20 cm) erosive based sheet sandstones. This facies association is distinguished from the poorly drained facies association by the absence of a number of key characteristics; the absence of the overbank heterolithic deposits, the absence of coals representing mire and swamp areas and the absence of laminated siltstones with siderite nodules representing lake

deposits.

Interpretation

The well-drained floodplain facies can be interpreted as having formed on the floodplain away from fluvial interactions or above the water table. Both of these are possible, as the identifying unit of the facies association, the oxidised rooted siltstone, can occur in the same unit laterally to the poorly-drained grey rooted siltstone, indicating that distance from a fluvial source or water table controlled the distribution of this facies association (Browne *pers. comm.*). The formation of this facies association above crevasse splay deposits is also important; the sandstones would allow for rapid draining of the silts forming soil therefore allowing for oxidation and a dry floodplain association.

2.5 Establishing regional environments by correlating from logs to

borehole in the MVS

Sedimentary logs from natural and opencast coal sites in the MVS (Fig. 2.5.1) have been used in this study to establish and assess those regional environmental interpretations that have been proposed for the MVS by Browne and Monro (1989), Read (1988) and Rippon *et al.* (1997). The sedimentary logs (Appendix 3) provide detailed information on the depositional setting locally in the MVS. Wider regional depositional settings are established by integrating the sedimentary logs into the boreholes dataset and palaeogeographic reconstructions.

An example of correlating between boreholes and sedimentary logs to establish the regional environment in the Douglas Coalfield is presented in Fig.



Fig. 2.5.1 Summary of logs spatially and temporally in the Midland Valley, logs are aligned on major correlation horizons across the MVS. However, if the correlation horizon is not present then coals are used as a correlation horizon. Approximately 1300 m of section have been logged in the MVS.

2.5.2. In the correlation major flooding surfaces have been identified at the bases of the McDonald Limestone (equivalent to the Hosie Limestone Fig. 4.1.2), the Johnstone Shell Bed, the Black Metals Marine Band and the Index Limestone. The succession above the McDonald Limestone coarsens upwards into the deltaic and fluvial facies associations, palaeoflow measurements indicate that flow direction was towards the centre of the Douglas Coalfield. The laterally discontinuous McDonald Coal tops the deltaic facies association. A minor flooding surface is placed above the coal based on the lithofacies change to the restricted marine facies association; laterally and vertically the succession is sandier with fluvial channels. The regional flooding surface of the Johnstone Shell bed is located above fluvial channel sediments. The succession in both boreholes coarsens upwards above the Johnstone Shell bed; however, a section gap exists in the log from the natural section at Dalquhandy. An example of a wet floodplain facies association overlies the coarsening-upwards cycles with coals, palaeosols and lake deposits or restricted marine conditions. The Black Metals Marine Band is a regional flooding surface that is identified throughout the MVS. The Black Metals Marine Band represents the thickest accumulation of marine mudstone from the Namurian- and Westphalian-aged formations. The succession coarsens upward to another regional flooding surface below the second Black Metals Marine Band. The succession coarsens upward through a small deltaic facies association. This is overlain by a substantial thickness of the waterlogged floodplain facies association that contains several substantial coals. A lithofacies change to fine-grained deposits represents a flooding surface, however, only the lowermost of three coarsening-upwards packages has been recorded in the sedimentary log because of a section gap. Above the section gap a MVS-wide



Fig. 2.5.2. Log to borehole correlation of sedimentology in the Douglas Coalfield. Symbols in Fig. 2.4.0. Abbreviations PF, palaeoflow; U, upper; L, Lower. The Mainshill bore is presented at a smaller vertical scale because the strata dip between 40-60° therefore, thickness measurements are exaggerated by ~30%.



important flooding surface represented by the Index Limestone is recognised.

The major flooding surfaces can be traced across the MVS in boreholes, whereas lithofacies correlation surfaces can be traced through the majority of boreholes in a particular coalfield. Using these correlation method palaeogeography maps (section 2.5.1) of the MVS can be constructed.

2.5.1 Palaeogeographic Reconstructions

Palaeogeographic maps are constructed from interpretations of the facies associations identified in this thesis. The palaeogeographic maps are produced by identifying multiple similar or repeated facies associations stacked vertically, within an identifiable time window. Thus a broad palaeogrographic environmental setting can be identified. This is applied to geographic areas where fieldwork investigations were undertaken thus producing a regional setting. Where no fieldwork studies were undertaken the interpretations of environment were produced by integrating borehole records in this study with published palaeogeography maps constructed from borehole studies and outcrops for the entire Carboniferous of the MVS by Browne and Monro (1989), Read (1988) Rippon *et al.* (1996).

In these palaeogeographic reconstructions the various formations tend to be dominated by a limited number of facies associations, that may reflect the subsidence evolution discussed in later chapters.

During the late Famennian to early Tournaisian, Browne and Monro's (1989) palaeogeographic reconstruction shows a ENE-orientated, longitudinal aeolian sand body, the Knox Pulpit Formation, located across the centre of the MVS. Laterally to this, fluvial sandstone deposits are present, while the area south of Glasgow is interpreted to have been non-depositional (Browne and











300000

Fig. 2.5.4 Mid Namurian palaeogeographic reconstructions (A) below the Index Limestone. (B) above the Index Limestone with the locations of fieldwork studies (white circles) undertaken in this work.

Monro 1989). The fieldwork investigations did not look at any of this age deposits.

In the late Tournaisian, fine-grained sedimentation was dominant in the central and eastern MVS, with fluvial sedimentation occurring along the margins of the MVS, predominantly along the southern margin (Browne and Monro 1989). By the early Viséan the fluvial deposition was more extensive and an oil shales were being deposited around the Lothians (Browne and Monro 1989). In the western MVS an area of volcanic rocks (Clyde Plateau Volcanic Formation) underlies an area of non-deposition (Browne and Monro 1989). By the mid-Viséan the area of non-deposition extended in the western MVS and oil shale deposition in the Lothians had become more extensive. The marginal fluvial deposits of the MVS are interpreted to have built an alluvial plain (Browne and Monro 1989). The fieldwork investigations did not look at any of this age deposits.

The Late Viséan palaeogeographic reconstruction shows fine-grained marine and deltaic sedimentation. Small areas of non-deposition occured in both the eastern and western MVS (Browne and Monro 1989). The fieldwork investigations did not look at any of this age deposits.

In the early Namurian (Fig. 2.5.3 A and B and 2.5.4 A) deltaic sedimentation became more widespread, although fine-grained sedimentation occurred with widespread marine incursions, especially in the western MVS, identified in the Ayrshire Coalfield and the south-eastern Central Coalfield, this study. Channel facies and an area of non- or slow-deposition are found in the north-western and eastern MVS (this study and Browne and Monro 1989). The Bathgate Hills Volcanic Formation was being extruded during this period and is interbedded with deltaic and fluvial deposits.

In the middle Namurian, (Fig 2.5.4 A & B) marine and deltaic deposits are restricted to the Aryshire Coalfield (Browne and Monro 1989). Whereas fieldwork in this study has identified that the Douglas and Central coalfields are dominated by fluvial and poorly drained floodplain facies associations.

In the late Namurian, (Fig. 2.5.5 A) fluvial sandstone channels are most widespread, however, some variation does occur in the western MVS (this study), and in Fife where a highly variable sequence rich in coal seams is present (Browne and Monro 1989). The palaeogeography of the Westphalian (2.5.5 B) show a generally deltaic and poorly drained floodplain facies associations this study and (Browne and Monro 1989). This study has also shown that the orientation of channel sandstone bodies has moved from a south-westerly to a southerly direction implying that the area of the Southern Uplands was being overtopped.

2.6 Summary of sedimentation in the Midland Valley

The sedimentological interpretations of the MVS made in this study are broadly similar to those of Read (1988), Browne and Monro (1989) and Rippon (1997). However, there are some differences between this study and those previously undertaken. These difference are detailed in the following section.

The MVS Carboniferous sediments were deposited on subsiding flat or gentle palaeoslopes. Temporal and spatial facies changes were minimal; depocentres were dominated by shallow-marine, deltaic and alluvial environments and no Carboniferous alluvial fans are recorded along basin margins. These flat or gentle plains were formed between topographically high volcanic areas.

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The logs record that marine sedimentation was more widespread in the south-western MVS (Ayrshire and Douglas coalfields) during the early period of deposition of the Limestone Coal Formation. This is preserved in the form of laminated claystones and siltstones. Restricted marine sediments and wavedominated deltaic sandstones are also preserved in this succession, with few fluvial channels and relatively small amounts of floodplain deposits.

In contrast, the Limestone Coal Formation in the Central Coalfield was only periodically flooded by marine transgressions, indicated by the presence of limestones and laminated claystones and siltstones. Small deltas are also present in the Central Coalfield, but the area was predominantly a floodplain with channels supplying sediment to the open marine areas of the western MVS. Browne and Monro (1989) showed that the eastern MVS was dominated during this time by floodplain sediments cut by fluvial channels.

The fluvial channels that supplied sediment to the deltas are observed to be restricted by topography created by syncline growth with a greater concentration of fluvial sediments present in the core of the synclines compared to the limbs; a similar observation has also been made in the Midlothian-Fife Coalfield (Shell *pers. comm.*). Therefore, deposition was actively being controlled by syncline subsidence.

Marine sedimentation continued to dominate in the Ayrshire Coalfield until the deposition of the Passage Formation. However, the Douglas Coalfield appears to have become isolated during the Upper Limestone Formation from both the Ayrshire and Central coalfields. This is apparent from the presence of lake deposits, and recorded palaeoflow indicating that flow was toward the centre of the Douglas Coalfield rather than towards the open sea to the west. During the deposition of the Passage Formation, palaeosol and fluvial channels predominantly formed the fill of the depocentres. Read (1988) suggested this was a result in a fall in relative sea-level; this is further discussed in Chapter 7 where an alternative explanation is proposed.

The Midland Valley has a distinctive Carboniferous sedimentary fill. Within the depocentres deposition appeared to have kept pace with accommodation generation. In contrast, deep marine Dinantian and Namurian deposits are preserved in the basins of central and northern England reflecting underfilled depocentres. In addition, thick successions of alluvial fan conglomerates that characterise fault-bounded margins are not observed in the MVS but occur in other Carboniferous basins, for example the Northumberland Basin. This suggests that faults only created minimal topographic relief.

Important for this study was also the identification of major stratal packages as these are the basis for the identification of seismic facies packages.

Chapter 3

Seismic Interpretation Methodology

3.1 Introduction and background

The reflection seismic lines distributed across the Central Coalfield have, to date, been scientifically underutilised. The dataset is predominantly located onshore but does include an offshore grid in the Forth estuary. Previous work has relied upon the borehole subsurface dataset (held by the BGS), and surface mapping to provide data to develop and test tectonic models (George, 1960; Read and Dean, 1967; 1968; Read 1969; Read et al. 1971; Read and Dean, 1973; Read and Dean, 1975; Read and Dean, 1976 Read, 1981; Bluck, 1984; Belt, 1984; Cameron and Stephenson, 1985; Fielding et al. 1988; Browne and Monro, 1989; Read, 1988; Read, 1989a; Read, 1989b; Read, 1989c; Gibbs, 1989; Read, 1994; Read, 1995; Andrews and Ghulam, 1994; Phillips et al. 1997). Although reflection seismic data has been in existence since 1982, the only studies that have made use of either reflection or refraction resources are: Hall et al. (1984; refraction); Conway et al. (1987; refraction); Armstrong and Owen, (2001; refraction); Ritchie and Browne (unpublished); Ritchie et al. (In Press reflection), previous to this no study has used the seismic reflection data in the Central Coalfield.

The reflection seismic dataset used in this study comprises 78 lines, varying both in vintage (lines were surveyed between 1982-1986) and quality. This chapter explains the details of five key methods used to interpret the seismic reflection profiles; seismic reflector termination picks; borehole depth correlation; comparison with mapped surface geology; comparison with cross-sections along the line of the seismic; subsurface plots of key seismic and mapped horizons from boreholes (processed in Winsurf V5.03).

Due to the varying quality and quantity of the data it was not necessary, or possible, to use all of these methods on all seismic lines. The initial seismic interpretation concentrated on the longer seismic lines and those seismic lines with the most abundant intersections with other lines. This approach enabled a more accurate interpretation of those seismic lines that have less geological control or are of poorer quality.

The seismic data were predominantly obtained from the UK Onshore Geophysical Library (UKOGL), others were obtained from DTI and BGS archives. The seismic dataset was shot by several companies for both the petroleum and coal exploration sectors of the onshore and nearshore energy industry. The data was commissioned by Saxon Oil PLC, Tricentrol Oil Corporation Ltd, Teredo Oils Ltd, Berkeley Resources Ltd, Enterprise Oil and Horizon Exploration Ltd, and have not been previously considered in their entirety or included in any published study. The history of the seismic data has also been confused because all of the original companies sold on the data, and have also undergone takeovers and mergers. Therefore, some of the data was only released for this study once the current owners were traced. The seismic data were obtained in paper format, and interpreted predominantly in two way travel time TWT (note section 3.1.2 on velocity conversion). The seismic lines have been static corrected, to account for topography, by the original processors and they are projected from a subsurface datum, which is predominantly at or near sea-level.

Seismic interpretation is based on three fundamental assumptions. (1) Coherent events on seismic records or on processed seismic sections are reflections from acoustic impedance contrasts in the Earth (Sheriff and Geldart, 1983). (2) The contrasts are associated with bedding which represents the geological structure. Therefore, mapping the arrival times of coherent events is related to the geological structure, and allowing for velocity and migration effects, a map is obtained showing the geological structure (Sheriff and Geldart, 1983). (3) The seismic detail (waveshape, amplitude, etc.) is related to geological conditions, that is, stratigraphy and interstitial fluids (Sheriff and Geldart, 1983).

The interpretation methods used in this study are covered in great detail in the next few sections.

3.1.1 Seismic example introduction

One example of a reflection seismic line is used to demonstrate the methods of interpretation. The chosen line, TOC85-V330, is located in the on the western limb of the northern part of the Clackmannan Syncline of the Central Coalfield to the west of the Firth of Forth and the River Forth (Fig. 3.1.1). Topographic relief along TOC85-V330 is approximately 30 m elevation from sea-level, however, the seismic line is projected from a sub-surface datum approximate to sea-level. The broadly N-S-orientated line has an arcuate trace (Figs, 3.1.1 & 3.1.2). The Lower Coal Measures crop out along the seismic line with a small area of Passage Formation occurring towards the north of the seismic line (Fig. 3.1.2). Five other reflection seismic lines cross TOC85-V330 (Fig. 3.1.1) and from south to north these are; TOC82-V301, TOC85-V328, TOC85-V329, TOC83-V317 TOC85-V327 and TOC82-V311. Nine boreholes are located within 1.5 km of the line and, of these boreholes, one is located directly on the seismic line (Fig. 3.1.2). The depth to key formation boundaries and prominent surfaces in boreholes are presented in table 3.1.1.



Figure 3.1.1 Geological map of the Central Coalfield of the Midland Valley. Modified from BGS sheets 30 E, 31 E & W, 32 W, 39 W & E, showing the position of TOC85-V330 and Figure 3.1.2.



	Borehole					Plean	Calmy	Orchard	Lyoncross	Index	Black Metals
	reference no. to		Grid Ref.	Grid Ref.	Castlecary	Limestone	Limestone	Limestone	Limestone	Limestone	Marine Band
Borehole name	figure 3.1.2	Sheet	Easting	Northing	Limestone (m)	(m)	(m)	(m)	(m)	(m)	(m)
East Carron		NS	8867	8260		-507	-584				
Carronhall 35	CV	SN	8716	8390	-302						
Cuttyfield		SN	8888	8432	-470	-549					
No.36 Carronhall	4	SN	8717	8521	-387	-465	-527				
South Letham No.1 Bore (1952)	4)	SN	8862	8525	-381	-472	-543	-613	-683	-802	-1024
Mossneuk	9	SN	8723	8609	-343.98	-425.88	-504.14	-422.24	-644.28	-766.22	-973.7
Airth Estate No.1 (Carron Co.)		SN	8834	8705	-457	-578	-666	-763	-829	-956	
On Westfield		SN	8834	8706	-451.36	-576.94	-658.84	-758.94	-826.28	-951.86	
Carnock No.4(Bullions) Bore	3	SN	8694	8720	-358	-462	-537	-622	-686		

Table 3.1.1 Depths to key formation boundaries related to TOC 85-V330 and location of line and boreholes



Boreholes

1 East Carron

- 2 Carronhall 35
- 3 Cuttyfield

- 4 No.36 Carronhall 5 South Letham No.1 Bore (1952)
- 6 Mossneuk
- 7 Airth Estate No.1 (Carron Co.)
- 8 On Westfield
- 9 Carnock No.4(Bullions) Bore
 - 2_ Dip direction and value

TER85-V330

Mapped fault

Middle Coal Measures MCMS

Lower Coal Measures LCMS

Passage Formation PGP



3.1.2 Time-velocity conversions

The velocities in the seismic lines were applied by the original processors and have not subsequently been reprocessed. These can be inaccurate, as they were applied to present the smoothest profile, not necessarily to reflect geology. This introduces problems when converting time to depth for integration of borehole and well depth to key horizons (drilled depth or logged depth). However, when analysed, the geological data in the boreholes and geophysical wells allowed the interpreter to establish that the velocities used to process the seismic are a fair representation of the stratigraphy. Comparable velocities are also available from Ritchie and Browne (unpublished) and Penn *et al.* (1984). In general, velocities recorded in the reflection seismic lines are accurate in the near surface 0.0s to 0.5s TWT interval, slightly high between 0.5s and 1s TWT and become increasingly high towards 1.5s TWT. Boreholes and wells within the MVS are predominantly drilled in fathoms, feet and inches (one Fathom i.e. $1^{11} =$ 6 ft or 1.82 m). Metres are used in the most recent boreholes and wells. In processing all data is converted into metres.

3.2 Interpretation Methods

3.2.1 Seismic picking and mapping of high amplitude and frequency

reflectors

This method has been applied to all seismic lines present in the MVS. The method is to pick reflector terminations either against other reflectors or reflector discontinuities. This process enables the identification of; erosional truncation, onlap, downlap, toplap, offlap, convergence and concordance (after Mitchum *et al.* 1977, Fig. 3.2.1) seismic reflector termination picks can establish the position

Mean Interval Velocities derived from stacking velocities after Penn et al (1984)				3.01 km s ¹				2 AB Um e ¹	0	3.77km s ⁻¹						4.17km s									
Regional	horizons (MVS)			Base Lower	Measures	No.3 MB		-Plean Lst -Calmy Lst	Orchard Lst	Black Metals Marine Band			Raeburn	Volcanics											
	Solway- Cheviot							Stainmor e. Group –					Group		Upper Border Group			Middle Border Group	Lower	Group					
	East Lothian												Aberlady Formation		1	Formation	anic anic noite	oteheco Volca smo7							
	West Lothian	I Measures						5	5	E	lon		West Lothian Oil-Shale	Formation		Gullane	s Seat Inic Inic	e'nurthA soloV smro [–] I	4						
Aidland Valley	Fife		Measures	I Measures	I Measures	I Measures	il Measures	al Measures	Measures		ormation		estone Format		Coal Formation	stone Format	Pathhead Formation	Sandy Craig Formation	and the second sec	Formation	Anstruther	Formation	Fife Ness Formation	ne Formation	ormation
~	Ayrshire & Central	Upper Coal	Middle Coa	Lower Coal		Passage F		Upper Lim		Limestone	Lower Lime	Lawmuir FM	Zew /		Clyde Plateau Volcanic Formation				Clyde Sandsto	Ballagan F	Kinnesswo				
	roup	Seaures Measures					dno	ค มยม	RMAR	dn	တဉ ခ	thgat	eg dn	Strathclyde Group				Group							
Miccore	zone	IX ×		SS	Æ	kV	SO	TK		NC						7 TC			<u>ال</u>	CM					
Change	orage	Bolsovian	Duckmantian	Langsettian	Yeadonian-			Arnsbergian		Pendlelan		briganuan	Asbian				Holkerian	& <	Chadian <	, achecing					
	Dates	308	- 311	- 313.5	- 316.5		320	070	470		- 326.5		- 331								354				
	oeries	U III			T			ueinun	^S N						nséail			(-1, -1)	U	IBIZIE	unoj				
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Table 3.2.1 Interval Velocities derived from stacking velocities after Penn et al (1984)compared to the lithostratigraphical and chronostratigraphical divisions of the Carboniferous in the Midland Valley and Scottish Borders. Adapted and updated from Francis (1991), Browne (1999) and Read *et al.* (2003). Radiometric dates are from Menning *et al.* (2000). Regional correlation horizons in the MVS (this study). Abbreviations; FM, Formation; Lst, Limestone; CC, Castlecary; TH, Top Hosie; MB, Marine Band.



of faults, erosion surfaces, flooding surfaces, facies changes, expansion and/or contraction of the succession. The position of reflector terminations is to some extent subjective in this MVS dataset, because the quality of onshore reflection seismic is not consistent. Reflectors are not always continuous and tend to reduce in amplitude and frequency as they approach other reflectors.

Strong reflectors are picked and traced out as surfaces to enhance interpretation confidence and supplement the picking of reflector terminations. Strong reflectors consist of high amplitude and high frequency continuous reflectors. The picking of strong seismic reflectors is important in the MVS dataset because strong reflectors occur as boundary layers between packages of different seismic reflection styles. Packages with similar reflectance properties form eight distinctive seismic facies (Fig. 3.2.2). These seismic packages can be used to correlate within and between seismic lines. Seismic facies may also be representative of changes in geological conditions and commonly separate strata deposited in different environments (Sheriff and Geldart, 1983). In this study it has been found that the seismic facies packages correlate to lithological formations (chapter 4) and therefore the strong reflectors between these packages represent the succession either side of and including the formation boundaries. Hence these reflectors are named as the formation boundaries.

However, there is a degree of uncertainty in the picking of seismic reflectors within the interpretations. This is the result of the lack of depth penetration of boreholes particularly into the Dinantian interval, thus restricting the identification of a precise reflector as a geological unit. Where there is a degree of uncertainty the picked strong reflector is labelled as a strong reflector (SRF) and its geological representation can only be assumed from its relative

-		the second se		_	and the second					
LO	ocal Seismic Regional Marker Seismic Marker		Formatio	n	Stage	Series	Seismic Characteristic			
			Middle Coal Measures	CMS	Duckmantian	ohalian	Seismic facies 8: sub-parallel discontinuous			
		Base Lower	Lower Coal Measures	L & M	Langsettian	West				
		Measures			Yeadonian					
			Passage	e.	Marsdenian					
	No.3 MB		Formation	P	Kinderscoutian		Seismic facies 7: parallel continuous reflectors.			
			_		Alportian					
		Castlecary Lst	1		Chokierian					
		Plean Lst								
		Calmy I st		(0)						
		Gainty Lot	Upper	Ö	Amsbergian	1				
			Ermation	5	, anosorgian		Seismic facies 6: strong transparent sub-parallel			
	Orchard Ls	t	1 onnauon	1		1.1	reliectors.			
		Indaly Lat				ian				
		Index Lst				J.				
						Var				
						_				
							51 V			
	Diack Mate	la la	Limestone		Pendleian					
	Black Meta	IS Id	Coal	Q			Seismic facies 5: strong parallel to sub-parallel			
	Marine Dar	iu i	Formation	2			continuous reflectors.			
				1.1						
		Ton Hosie Let								
		Top Tioble Lot					Seismic facies 4: weak parallel to sub-parallel			
			Lower	GS			discontinuous reflectors.			
			Limestone	E		1	Seismic facies 3: sub-parallel reflectors. Raeburn			
			Formation		Brigantian		Shale is the best candidate for the top reflector of			
		Hurlet Lst					this seismic facies.			
				SYG		an	Seismic facies 2: sub-parallel and moderately			
	Raehum					isé				
	. acount		Strathclyde			>	Seismic facies 1: hummocky and discontinuous			
			Group		Asbian	-	migrated reflectors.			
		LowerCarb.			Holkerian					
		Volcanics			Arundian					
			Inverciyde	>	Chavian					
	Carbonif	erous Devonian	Formation	Z	Courceyan					

Figure 3.2.2 Key seismic reflector characteristics, seismic reflector horizons and stratigraphy in the Midland Valley. The picked seismic markers include the labelled horizons, therefore they are named after these horizons.

stratigraphical position. With the existing limited borehole dataset (Section 3.2.2), the interpretations of the Dinantian seismic reflectors is limited to assumptions based upon unknown stratigraphical horizons and therefore the conclusions for this time period are limited.

The seismic interval velocities derived from stacking velocities in the MVS has been calculated by Penn *et al.* (1984) the results of this are presented in table 3.2.1. These can further the interpretation of seismic sections where there is limited depth penetration, especially in the Dinantian of boreholes..

3.2.1.1 Example of seismic picking and mapping of high amplitude and frequency reflectors

From the example line, TOC85-V330, (Fig. 3.2.3) downlap, onlap and toplap surfaces have revealed the presence of erosional or depositional hiati towards the south and north of the seismic section. Seismic reflector convergence shows that there is some expansion of the succession towards the north and in lense structures within the seismic line. Picking of seismic reflector discontinuities reveals that the seismic line images five major faults that offset the succession. These five faults are also observed by mapping of the strong reflectors, which show clear offsets across the seismic line.

Six of the eight seismic facies identified from seismic data across the Central Coalfield occur within the (example) section example (Fig. 3.2.4). As described in section 3.2.1, the seismic facies are recognised using the seismic reflector characteristics and the reflector terminations. Using this combined approach increases the confidence in the interpretation of fault positions, the correlation of the seismic section and the systematic identification of variations in facies thickness within and between seismic lines.





Figure 3.2.4 Seismic line TOC85-V330 illustrating seismic facies variations between the major reflector horizons. These aid in the identification of faults and correlation of the succession between and across reflection seismic lines in the MVS.

Although the identified seismic facies correlate with formations or parts of formations, which are dominated by groups of similar sedimentary facies, they cannot be correlated with individual sedimentary facies. Therefore, these two facies types are considered not to be directly related because the seismic facies tend to represent bulk properties of the deposit as opposed to individual types of rock stacked in a particular manner to give a sedimentary facies. Additionally the sparse nature of sedimentary information recorded in this study, and sometimes limited sedimentary information recorded in boreholes, mostly in areas where seismic data has not been available would in the authors view make any correlation between the two facies types dubious.

3.2.2 Borehole and well correlation to establish geological control

There are several types of subsurface data derived from drilling: boreholes are drilled for mineral exploration or water extraction; wells are drilled for hydrocarbon exploration and extraction. Borehole and well records can be derived from either cores or cuttings. Well records can also be accompanied by geophysical downhole measurements, for example gamma logs, calliper measurements, etc. In this study four wells drilled in the MVS have been used for correlation with seismic data. They were drilled by the same companies that collected the seismic data and are located on seismic lines, and so have proved to be very useful in correlating seismic data to geology. Three of these wells are located on the Salsburgh Anticline in the centre of the Central Coalfield; Salsburgh 1, Salsburgh 2 and Craighead 1, the other well is located in the northeast of the Central Coalfield the Inch of Ferryton well.

The approach taken here that boreholes and wells drilled in proximity to

seismic lines must be consistent with the interpretation applied to the seismic data. Boreholes provide information on the subsurface data including; depth to and characteristics of formation boundaries, positions of faults, unconformities, dip, formation thickness and lithological variations. Cored boreholes can also provide information on sedimentology and be used to interpret the depositional environment (chapter 2).

There are a number of problems that must be resolved to produce a robust borehole to seismic correlation. Reflectors may be influenced by the product of noise, static or multiples and therefore don't always reflect geology. Reflectors may also represent multiple lithological changes, not one single transition. Wells and boreholes need to be projected onto the seismic line, if they are located away from the seismic geophones and shot locations. This projection can be difficult due to lateral variations in geology, for example stratal thickness changes, faulting, etc, between the seismic and borehole or well locations. Even if the borehole or well is located directly on the seismic line, the size of the Fresnel-zone and variation in dip of the stratigraphy may alter seismic properties. Any deviation of the borehole or well from vertical can also create misfit correlations.

The borehole and well dataset is further restricted because of the depth of penetration of the boreholes. Only four penetrate, to any great extent into the Dinantian, these are the Salsburgh no. 1 and 2 boreholes, the Craighead borehole and the Inch of Ferryton well.

3.2.2.1 Example of borehole and well correlation to establish geological control

The borehole locations (Fig. 3.2.5) around TOC85-V330 (Fig. 3.1.2) show that the correlation of boreholes to seismic lines is not affected by the presence of



Figure 3.2.5 Boreholes used to correlate between the geology and the reflection seismic profile of TOC85-V330.

faults between the borehole and the seismic line, and there are no known major erosional surfaces between the boreholes and the seismic line. The East Carron and Carronhall 35 boreholes (Fig. 3.2.5 and Table 3.1.1) are separated by faults that downthrow to the north (Fig. 3.1.2). Therefore, the depth to formations from surface will be different. The vertical resolution of TOC85-V330 is 20-23 m near surface (0.2s TWT) decreasing to 32-34 m at 1s TWT. Therefore, faults with throws less than 34 m calculated resolution cannot be identified. The calculated horizontal resolution of TOC85-V330 is 17.5 m at 0.2s TWT decreasing to 59 m at 1.0s TWT.

Projecting boreholes onto the reflection seismic line (Fig. 3.2.6) allows for the correlation of geology and seismic reflectors. In order to obtain an accurate correlation, depths to the picked seismic reflectors were converted from TWT to metres at various shot points along the line. For TOC85-V330 this calculation had been done by the processors of the seismic data, and therefore only needed to be checked for errors. The borehole and seismic correlations were also adjusted to account for different datum surfaces. Depths to formation boundaries in boreholes were then compared to the calculated depth of the picked seismic reflector; if the depth to the seismic reflector matches that of a formation boundary in a well or borehole then a geological correlation is established.

3.2.3 Map, cross-section geological and reflection seismic correlation

The surface mapping of the MVS has been carried out for many years by the British Geological Survey (BGS). There are several 1:50,000 map sheets that cover the central area of the MVS, (BGS, 1967; BGS, 1977; BGS, 1984; BGS, 1992; BGS, 1997). These 1:50,000 sheets were compiled from more detailed 1:10,000 BGS map sheets.

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In order to make use of the geological map sheets within the MVS to aid in seismic interpretation it is important to understand how they have been compiled. The BGS undertake regular revisions of map sheets. The maps are based upon field mapping of natural and man-made exposures. However, the large MVS borehole dataset (Fig. 3.2.7) has also been integrated with the field mapping programme to constrain mapped outcrops.

The correlation of surface mapping and seismic can be undertaken in two ways: (1) Projecting the seismic line beneath the mapped geology. (2) Constructing a cross-section, from the map, to compare physically recorded data with the geophysically derived data and its interpretation. Projecting the seismic lines below surface mapped data allows for direct correlation of geological formations to seismic facies, therefore constraining the geology. Although largescale fault and fold locations, orientations, direction of throws and aerial extents can be compared easily between seismic lines and mapped geology, the smaller faults and folds could be often only identified in a single seismic line. In these cases the locations, orientations, direction of throws and aerial extents of these structures can be constrained from the geological maps, while boreholes can provide additional information on formation thickness.

There are some limitations to this method. The most important limitation is that surface mapping can only identify structures, faults and folds that penetrate the exposed formations. Therefore synsedimentary structures may not be recorded on the map. However, mine plan data can constrain these features in the subsurface, but mines have a limited area when compared to seismic lines and map out coal horizons that cannot be identified in the seismic data. Formation thickness commonly varies in the subsurface and this may not be identified from





the maps or derived cross-sections. There may also be correlation errors of individual geological formations between map sheets.

3.2.3.1 Example of seismic, geological map and cross-section correlation

Projecting the seismic line TOC85-v330 below the surface map (Fig. 3.2.6) and producing a cross-section derived from the geological map (Fig. 3.2.8) illustrates the problems correlating between surface mapping and geophysical interpretations. The subsurface seismic interpretation correlates with geology mapped at the surface. In this particular line only one formation boundary crops out at the surface allowing correlation from surface to sub-surface. There is a general similarity between the position of the faults identified in seismic and on the cross-section. However, some faults that have been mapped at the surface are not present in the seismic interpretation, and some of those identified in the subsurface are not present on the geological map. For example faults 3 and 4 (Fig. 3.2.6), mapped at the surface, are not present in the seismic interpretation, because there is no offset of the reflectors. This absence is most likely due to poor seismic resolution in the top 0.1ms TWT. Fault 6 is also not included in the seismic interpretation, however, seismic quality is poor in the location of the fault. There are three faults in the seismic interpretation that are not represented in the crosssection derived from surface mapping because these faults do not offset the uppermost exposed formation.

There has been a much greater success in matching formation boundaries from the mapped geology and derived cross-sections to formation boundaries in the seismic dataset compared to matching of faults. This is partially explained by the fact that many surface faults are small and post-Carboniferous, while larger syn-sedimentary structures are buried and not always present on geological maps.

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Figure 3.2.8 A: Cross-section constructed from the geological map 39 W Stirling BGS, (1974) along the line of TOC85-V330; boreholes were used to establish formation thicknesses. B: Interpretation of seismic line TOC85-V330 for comparison.

3.2.4 Contour models of key seismic reflectors

It can be difficult to tie seismic reflectors to geological formations where direct borehole or well correlation to seismic is not available, and/or the seismic line is located over only one formation. The method used to overcome this problem was to map out the key reflector horizons in the subsurface in 3-D. Depths to formation boundaries, that form the key seismic reflectors, in boreholes and wells located in the area of the seismic line were entered into an Microsoft Excel spreadsheet (table 3.1.1). The data was then transferred to Winsurf v5.03 where using the Minimum Curvature gridding method, contour maps of each formation boundary being produced. These surface plots of key seismic surfaces were then used to determine the depth of formation boundaries in the seismic reflection profile where no other information existed.

Similar problems exist, such as lateral variation in geology, for this method as when correlating boreholes and wells with seismic lines (section 3.2.2). Additional problems encountered are that Winsurf plots cannot account for faults. This imaging problem can be overcome by careful consideration of the seismic line and geological map to find structures. Winsurf surface plots become more accurate as the density of borehole and well coverage increases.

3.2.4.1 Example of Winsurf 5.03 surface plots of key horizons

The Winsurf plots around TOC85-V330 (fig. 3.2.9) for the three upper key horizons show the same general pattern as in the seismic line interpretation. Strata dip gently to the west, along the southern part of the line and a high area exists in the north. These features correspond to a southerly downthrown block and a northern footwall block, where the Passage Formation crops out as recognised in both the seismic interpretation and the cross-section. These plots are useful in



predicting levels on seismic lines to the west that have poorer borehole or well control proximal to the line. However, the three plots in the lower part of the succession (including the Orchard, Lyoncross and Index limestones) are of limited use because there is insufficient borehole data (table 3.1.1). The plots from boreholes do not reflect the structure of the subsurface below the seismic line.

3.3 Summary

The key to the interpretation of this 2-D seismic dataset is to follow a methodical and iterative approach using all the tools available. The variable quality of seismic data and the presence of abundant and detailed surface and subsurface data mean that the approach taken in this study was to integrate all information. This chapter has given examples of how the integration and interpretation was undertaken. However, as stated earlier in this chapter not all methods could be applied to all seismic lines. Once the interpretations of several seismic lines have been completed it is possible to compare between seismic lines at the points where they cross over. The interpretation of seismic data is further restricted by a poor signal-to-noise-ratio which obscures many of the smaller features in the seismic lines.

Chapter 4

The Central Midland Valley of Scotland: seismic interpretation

and tectonic evolution

In this chapter the seismic profiles across the Central Coalfield provide the information needed to clarify the orientation of major faults and folds, and determine when these were active. Aspects of published models determined from surface mapping and boreholes can be thus tested and developed with the help of this seismic interpretation.

Published models have used fault orientations from the BGS 1: 50,000 map sheets to explain the Carboniferous tectonic evolution of the MVS (for example Gibbs, 1989; Read, 1988). However, the seismic data presented have allowed faults that were active during the Carboniferous to be distinguished from post-depositional faults. Only by differentiating these fault sets can an accurate and realistic tectonic model be proposed. The methodology for the seismic interpretation is covered in Chapter 3.

4.0 Background: Main tectonic elements

The central area of the MVS contains four major Carboniferous structural elements, recognised on the geological maps of the MVS, (1) the Clackmannan and Falkirk-Stane synclines: these two names refer to the same structure and in this study is referred to only as the Clackmannan Syncline (Fig. 4.0.1). (2) The Uddingston Syncline to the south-west of the Clackmannan Syncline (Fig. 4.0.1). (3) The Salsburgh Anticline between the Uddingston Syncline and the Clackmannan Syncline (Fig. 4.0.1). (4) The Kilsyth Trough in the western



Figure 4.0.1 Geological map of the Central Coalfield of the MVS. Modified from BGS sheets 30 E, 31 E & W, 32 W, 39 W & E

Central Coalfield, west of the Clackmannan Syncline and north of the Uddingston Syncline (Fig. 4.0.1). Pre cursors of these structural elements have sometimes been given separate names in the literature e.g. an early phase in the development of the Clackmannan Syncline is referred to (Rippon *et al.* 1996; Read 1988) as the Kincardine Basin. The structural elements that form the depocentres are faultbounded to the north by the West Ochil fault and to the NW by the Campsie fault.. The western margin of the Clackmannan Syncline, the Kilsyth Trough and the Motherwell Basin are bounded by the Clyde Plateau Volcanic Formation, the sedimentary deposits appearingly onlap onto these volcanic rocks. The eastern Clackmannan Syncline is bounded by the Bathgate Hills Volcanic Formation. To the south, Devonian strata and Carboniferous volcanic rocks bound the Clackmannan Syncline and the Motherwell Basin (Fig. 4.0.1).

4.0.1 The Clackmannan Syncline

Geological maps of the NNE-SSW orientated Clackmannan Syncline show that it extends for ~50 km from south to north and is ~30 km wide in the south narrowing northwards to ~27 km (Fig. 4.0.1). The Clackmannan Syncline is an asymmetrical fold with dips on the eastern limb up to 30°, while on the western limb dips rarely exceed 5° (Cameron *et al.* 1998). The Clackmannan Syncline closes to the south, and is terminated to the north against the West Ochil fault (Fig. 4.0.1). The Bathgate Hills Volcanic Formation, that bounds the eastern limb of the Clackmannan Syncline have been interpreted by (Read, 1988 and Rippon *et al.* (1996) as an important structural element termed the Bo'ness Line (Fig. 4.0.1).

4.0.2 The Uddingston Syncline

The Uddingston Syncline forms part of the depositional area of the Motherwell Basin. This area contains the best preserved area of Coal Measures strata in the Central MVS, as a result of post Carboniferous displacement on the Dechmont fault. Mapped at the surface, the Uddingston Syncline is a NW-SE orientated asymmetrical syncline that closes to the SE and NW; dips on the NE limb of the syncline rarely exceed 12° while dips of up to 22° are recorded on the SW limb BGS, (1967) and BGS, (1992). The Motherwell Basin is bounded to the SW by the Clyde Plateau Volcanic Formation and a series of NW-orientated faults (Paterson *et al.* 1998).

4.0.3 The Salsburgh Anticline (High)

The Salsburgh Anticline is a NW-SE trending structure mapped at the surface where the Chokierian-Yeadonian Passage Formation forms a series of NW-SE striking inliers that bisect the outcrop of the Coal Measures (Fig. 4.0.1). The outcrop pattern suggests an anticlinal structure. Strata dip between 5° and 15° on the SW limb and at about 6° on the NE limb (Cameron *et al.* 1998).

4.0.4 Introduction to faults in the Central Midland Valley

There are five major recorded fault orientations in the central MVS with a variety of cross-cutting relationships observed in the field. These fault orientations are not unique to the central MVS but have been recognised in the coalfield basins across the MVS. Some fault sets, for example the NE-SW trending faults, are interpreted to have an inherited trend from earlier events. During the Silurian, closure of the Iapetus Ocean by subduction brought the Eastern Avalonian plate into oblique collision with the Laurentian plate (Soper *et*

al. 1992). This collision caused sinistral motion on NE-orientated faults, including the Great Glen, the Highland Boundary and Southern Upland faults. This collision event has also been related to the development of lineaments (Paterson *et al.* 1998; Dentith and Hall 1990; Rollin, 2003) in the MVS beneath later important Carboniferous structures, for example the Kerse Loch fault in Ayrshire and the Ochil fault in the central MVS.

4.1 Seismic interpretation

4.1.1 Background

The seismic lines presented in this chapter (Fig. 4.1.1) have been interpreted using the methods presented in Chapter Three, the limitations and degrees of uncertainty of the methods used to interpret the seismic dataset are also presented there. The key seismic marker horizons and Carboniferous stratigraphy are shown in figure 4.1.2. Some 78 seismic lines (Appendix 1) and 223 deep wells and boreholes (Appendix 2) are integrated to produce this seismic interpretation. The 78 seismic lines are located across the northern Clackmannan Syncline, the Motherwell Basin, the Kilsyth Trough, the Salsburgh Anticline and the Kincardine Basin (Fig. 4.1.1). No seismic lines were was shot in the southern Clackmannan Syncline, and so in this area only boreholes can be used to reconstruct the basin.

4.2 Thickening of the Carboniferous succession in the Central Coalfield

Seismic lines in the Central Coalfield (Appendix 1) show divergence, bifurcation and increased separation of reflectors between known reflection



Figure 4.1.1 Geological map of the Central Coalfield of the MVS. Modified from BGS sheets 30 E, 31 E & W, 32 W, 39 W & E. Showing the position of all 78 reflection seismic lines in the Central MVS.

Tectonic framework interpreted from seismic data only			in seismic	8	regional subsidence and some	reversed fault motion	American sect of sectors	Syndine growth, extension and regional subsidence		Mid-Brigantian to Pendleian Syncline growth, minor extension and regional		subsidence	Lower to mid-Brigantian main period of Central Coaffeld Syncline growth extension and regional subsidence										
Seismic Characterístic			Not imaged	Seismic facies 8 sub-parallel discontinuous reflectors.		Seismic facies 7 parallel continuous reflectors.			Seismic facies 6 strong transparent sub- parallel reflectors. Seismic facies 5 strong parallel to sub- parallel continuous reflectors.			Seismic facies 4 weak parallel to sub- parallel continuous reflectors & sub-parallel Seismic facies 3; sub-parallel reflectors. Raebur Shale is the best candidate for the ppuraflector of this seismic facies – – – moderately discontinuous reflectors. Seismic facies 1 hummocky and discontinuous migrated reflectors.											
Local Seismic Marker							No.3 MB		Orchard Lst Black Metals Marine Band					Contraction	Vaeonu								
Regional Seismic Marker					Base Lower	Measures	-CC Lst				THINGY LOL		-Hurlet Lst-	- Hunet Lst. Lower Carb. Volcanics									
Solway- Cheviot							Stainmore - Group -							Liddesdale	Group	Upper Border	Group	Glencartholm	Middle Border Group	Lower	Group		
Midland Valley	East Lothian				Measures										Aberlady Formation		Formation	on ic	formati Volcan Formati				
	West Lothian								ion		c	tion			West Lothian Oil-Shale Formation		Gullane	Arthur's Seal Volcanic Formation					
	Fife		Measures	Measures		ormation			stone Format		Coal Formatio	stone Formati	Pathhead	Formation	Sandy Craig Formation	Pittenweem	Anstruther	Formation	Fife Ness Formation	he Formation	ormation	od Formation	
	Ayrshire & Central		Upper Coal	Middle Coal	Lower Coal		Passage Fo		Upper Limes		Limestone (Lower Lime	awmuir FM	Cirkwood /	Zen Z	Clyde Plateau Volcanic Formation				Ivde Sandstor	Ballagan Fo	Kinnesswoo	
	Group		Soal Measures				dno		nennem		nb Cl ^e	တဉ eteg		the	quonD et		Strathclyd			onb cjÀqe		noer D	
Minsonre	zone	XI	× ⊼≧₽ % ₭ ≷ % ¥																				
Stage		Bolsovian		Duckmantian	Duckmantian Langsettian		Yeadonian- Chokierian		Pendleian			Brigantian			Asbian <			Holkerian & Arundian			Chadian <		
Radiometric Dates		308		- 311 - 313.5		- 316.5	- 316.5		- 324		- 326.5			- 331						- 342.5		354	
Series		U UE				T		nsin	nmeN							nsèsiv				1	nsieie	ewnoj	
system						nsiaelic							neÿnsniQ										

Francis (1991a), Browne *et al.* (1999) and Read *et al.* (2003). Radiometric dates are from Menning *et al.* (2000). Seismic reflector characteristics, seismic reflector horizons and tectonic framework interpreted from seismic in the MVS (this study). Abbreviations; FM, Formation; Lst, Limestone; CC, Castlecary; TH, Top Hosie; MB, Marine Band.

horizons, these changes in the seismic profiles bring interpreted as thickening of the succession.

Seismic reflectors packages increase in TWT towards the fold axis of the Clackmannan syncline, though no single seismic line crosses the Clackmannan Syncline and therefore a minimum of 2 lines are required to illustrate the entire structure. Increased separation of identified reflectors is observed from the eastern margin to the centre of the Clackmannan Syncline in seismic lines TOC85-V324, BRK85-02, TOC86-M111, TOC86-M112, TOC85-V03, TOC82-V308, TOC83-V31 and TOC82-V311 (Appendix 1). Thickening of the reflector packages between marked horizons is observed from the western margin to the centre of the Clackmannan Syncline in seismic lines TOC85-V327, TOC82-V201, TOC82-V301, TOC83-V315, TOC83-V316, TOC83-V317, TOC83-V320 and TOC85-V329 (Appendix 1). Three key seismic examples are chosen to illustrate this regional feature (Figs. 4.2.1, 4.2.3 and 4.2.4).

4.2.1 Example TOC82-V201

Line TOC82-V201 (Fig. 4.2.1) is located in the northern Central Coalfield across the Clackmannan Syncline, 2 km south of, and parallel to, the West Ochil fault (Fig. 4.1.1). The seismic line is orientated WSW-ENE and has a line length of 20 km. The seismic line images the Westphalian, Namurian, Viséan and Devonian successions; this is the only line that images the Devonian well as it crops out in the east of the line. The picked seismic markers are the base of the Lower Coal Measures, the Castlecary Limestone, a strong reflector (SRF 2/V-201) either representing the Plean or Calmy limestone, the Index Limestone, a strong reflector (SRF 1/V-201), the top of the Clyde Plateau Volcanic Formation and internal Devonian reflectors. SRF 1/V-201 is above the reflector picked as the



Reflector; Top CPV FM Top of Clyde Plateau Volcanic Formation. Seismic interpretation based upon cropping out of the Middle and Lower Coal Measures, Castlecary Limestone, Index Limestone, cross-correlation with eight seismic lines (Fig. 4.1.1) and isopached boreholes to Fig. 4.2.1 TOC82-V201 located in the northern Central Coalfield across the Clackmannan Syncline (Fig. 4.1.1). Abbreviations; Base LCMS, Base Lower Coal Measures; Castlecary, Castlecary Limestone or Base Passage Formation; Index, Index Limestone; SRF (1 & 2), Strong the south of this seismic line refer to chapter 5. Lower Carboniferous Volcanic Formation, but its depth indicates that it is below the position of the Top Hosie or Hurlet limestones; therefore this reflector is most likely located in the Viséan and could possibly be a sill or a facies association change from terrestrial to marine sediments. The seismic reflectors are offset by a series of faults interpreted in the seismic profile (labelled 1-4 Fig. 4.2.1). Faults labelled 1 and 4 are examined in greater detail in sections 4.9 and 4.6 respectively. Faults 2, 3 and 4 correspond to faults mapped at the surface by the BGS and are therefore orientated NW-SE. The largest displacement occurs across fault 4 (the Arndean fault BGS, 1973) where the Carboniferous succession is juxtaposed against the Devonian. Faults 2 and 3 have relatively small offsets, but displace the entire imaged Carboniferous succession.

The seismic reflectors between all picked marker horizons increase in TWT from the western margin of the syncline towards the syncline centre. The reflector package is 0.65s TWT (from shot point 160 to 320), and represents only a section of the full syncline limb. This represents an increase in thickness of \sim 1331 m (see Chapter 3, Section 3.1.2 for depth conversion).

This change in thickness of the succession is not evenly spread through time. The greatest thickness change occurs between the top of the Clyde Plateau Volcanic Formation and the Index Limestone where the succession thickens by ~1052 m. In contrast, the measured thickness change between the Index limestone and SRF 2/V-201 (Plean or Calmy limestones) is below the resolution of the seismic data, and therefore can be discounted as representing any significant change. Between the SFR 2/V-201 (Plean or Calmy limestones) and Castlecary Limestone thickening is again below seismic resolution. Although there is an apparent thickness increase from the syncline margin to the centre between the Castlecary Limestone and base of the Lower Coal Measures of ~264 m, the Westphalian succession and the upper Passage Formation have been eroded from shot point 260 eastwards, and so an assessment of thickness change is not possible. However, within the seismic package representing the Passage Formation reflectors bifurcate (shot point 390) and diverge indicating a minimum growth of ~35 m (9 m above seismic resolution) toward the axis of the syncline.

4.2.2 Example TOC86 M112

TOC86 M112 (Fig. 4.2.2) located in the northern Central Coalfield, images the eastern margin of the Clackmannan Syncline along the Forth estuary and River Forth (Fig. 4.1.1). The seismic line is orientated WNW-ESE and has a line length of 24 km. The seismic line images the Westphalian, Namurian and Viséan successions. The picked seismic markers represent the unconformity at the base of the recent deposition in the Firth of Forth, the base Westphalian (LCMS, Fig. 4.2.2), the Castlecary Limestone, the Index Limestone, the Top Hosie Limestone and two strong reflectors (SRF 1/112 and 2/112) below the Top Hosie Limestone.

The reflector characteristics below the Top Hosie Limestone and between these two strong reflectors correspond to seismic facies 2, 3 and 4 (Fig. 4.1.2). Therefore this lower succession, between SRF2/112 and the Top Hosie reflector, is interpreted as the Strathclyde Group. There is one fault identified in the profile that is orientated obliquely to the seismic profile and offsets the Top Hosie Limestone. This is interpreted as a fault as it has a downlap onto the surface and there is no evidence for an unconformity from the borehole data in the area. A fault is also recognised in several other seismic lines that can be traced through this area. Subsurface mine plan data (BGS 1997) also measures a fault with a



Căstlecary Limestone or Base Passage Formation; Index, Index Limestone; Top Hosie, Top Hosie, Limestone; SRF (1/112 & 2/112), Strong Reflector, redline is a fault parallel to the seismic line; this fault is identified on mine plan data in the Forth Estuary, on the geological map BGS (1997) and can be correlated with faults interpreted in other seismic lines (Section 4.7). Interpretation based upon borehole correlations to the Kincardine Bridge Borehole, the Blair Mains Borehole and borehole panels constructed in the northern Clackmannan Syncline (Chapter 5 section Fig. 4.2.2 TOC86-M112 located along the Forth of Forth (Fig. 4.1.1). Abbreviations; Base LCMS, Base Lower Coal Measures; Castlecary, 5.3.4).

throw of ~260 m in this location.

The seismic reflectors in this profile increase in TWT westward into the Clackmannan Syncline by ~0.74 s TWT (~886 m) between shot points 820 and 1460. Between the SRF 2 and SRF 1 reflectors the succession thickens by ~158m. Between the SRF 1 reflector and Top Hosie Limestone the succession thickens by ~111 m. Between the Top Hosie Limestone and Index limestone the succession thickens by ~217 m. Above the Index Limestone the reflector packages indicates that there is little difference in thickness at the margin compared to at the centre of the syncline. The distribution of any thickness changes is similar to that described in line TOC82 V201.

4.2.3 Example TOC85-V324

TOC85-V324 (Fig. 4.2.3) is located in the northern Central Coalfield and images the eastern margin of the Clackmannan Syncline, south of the Firth of Forth and River Forth (Fig. 4.1.0). The seismic line is 12.5 km long and broadly orientated E-W, arcing to the north between shot points 460 and 100. The seismic line images the Westphalian, Namurian and Viséan successions. The picked seismic markers are the base of the Lower Coal Measures, the Castlecary Limestone, an unidentified upper strong reflector (SRF 1/V-324), probably representing the Calmy Limestone, the Upper and Lower Hirst Coals or both, the Index Limestone, the Top Hosie Limestone and a lower, strong reflector (SRF 2/V-324) below the Top Hosie Limestone, possibly representing the top of the Bathgate Hills Volcanic Formation. There are two identified faults in the profile, located at shot points 285 and 340, that offset the picked reflectors. These faults correspond to ENE-WSW-orientated faults on the geological map (BGS, 1974).

The seismic reflectors in this profile increase in TWT westwards into the

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Clackmannan Syncline. Between the upper strong reflector and the lower strong reflector, the succession thickens by 0.24s TWT between shot points 1000 and 460. This represents a total thickness increase of ~365 m. Approximately 275 m of this change in thickness occurs between the Top Hosie Limestone reflector and the lower strong reflector (SRF 2/V-324), with ~55 m of thickening between the Index and Top Hosie limestones and ~35 m of thickening between the upper strong reflector and the Index Limestone; these thickness increases are above the 29 m average seismic resolution calculated between these reflectors. Westwards the succession between the Castlecary Limestone and the upper strong reflector increases in thickness by ~81 m from shot points 670 to 360, (SRF 1/V-324). Between shot points 360 and 100, the arcing of the seismic line to the NNE takes the profile away from the axis of the Clackmannan Syncline and therefore no thickening can be observed.

4.2.4 Temporal distribution of Two Way Time and thickness change

The previous descriptions have highlighted how changes in thickness between reflectors, interpreted from TWT in the seismic profiles, vary in time and space. Documenting the temporal and spatial distribution of thickness changes is key to determining the timing and location of accommodation generation. The orientations of key depocentres can also be identified.

The seismic lines (Figs. 4.2.1 to 4.2.3) show how the greatest change in thickness from the margins of the Clackmannan Syncline to its centre occurs below the Top Hosie limestone reflector. This major change in thickness is also identified below the Index Limestone or the Hurlet Limestone, but only where the Top Hosie reflector cannot be identified; however, all seismic lines in the central



Fig. 4.2.3 TOC85-V324 located on the eastern margin of the Clackmannan Syncline. Abbreviations; Base LCMS, Base Lower Coal Measures; Castlecary, Castlecary Limestone or Base Passage Formation; Index, Index Limestone; Top Hosie, Top Hosie Limestone. Interpretation based upon croping out of the base of the Lower Coal Measures, the Castlecary Limestone, the Index Limestone, cross referencing with three overlapping lines and two adjacent lines and the Orchard Head borehole.

MVS the Top Hosie reflector represent this change in accommodation creation. Thickening of the succession below the Top Hosie Limestone reflector was observed in all seismic lines where resolution allowed the lower reflector to be picked. This lowermost reflector could not always be identified because of a lack of deep boreholes to correlate with. However, where no continuous strong reflector could be identified and correlated with a formation body, bifurcation and increased separation of reflectors was used to indicate thickening of the succession towards the syncline centre. Features suggesting a major thickness change from the margins to the centre were observed in all seismic lines. Comparing the regional changes in thickness between seismic reflectors illustrates that 80-90% of the total thickness change in the Clackmannan Syncline occurs within the succession below the Top Hosie. Above the Top Hosie reflector, there are minor changes in thickness with each seismic package representing a change in thickness of up to 70 m. The thickness change is also not uniformly distributed from the syncline margin to the syncline centre. The greatest thickening between key reflectors predominantly occurs within a relatively narrow zone on the steeply dipping syncline limbs, whereas the TWT between reflectors is relatively constant and reflectors appear flat (Fig. 4.2.4).

The \sim 7 km wide zone of major thickness change occurs below the present outcrop of the Passage Formation. Therefore, any significant change in thickness of the Passage Formation and the Coal Measures has been eroded off, as these deposits are preserved in the core of the syncline only and not on the limbs. The poor seismic quality in the upper 0.1 s TWT, where these deposits are preserved, also hinders any recognition of thickness changes.

Syncline growth reflects the timing of accommodation creation. The





4.2.4 (A) Simplified map of the Central Coalfield with the location of the zones of maximum thickening highlighted and (B) schematic cross-section of the Clackmannan Syncline based upon TOC82-V201, TOC86 M112, TOC85-V324.

major thickening into the axis of the syncline during the early/mid Viséan to mid-Brigantian represents the main period of syncline growth (Fig. 4.1.2). The slight thickening into the axis of the syncline between the mid-Brigantian and the base of the Westphalian represents minor syncline growth (Fig. 4.1.2).

4.3 Development of the Uddingston Syncline

The geological maps (BGS, 1967; BGS, 1992) of the Motherwell Basin show that the basin contains a NW-orientated syncline, the Uddingston Syncline. Eighteen seismic lines cross the Motherwell Basin; SAX-84-01, SAX-85-01, SAX-85-02(VIB), SAX-85-02(HYD), SAX-85-03, SAX-85-04, SAX-85-05, SAX-85-06, SAX-85-07, SAX-85-08, SAX-85-09, SAX-85-37, SAX-85-38, SAX-85-39, SAX-85-40, SAX-85-41, E86b-16 and E86b-19, however, the quality of these seismic lines is generally extremely poor. Only four of the eighteen seismic lines can be interpreted along their length, with good depth correlation to boreholes. These lines are the NW-SE-orientated SAX-85-02(VIB), the N-Sorientated SAX-85-06 and the SW-NE-orientated SAX-85-07 and SAX-85-41. The other seismic lines only contain small sections that can be interpreted and have poor depth control. This limits the study of syncline development in the Motherwell Basin both spatially and vertically. Two example lines are described to illustrate those structures present in the Motherwell Basin that are considered to have controlled accommodation generation during Carboniferous sedimentation.

4.3.1 Example SAX-85-02(VIB)

SAX-85-02(VIB) (Fig. 4.3.1) is located in the Motherwell Basin and images the north-eastern limb of the Uddingston Syncline, parallel to the axis



Fig. 4.3.1 SAX85-02(VIB) located in the Motherwell Basin. Abbreviations; MCMS, Middle Coal Measures; LCMS, Base Lower Coal Measures; SFR 2/V-02, possibly the base of the Passage Formation; Index, Index Limestone; Top Hosie, Top Hosie Limestone; SRF 1/V-02, Strong Reflector. Interpretation based upon outcrops of the Middle Coal Measures, corresponding fault positions and borehole correlations with the Birkshaw, Glenavon, Clyde Bridge, Tannockside, Rosehall estate and Orchard Farm boreholes.

of the syncline. The seismic line is 20.5 km long and broadly orientated NW-SE. The picked seismic markers are the bases of the Lower, Middle and Upper Coal Measures, a strong reflector (SRF 2?V02, Fig. 4.3.1) that probably represents the base of the Passage Formation, because of its depth and the proximal seismic facies (Fig. 4.1.2), the Index Limestone, the Top Hosie Limestone and a lower strong reflector (SRF 1/V02), that is located above the discontinuous hummocky seismic facies that represents the Clyde Plateau Volcanic Formation and therefore is located somewhere in the middle Viséan. There are four faults identified in the profile, located at shot points 200, 370, 700 and 870 that offset all reflectors. On the geological map BGS (1992); BGS (1967) four faults correlate with those interpreted on the seismic line; these faults downthrow to the NNW and are orientated ENE-WSW.

The seismic packages between key reflectors are observed to increase in TWT into the faults indicating thickening of the succession in the fault hangingwalls. The greatest change of \sim 0.12 s TWT occurs below the Top Hosie Limestone and the strong reflector (SRF 1/V-02) into the fault at shot point 200. Some TWT increase is observed between the Top Hosie and Index limestones into the faults, with only minor thickening observed in seismic units above the Index Limestone reflector into the hangingwalls of the faults.

Although the orientation of the seismic line prevents a detailed analysis of the Uddingston Syncline, thickening, not associated with the faults and with the syncline, is observed between the upper strong reflector (base of the Passage Formation) and the base of the Lower Coal Measures. This thickening was observed from the south ~0.1 s TWT between shot points 220 and 600 and from the north ~0.13 s TWT from shot points 1060 to 600 and is interpreted as related

to the growth of the Uddingston Syncline during the Westphalian.

4.3.2 Example SAX-85-07

SAX-85-07 (Fig. 4.3.2) is located in the Motherwell Basin and provides a profile across the Uddingston Syncline axis. The seismic line is 11 km long and broadly orientated WSW-ENE. The seismic line images the Westphalian, Namurian and Viséan successions. The seismic markers recognised are the base of the Upper Coal Measures, Middle Coal Measures and Lower Coal Measures, the base of the Passage Formation, the Calmy Limestone, the Index Limestone and two strong reflectors, SRF 1/V-07 possibly the Top Hosie Limestone or Hurlet Limestone reflectors and a Viséan reflector SRF 2/V-07. There are two faults in the profile, one at shot points 480 that corresponds to the Dechmont fault orientated SE-NW from the geological map (BGS, 1967) and one at shot points 240, that also corresponds to a SW-NW fault on the geological map (BGS, 1967). These faults offset all the named reflectors in this profile.

Seismic reflector packages between the SFR 1/V-07 and SFR 2/V-07 increase slightly ~0.05 s TWT into the NW-SE-orientated Dechmont fault indicating a small thickening of the succession into the hangingwall. The reflector package between the Index and the strong reflector 2 (SFR 2/V-07) is not associated with any systematic changes in thickness into the hangingwall. The packages between the Index Limestone and Castlecary Limestone were observed to thicken slightly into the fault hangingwall by ~0.04 s TWT. The package between the Castlecary Limestone and Upper Coal Measures appears to thicken slightly from shot point 430-320 but does not change into the Dechmont fault.

Towards the NE, away from the Dechmont fault, between shot points 360 and 260 the succession between the Index Limestone and the strong reflector 2



(SFR 2) thickens to the NE very slightly, ~0.02 s TWT. The reflectors below the base Passage Formation reflector are either flat or dip gently to the NE. Seismic line SAX-85-41 also crosses the Uddingston Syncline showing similar minor thickening into the syncline and reflectors dipping shallowly to the west below the Castlecary Limestone.

4.3.3 Interpretation of the Uddingston Syncline and Motherwell Basin

The limited subsurface seismic data shows that the Uddingston Syncline is a small structure confined to the Passage Formation and Lower, Middle and Upper Coal Measures. Below the base of the Passage Formation the succession thickens slightly towards the centre of the Central Coalfield, towards the Salsburgh Anticline and Clackmannan Syncline. In the Motherwell Basin, thickness changes appear to be related to ENE-orientated faults (Fig. 4.3.1) while the apparent western bounding fault to the Motherwell Basin, the NW-SE-orientated Dechmont fault, has only a minor influence on accommodation. Therefore the majority of movement on this fault is interpreted to be post-Carboniferous. This contrasts with the formation of the Clackmannan Syncline as discussed in section 4.2.

The reflectors indicate that there is little or no thickening of the Passage Formation and some thickening of the Lower Coal Measures into the syncline. The changes in thickness across the Motherwell Basin suggest that the syncline was initiated during the early Westphalian.

4.4 The Salsburgh Anticline

The Clackmannan Syncline is separated from the Motherwell Basin by the Salsburgh Anticline. The anticline dips $\sim 17^{\circ}$ on the SW limb and $\sim 14^{\circ}$ on the NE

limb (BGS, 1997). The Salsburgh anticline is identified from the outcrop pattern (Fig. 4.0.1). This area is imaged by six seismic lines TER 85-01 to -06.

On the SW limb of the Salsburgh Anticline, a NW-SE-orientated, NE dipping fault is recognised in the six seismic lines TER 85-01 to -06 (e.g. Fig. 4.4.1). This fault appears on the geological map as a series of fault segments offset by E-W faults (BGS, 1992, 1997), and is named here as the Salsburgh fault. This fault is a minimum of 7 km long; this length was calculated by restoring the offset caused by the later E-W faulting, and tracing the fault between seismic lines. The Salsburgh Anticline is one of the locations in the central MVS that was drilled for oil. This exploration was unsuccessful but has left good well control on the seismic data from three deep exploration wells, Salsburgh 1A, Salsburgh 2 and Craighead 1.

4.4.1 Example TER 85-01

TER 85-01 (Fig. 4.4.1) is located between the Clackmannan Syncline and the Motherwell Basin, perpendicular to the axis of the Salsburgh Anticline. The seismic line is 8 km long and orientated SW-NE. The picked seismic markers are the base of the Lower Coal Measures, the base of the Passage Formation, the Calmy Limestone, the Index Limestone, the Hurlet Limestone and the top of the lower Carboniferous Volcanic. There are four major faults identified in the profile offsetting all the reflectors, located at shot points 190, 310 (the Salsburgh fault), 540 and 600. There are an additional 21 minor faults identified in this seismic line. The 21 minor faults are largely located over the core of the anticline.

TER 85-01 shows how the package of seismic reflectors representing the Lower Carboniferous succession below the Hurlet Limestone thickens westwards



Fig. 4.4.1 TER85-01 located over the Salsburgh Anticline and imaging the Salsburgh fault. Abbreviations; LCMS, Base Lower Coal Measures; Castlecary, Castlecary Limestone or Base Passage Formation; Calmy, Calmy Limestone; Index, Index Limestone; Hurlet, Hurlet Limestone. Interpretation based upon correlation with the outcrops of the base of the Lower Coal Measures: the subsurface depth control is provided by the boreholes and well located in the hangingwall of the Salsburgh fault: these are the Salsburgh 1A well, the Salsburgh 2 well, the Jersey Bridge bore and the Craighead well located directly on this line. by 0.2 s TWT (~386 m) into the hangingwall of the Salsburgh fault (Fig. 4.4.1). The reflector package between the Hurlet Limestone and Index Limestone slightly increases in thickness towards this fault by ~0.01 s TWT (Fig. 4.4.1) but this is below the seismic resolution of 34 m. Seismic reflectors between the Index Limestone and the Calmy Limestone change by ~0.07 s TWT (~149 m) towards the Salsburgh fault. However, the seismic reflector package between the Calmy Limestone and the Castlecary Limestone thins over the fault (Fig. 4.4.1) by 0.02 s TWT (~40 m); this is above the seismic resolution of 12.5 m. However, this resolution is partially calculated from the wavelength above 0.0 s TWT, and is probably a result of processing error. The present erosional surface between the Castlecary Limestone and the Lower Coal Measures prevents any analysis of the change in stratal thickness.

4.4.2 Interpretation of the Salsburgh Anticline

The formation of the Salsburgh Anticline can be interpreted in terms of five main periods of development (Fig. 4.4.2). The significant thickness change of the succession beneath the Hurlet Limestone in the hangingwall of the Salsburgh fault represents the main phase of fault-controlled accommodation creation. The smaller or negligible change in thickness of the succession between the Hurlet Limestone and the Index Limestone suggests a period of minor or no fault movement or simply topographic infill (Fig. 4.4.2). Renewed fault-related accommodation generation is suggested by the increase in thickness of the package between the Index Limestone and Calmy Limestone into the fault hangingwall (Fig. 4.4.2). The small length of the fault implies that accommodation generated by the Salsburgh fault would have only influenced sedimentation over a relatively small area of a few kilometres.





The thinning of seismic reflectors above the Castlecary Limestone towards and over the Salsburgh fault suggests inversion of the fault. This inversion, during the Westphalian, produced the observed anticlinal structure of the Salsburgh Anticline (Fig. 4.4.2).

Previously, the Clackmannan Syncline and the Motherwell Basin have been considered to be two separate depocentres separated by the Salsburgh Anticline (Read, 1988; Francis, 1991a). This new interpretation of the Salsburgh Anticline as a structure created by an inverted fault at depth indicates that the Clackmannan Syncline and the Motherwell Basin may have been one depocentre until the Westphalian when inversion of the Salsburgh fault occurred. The seismic interpretation illustrates that deposition during inversion did occur over the anticline indicating that it never formed a complete barrier to sedimentation.

Gibbs (1989) interpreted the Salsburgh Anticline as an extensional ramp anticline formed between two normal faults extending toward the NE. However the seismic evidence presented here is not consistent with Gibbs' (1989) interpretation because no NE-orientated faults can be identified and stratal growth patterns are not consistent with a NE-orientated fault. This interpretation is unlikely because seismic data demonstrates that the anticline was formed by inversion of the Salsburgh fault in the late Namurian (Fig. 4.4.2). Monaghan *pers. comm.* identified a similar fault-controlled anticline developed in the eastern MVS on the margin of the Leven Syncline. This is a NNE-orientated anticlinal structure, the Earl's Seat Anticline, that is interpreted to have been formed by fault inversion during the late Namurian.

4.5 SW-NE orientated faulting in the Central Coalfield

Only one SW-NE orientated fault (BGS, 1974) is identified in seismic in
the Central Coalfield. The fault is located in the north of the Clackmannan Syncline on its western margin, 5 km from the Clyde Plateau lavas. This fault may be an extension of the East Campsie fault (Fig. 4.0.1). However, these structure are not linked on the geology map (BGS, 1997 and BGS, 1974). Three seismic lines image this fault TOC83-V317 (Fig. 4.5.1), TOC85-V327 and TOC85-V212 (Appendix 1).

4.5.1 Example TOC83-V317

TOC83-V317 (Fig. 4.5.1) is located in the northern Central Coalfield and runs from the western margin of the Clackmannan Syncline to the River Forth (Fig. 4.1.0). This 7.5 km long seismic line has an arcuate E-W orientation. The picked seismic markers are the base Westphalian, the Castlecary Limestone, the Index Limestone, the Top Hosie Limestone and three strong reflectors (SRF1/V-317, SRF2/V-317 and SRF3/V-317) below the Top Hosie Limestone. SRF1/V-317 probably represents the top of the Clyde Plateau Volcanic Formation because of the presence of seismic facies 1 below the reflector (Fig 4.1.2). SRF2/V-317 and SRF3/V-317 are therefore reflectors in the Viséan; because of its depth SRF3/V-317 may represent the Hurlet Limestone but due to the lack of borehole depth penetration no definitive interpretation can be made.

There are two identified faults, labelled 1 and 2, in the profile and seismic reflectors below the Top Hosie Limestone reflector increase in TWT into the SW-NE fault 1 by 0.2 s TWT indicating a thickening of the succession in the fault hangingwall. The reflector package between the Index and Top Hosie limestones shows no systematic changes from E to W whereas the overlying package between the Index and Castlecary limestones does thicken into the fault hangingwall.

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4.6 NW-SE orientated faulting in the Central Coalfield

Several NW-SE-orientated faults are identified in seismic lines in the Central Coalfield. Two NW-SE faults the Dechmont and Salsburgh faults have been documented in detail (sections 4.3 and 4.4).

TOC82-V201 (Fig. 4.2.1) images a fault (labelled 3, Fig. 4.2.1) that corresponds to a 8 km long NW-SE-orientated fault on the geological map (BGS, 1974). This fault is located on the eastern limb of the Clackmannan Syncline. The succession between the Index Limestone and SRF 1/V-201 thickens in the hangingwall of this fault by 0.9 s TWT. Between the Index and Castlecary limestones the succession thickens only slightly (0.03 s TWT) whereas the interval between the Castlecary Limestone and base Lower Coal Measures shows no hangingwall thickening.

The same seismic packages show increases in thickness into the hangingwall as the Salsburgh fault. Therefore, the NW-SE-orientated faults in the Central Coalfield, identified from seismic data in this study, show similar displacement histories between the Viséan and Arnsbergian. However, only the seismic package between the Calmy and Castlecary Limestones thin across the Salsburgh fault, whereas the same packages show no systematic thickness changes around this fault. Therefore, thickness of the seismic packages suggests that not all NW-SE-orientated faults experienced a later inversion phase.

4.7 ENE-WSW orientated faulting in the Central Coalfield

The thickening of reflector packages into ENE-WSW orientated faults is observed in seismic lines both in the Clackmannan Syncline and the Motherwell Basin (e.g. section 4.3 SAX-85-02(VIB) Fig. 4.3.1). In the northern Clackmannan Syncline thirteen seismic lines show two ENE orientated faults 6 km apart. Appendix 1: TOC82-01, TOC82-V301, TOC82-V311, TOC85-V03, TOC85-V212, TOC85-V215, TOC85-V330, TOC85-V324, TOC86-M103, TOC86-M104, TOC86-M105, TOC86-M106 and TOC86-M107.

TOC 82-V330, images two faults, the southerly of which corresponds to an ENE-orientated fault on the geological map (BGS, 1997), whereas the northerly fault is orientated by correlation with faults in other seismic lines. The southern most of the two ENE-orientated faults downthrow to the NNW and the northern fault downthrows to the SSE (Fig. 4.7.1).

Significant differences in thickness can be interpreted across both faults. The combined thickness from SRF 1/V-330, that is probably in the middle Viséan from its depth and above the seismic reflector package that represents the Clyde Plateau Volcanic Formation, ~2718 m, to the Passage Formation is ~350m thicker (~0.205 s TWT) in the immediate hangingwall (~1700 m) of the southern fault compared to the adjacent footwall (~1350 m). On the hangingwall of the northern fault, 1830 m of strata is present compared to only ~1600 m on the footwall. TOC85-V324 (Fig. 4.2.3 section 4.2, which images the southern fault) shows an increased interval of ~0.05s TWT between the Top Hosie Limestone reflector and the Castlecary Limestone into the southern faults; this represents a succession thickness increase of ~112 m. Similar thickness distribution between the faults was also observed in the other 12 seismic lines (Appendix 1).

On the geological maps of this area (BGS, 1974; BGS, 1977; BGS, 1997), two continuous faults are not recognised but a series of ENE-WSWorientated faults that downthrow to both the NNW and SSE are identified. The seismic interpretation suggests the faults can be linked for 3 reasons: (1) The



Fig. 4.7.1 TOC82-V311 located from the eastern margin to the axis of the Clackmannan Syncline. Abbreviations; LCMS, Base Lower Coal Measures; Castlecary, Castlecary Limestone or Base Passage Formation; Calmy, Calmy Limestone; Index, Index Limestone; SRF 1/V-311, Strong Reflector. Interpretation based upon outcrops of the base of the Lower Coal Measures, the Passage Formation, cross-correlation with thirteen seismic lines (Fig 4.1.1) and the Tippethill, Dale's Farm, Whitrigg, Redding Diamond, East Carron, Cuttyfield, Mossneuk and Rosehill Farm boreholes.

occurrence of faults along the same geographic line, in thirteen seismic lines, over a distance of 15 km suggests that these faults are connected, (2) The geological maps of the area (BGS, 1997 and BGS, 1974) show there to be a near-continuous fault located where the southern fault is imaged across the Clackmannan Syncline and the presence of discontinuous faults along the same geographic line for the northern fault suggests that connection into a single structure is possible, and (3). The interpreted throw in each of the seismic lines (300-350 m) suggests that the fault lengths may overlap or be connected *sensu*. Walsh and Watterson, (1987) and Walsh *et al.* (1998). A number of antithetic and synthetic faults are present in other seismic lines (Appendix 1). However, the details of the smaller antithetic and synthetic fault sets cannot be fully resolved, given the spacing of the 2-D seismic lines.

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The thickness variations observed from the thirteen seismic lines (Appendix 1) are interpreted as controlled by active fault movement during the Viséan-Yeadonian onwards. The presence of two faults *c*. 6 km apart in these thirteen seismic lines over a distance of 25 km is used to define a continuous ENE-orientated graben, named in this study as the Forth Graben. This 25 km-long graben may be an extension of the Kilsyth Trough (Fig. 4.0.1) in the west, where the graben is estimated from the geological map (BGS, 1997) to be less than 500m wide. The graben thickens eastwards from the Kilsyth Trough, reaching 6 km wide where it is imaged by seismic line TOC85 V-212 (Appendix 1). The structure remains consistently 6 km wide as far to the ENE as it can be traced on seismic lines.

Thickness variations are also identified from reflection seismic lines along the length of the graben parallel to the bounding faults. These thickness changes

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suggest spatial variations in subsidence within the Forth Graben. However, the spatial variations in thickness observed could reflect deposition in local depocentres adjacent to initially small faults which subsequently grew and then linked to form a single major structure (*sensu*. Sharp *et al*, 2000).

This graben structure has not been recognised before. However, Read (1989c) interpreted a WSW-orientated Passage Formation multistorey, fluvial channel deposit in this area. He postulated that the fluvial system was exploiting a topographic low in the hangingwall of a fault, causing preferential multi-storey stacking of river channels. The fault system interpreted from seismic in this study suggests that this river system was actually confined within a graben, rather than simply influenced by a single fault.

4.8 WNW-ESE orientated faulting in the Central Coalfield

Seismic lines in the Central Coalfield (Fig. 4.1.0 and Appendix 1) show thickness increases into the hangingwalls of WNW-ESE orientated faults. Eight seismic lines image thickening of the succession in the hangingwalls of WNW-ESE orientated faults. Seismic lines TOC82-V201 (Fig. 4.2.1 fault 2), TOC82-V205, TOC83-V207, TOC83-V212, SAX-85-02(VIB), TOC85-V212, TOC86-M101 and TOC86-M109 (Appendix 1).

Example TOC83-V207

TOC83-V207 (Fig. 4.8.1) is located in the northern Central Coalfield and images the eastern margin of the Clackmannan Syncline. The seismic line is 10 km long and broadly orientated SSW-NNE. The picked seismic markers are the base of the Lower Coal Measures, the base of the Passage Formation, the Index Limestone, the Top Hosie Limestone and an unidentified strong reflector (SRF



Fig. 4.8.1 TOC83-V207 located in the northern Central Coalfield imaging the eastern margin of the Clackmannan Syncline. Abbreviations; LCMS, Base Lower Coal Measures; Castlecary, Castlecary Limestone or Base Passage Formation; Index, Index Limestone; Top Hosie, Top Hosie Limestone; SRF 1/V-207, strong reflector. Interpretation based upon outcrop of the base of the Lower Coal Measures, cross correlation with seven seismic lines (Fig. 4.1.1), and the Gartarrytoll, Inch of Ferryton well and Forth Bridge boreholes.

1/V-207), that is located below the position of the Hurlet Limestone but above seismic facies 1 and therefore is interpreted to be located within the middle Viséan strata. There are three identified faults in the profile, located at shot points 150, 210 and 335, that offset all the reflectors. These faults correspond to WNW-ESE orientated faults on the geological map (BGS, 1974) and are shown to downthrow to the SSW. The fault located at shot point 335 shows thickening of the seismic package from SRF 1/V-207 to the Castlecary Limestone in the hangingwall zone of the fault. The largest observed thickening (~0.11 s TWT) occurs below the Top Hosie Limestone and SRF 1/V-207. Between the Index Limestone and the Top Hosie Limestone the succession thickens by ~0.06 s TWT. Only minor thickening (~0.02 s TWT) is observed between the Castlecary Limestone and the Index Limestone.

4.9 Probable N-S orientated faulting in the Central Coalfield

There can be no exact fault strike direction given to these faults as they are imaged only in individual seismic lines and are not mapped at the surface. However, a number of key features were used to interpret a broad N-S orientation. Consideration of their angle of intersection with the seismic lines i.e. apparent fault plane dip, indicates that the faults are perpendicular to the seismic line. The location of these faults around the syncline margin indicates that they are probably related to syncline growth. The type of fault also indicates that they were formed by different mechanisms to other faults identified in the MVS. Comparisons to faults observed in seismic data from the Midlothian-Fife Syncline eastern MVS (Underhill, *pers. comm.*) show that the fault styles and displacements are similar to the N-S-orientated faults in Midlothian-Fife region; therefore, a general N-S orientation can be implied.

N-S orientated faulting was observed on the margins of the Clackmannan Syncline in three seismic lines TOC82-V310, TOC83-V317 and TOC82-V201 (Fig. 4.2.1). In TOC82-V201 (Fig. 4.2.1) these faults (labelled 1) have a listric appearance and offset the Carboniferous succession below the Index Limestone. The increased separation of the seismic reflector package below the Index Limestone reflector shows that the Viséan to Pendleian succession thickens into the hangingwalls of these faults.

These N-S-orientated listric faults, which are probably less than a few km long, are present along the margins of the Clackmannan Syncline. Based on the stratigraphic interval, these faults probably developed during Chokierian to Pendleian times. These faults post-date the initiation and main growth of the syncline and are interpreted as faults accommodating strain associated with syncline development.

Read (1988) described the Bathgate Hills as an important structural line, the Bo'ness Line, that acted as an area of low subsidence, forming a hinge for the eastern limb of the Clackmannan Syncline (Fig. 4.0.1). Rippon *et al.* (1996) developed this idea and proposed a NNE-SSW trending normal fault along the Bo'ness line that controlled both volcanicity and deposition of successions older than the Limestone Coal Formation. Six seismic lines TOC82-V313, TOC82-V310, TOC83-V324, TOC82-V308, TOC85-V324 (Fig. 4.2.3) and TOC86 M112 (Fig. 4.2.2), are located across the proposed position of the Bo'ness line and identify no NNE-SSW trending normal fault. The reflectors show westward thickening of the Viséan into the Clackmannan Syncline, as opposed to an eastward thickening into a fault beneath the syncline margin. This westward thickening pre-dated the extrusion of the Bathgate Hills volcanic succession (Monaghan & Pringle, in press), indicating that the Clackmannan Syncline was developing prior to any volcanic extrusion. The area is simply a low subsidence area, associated with volcanism, on the margin of a major syncline.

4.10 E-W orientated faulting in the Central Coalfield

E-W orientated faults on the geological map sheets and imaged on seismic lines TOC 82-V330 (Figs 4.7.1) and TOC85 V-212 (4.10.1) are located in the northern Central Coalfield. These faults offset all of the seismic packages recognised, but there is no associated stratal thickening of the succession into the hangingwalls of these faults. Therefore these faults were not active during the Carboniferous. These E-W faults are also intruded by Permian quartz-dolerite dykes suggesting that the faults are Late Westphalian to Early Permian in age (BGS, 1967; 1977; 1984; 1992; 1997).

The northern end of the eastern margin of the Central Coalfield is bounded by the NW-trending Arndean fault labelled 4 (TOC82-V201 Fig. 4.2.1). This fault is mapped at the surface to link with the E-W orientated West Ochil fault, and may represent a splay of that fault. The Carboniferous succession is present in the hangingwall of this fault, while an Upper Devonian succession is present in the footwall. Minor thickening of the Carboniferous succession occurs towards this fault, suggesting that it was an active structure controlling accommodation generation. Previous models have suggested that the West and East Ochil faults exerted a major control on accommodation development during Carboniferous depocentre formation (Francis, 1991). However, Rippon *et al.* (1996) and evidence from the seismic across this apparently related Arndean fault both



Fig. 4.10.1 TOC85-V212 Located in the north-central Clackmannan Syncline. Abbreviations; LCMS, Base Lower Coal Measures; Castlecary, Castlecary Limestone or Base Passage Formation; Index, Index Limestone; Top Hosie, Top Hosie Limestone. Interpretation based upon correlation with outcrops of the base of the Lower Coal Measures and Passage Formation, cross correlation with five seismic lines and the Inch of Ferryton well.

suggest that there was no major displacement during the Carboniferous, and therefore the Arndean and possibly West and East Ochil faults were post-Carboniferous in age.

4.11 Summary of active structures through the Carboniferous

This study provides evidence for the timing of the main phases of tectonic activity and for the first time fully distinguishes between syn-depositional and post-depositional structures. A summary of the variation of the active structures through the Carboniferous is presented in Fig. 4.11.1. The summary of the Motherwell Basin and Clackmannan Syncline was based on interpretation of all the seismic lines (Appendix 1). The fault orientation summary was constructed from the seismic lines illustrated in this chapter. However, if there was a discrepancy, for example where Top Hosie or Hurlet Limestone had not been identified, then the summary was constructed from seismic lines with good borehole control.



Central Coalfield Syncline, both from the Motherwell Basin and Clackmannan Syncline. (C) Some growth into the Central Coalifield Syncline, both from the Motherwell Basin and Clackmannan Syncline. (D) Inversion of the Salsburgh fault separating the Motherwell Basin from the Clackmannan Syncline. (E) Westphalian subsidence across the Central Coalifield and MVS. (1) Fault displacement with synchronous syncline growth. (2) Minor fault displacement with topographic infilling and syncline Francis (1991), Browne (1999) and Read et al. (2003). Radiometric dates are from Menning et al. (2000), scale B which gives maximum values. Seismic reflector horizons and tectonic models interpreted from seismic in the MVS (this study). Abbreviations; FM, Formation; Lst, Limestone; CC, Castlecary; TH, Top Hosie; MB, Motherwell Basin; CS, Clackmannan Syncline.. (A) Central Coalifield Syncline initiation and Clyde Plateau Volcanic Formation extrusion. (B) Major growth into the growth. (3) Renewed fault displacement and syncline growth. (4) Minor fault displacement, topographic infilling and regional subsidence. (5) Inversion of fault and esulting anticline growth within subsiding syncline. (6) Listric faults on the syncline margin.

Chapter 5

Analysis of borehole data in the central Midland Valley of

Scotland

5.1 Introduction

Tens of thousands of boreholes and a relatively small number of wells have been drilled in the MVS over the past 150 years. These have been drilled for a variety of purposes, the most common being for ground stability examination and construction, with most being less than 50 m in depth, coal exploration boreholes represent the majority of boreholes drilled over 50 m. A limited number of boreholes have been drilled for mineral extraction, water extraction, geothermal research (Browne et al. 1985; 1987b), coal bed methane exploration and extraction and hydrocarbon (wells) exploration. This borehole and well data resource is maintained by the BGS as a national archive and has been used by their geologists and by many other researchers in the MVS. In this study 233 boreholes and wells have been used (Appendix 2), however, due to publication restrictions only the names and locations of this subsurface data set have been included apart from a few key boreholes. The dataset has, and continues to be, used for purposes not originally intended. For example, to aid in the construction of geological maps where there is limited exposure, or to produce conceptual models of basin formation (e.g. Gibbs, 1989 or Read, 1988).

The boreholes records are stored in three main formats; graphic logs, largely hand drawn at a scale of 1 cm to 5 m or equivalent, written log journals, and more recently in a digitised format.

The different reasons for drilling boreholes means that they often vary in quality, and only penetrate the formations that were of interest to the parties drilling the boreholes. Therefore, the majority of boreholes drilled for coal exploration penetrate the Coal Measures, Passage Formation, Upper Limestone Formation, Limestone Coal Formation and the Lower Limestone Formation. Relatively fewer boreholes penetrate the Viséan in the central MVS to any significant depth.

Boreholes were and are predominantly logged from mud chippings and were not cored, limiting the recovered information. However, they do record depths to interpreted formation boundaries and depths to coal horizons which can be used as a secondary correlation tool. All of the borehole records measure lithologies. The scale that this is recorded on and the terminology used means that only a few of the records contain usable information on the sedimentology or palaeo-assemblages, for example in pre-1940's bores the description "fakes" is used for siltstone. Pre-1960's boreholes were drilled in fathoms, feet and inches, those after in metres. Wells were drilled in feet. The variety of units used for measurement has meant that in order to compare boreholes in fence diagrams, panels or isopach maps, all had to be converted into the same scale. Once at the same scale the boreholes were projected from an ordinance datum sea-level; for many of the boreholes this had already been done prior to this study.

The purpose of this chapter is to illustrate the evolution of the central area and wider MVS where there is limited or no seismic data. This is achieved by constructing borehole panels in, and studying the isopach maps, of Brand (1983); Browne *et al.* (1987a; 1987b); Read (1988); Rippon *et al.* (1996) of the central MVS. The interpretations from this chapter can then be integrated with the

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tectonic history developed from seismic data.

5.2 Previous studies

The production of isopach and palaeogeography maps from borehole records and surface mapping in the MVS have been used to create conceptual models of MVS basin formation Brand (1983); Browne *et al.* (1987b); Read (1988); Rippon *et al.* (1996).

The most comprehensive studies of these borehole studies was conducted by Browne and Monro (1989); seven isopach maps of the main lithostratigraphical divisions within the Upper Devonian and Carboniferous are redrawn here from Browne and Monro (1989) Figs. 5.2.1, 5.2.2, 5.2.3, 5.2.4, 5.2.5, 5.2.6 and 5.2.7. The studies of Brand (1983) were concentrated in the Ayrshire Coalfield, while Read (1988) considered the whole MVS but only during the Silesian, whereas Rippon (1996) considered the development of the northern Kincardine Basin adjacent to the Ochil fault.

5.2.1 Isopach maps from the Upper Devonian to the end Carboniferous

The isopach map of the Stratheden Group (Fig. 5.2.1), Upper Devonian, is thickest in the Clyde coast area reflecting the proximity of the deposits to the upland source of western Scotland (Browne and Monro 1989). There are indications of distinct depocentres developing during sedimentation of the Kinneswood Formation in central Ayrshire, the Lothians and around Glasgow (Browne and Monro 1989). However, the evidence for this is limited because only a few boreholes penetrate to this depth within the major depocentres.

The isopach maps during the Inverclyde and Strathclyde Groups (Fig. 5.2.2) show that the major depocentres are all in the eastern MVS and trend NE-



Fig. 5.2.1 Isopach map of the Stratheden Group and Kinnesswood Formation. Reproduced from Browne and Monro (1989).















SW (Browne and Monro 1989). The successions in these basins are thought to be 2-2.5 km thick. A shelf trends ENE-WSW in central north Fife around the Lomond Hills while the Pentland Hills and Burntisland Anticline form relative high areas (Browne and Monro 1989). In the western MVS a predominantly volcanic sequence is preserved within a NE-SW trending depocentre situated against the west Campsie fault (Browne and Monro 1989). In Ayrshire, a depocentre occurs in the Dailly-Straiton area.

The isopach map of the Lower Limestone Formation (Fig. 5.2.3) shows depocentres located along the Campsie fault, and a broad flat depocentre beneath the Kincardine Basin and Motherwell Basin. In West Lothian a NNE-SSW depocentre is present west of the Clackmannan Syncline, while in Midlothian a depocentre is associated with the Pentland fault, and in Leven Bay a depocentre extends north-eastwards into East Fife (Browne and Monro 1989). In Ayrshire narrow NE-SW trending basins are present at Dalry and around New Cumnock adjacent to the Southern Upland fault (Browne and Monro 1989).

The major depocentres during Limestone Coal Formation times (Fig. 5.2.4) are located broadly in similar areas to those of the Lower Limestone Formation (Fig. 5.2.3). They occur along the Campsie fault, in the southern and northern parts of the Kincardine Basin, trending NNW-SSE and NE-SW respectively, adjacent to the Pentland fault and in Leven Bay (Browne and Monro 1989). The relative high areas are located in Ayrshire. Minor depocentres occur in North Ayrshire and proximal to the Southern Upland fault around New Cumnock and Douglas. No deposits are preserved across a broad strip trending ENE from Ayr. Read (1988),though, shows the thickest deposits in the Limestone Coal Formation in an ENE trend along the Campsie fault to the east Ochil fault. Both Read (1988) and Rippon *et al.* (1996) show the thickest area in the Kincardine Basin orientated N-S.

Although the pattern of depocentres observed for the Limestone Coal Formation (Fig. 5.2.4) did not change during the deposition of the Upper Limestone Formation, which is thickest in the northern Kincardine Basin and Kilsyth Trough (Fig. 5.2.5), the axis of the Kincardine Basin has moved to the WSW Browne *et al.* (1985); to the W in Read (1988), and Rippon *et al.* (1996). In South Ayrshire a graben complex is shown to have developed between the Southern Upland and Kerse Loch faults.

The isopach map of the Passage Formation (Fig. 5.2.6) shows that the axes of the Kincardine Basin and Midlothian-Leven synclines have moved to a north-south orientation, slightly to the west of that observed in the Upper Limestone Formation, however, accommodation is no longer thought to have been occurring in the Kilsyth Trough, Browne and Monro (1989) and Read (1988). The Ochil fault is seen to have influenced the Westfield Basin, and in Ayrshire a depocentre occurs between the Southern Upland and Kerse Loch faults (Browne and Monro 1989).

The isopach map of the Westphalian (Fig. 5.2.7) shows relatively even sediment distribution thicknesses across the MVS with maximum thicknesses occurring at Dalmellington to New Cumnock, Douglas and Midlothian-Leven Bay; of 450, 600 and 500 metres respectively.

5.3 Borehole panels

These previous studies carried out using the borehole dataset have meant that there is no need to reproduce the large basinwide isopach maps. However, certain aspects of the seismic interpretations and tectonic history presented here can be explored and further documented using the borehole dataset (Appendix 2). Therefore, a series of fourteen borehole panels located on Fig. 5.3.0 have been constructed across the Central Coalfield to examine the changes in thickening patterns associated with the Kincardine Basin, the Motherwell Basin the Salsburgh Anticline and the previously undocumented Forth Graben. Borehole panels have been integrated with seismic data where appropriate to show structures, e.g. faults, to aid in the interpretation and to construct correlation surfaces where only one borehole may penetrate the succession. Boreholes occasionally do not have the correlatable surface e.g. the limestone, preserved in the record, due to erosion or faulting, and in these situations the correlation is taken through the formation boundary and correlated to the limestone laterally.

5.3.1 N-S borehole panels (Fig. 5.3.1 and 5.3.2)

The N-S borehole panels (Figs. 5.3.1 and 5.3.2) are located from the middle to the southern margin of the Kincardine Basin and N-S along the eastern margin of the Kincardine Basin respectively. The northern end of Fig. 5.3.1 is located in the Clackmannan Syncline (NS 8167,6487); the panel crosses the Salsburgh Anticline and terminates in the Uddingston Syncline at (NS 8092,4508). There are seven stratigraphic correlation horizons within the borehole panel; these are either formation boundaries or major basinwide correlative horizons. They are the base of the Lower Coal Measures, the top of the Castlecary Limestone (or base of the Passage Formation where the Castlecary Limestone, the Index Limestone, the Top Hosie Limestone, the Hurlet Limestone, the upper surface of the Clyde Plateau Volcanic Formation and



Fig. 5.3.0 Borehole and well locations and borehole panel locations in the Central Coalfield.



Colour key to all borehole panels



the Devonian/Carboniferous transition zone.

Borehole panel Fig. 5.3.1 shows that between the top of the Lower Carboniferous volcanic rocks and the Castlecary Limestone, the succession thickens towards the centre of the Kincardine Basin. The greatest increase in succession thickness is between the Carboniferous volcanic rocks and the Hurlet Limestone (465 m). Thickening also occurs in the Lower Limestone Formation (47 m), Limestone Coal Formation (154 m) and Upper Limestone Formation (108 m) towards the centre of the Kincardine Basin. The zone of maximum thickness change is located around the margin of the Motherwell Basin. This panel also crosses the Salsburgh Anticline and fault at an oblique angle, therefore stratal thickening interpreted from seismic across the Salsburgh fault between the Jersey Bridge and Craighead 1 boreholes has been integrated into the panel. Borehole panel Fig. 5.3.2 shows that thickening also occurs in the Upper Limestone Formation towards the centre of the Kincardine Basin.

5.3.2 E-W and WNW-ESE Borehole Panels (Fig. 5.3.3 and 5.3.4)

These borehole panels are located across the Motherwell Basin, Salsburgh Anticline and Kincardine Basin. Fig. 5.3.3 is approximately located along northing 6200 (Fig. 5.3.0) and Fig. 5.3.4 is orientated WNW-ESE (Fig. 5.3.0). There are five stratigraphic correlation horizons within these panels. They are the base of the Middle Coal Measures, the base of the Lower Coal Measures, the Castlecary Limestone, the Index Limestone and the Top Hosie Limestone.

The panels (Figs. 5.3.3 and 5.3.4) show thickening of the succession between the Index Limestone and base of the Lower Coal Measures into the axis of the Clackmannan Syncline (34 m). The majority of this thickening occurs



Fig. 5.3.3 Panel along northing 6200 0.5 cm to 1 km. Information in the Motherwell Basin has been derived from cross-section seismic interpretation and the limited borehole penetration





between the Index Limestone and the Castlecary Limestone. Thickening also occurs into the Salsburgh Fault (Figs. 5.3.3) in the Upper Limestone Formation, whereas the Passage Formation thins over the Salsburgh Anticline. There is relatively little available information on thickening in the Motherwell Basin due to lack of borehole depth penetration.

5.3.3 Borehole panels in the Motherwell Basin

The borehole panels Figs. 5.3.5 A and B are located in the Motherwell Basin, originating in the SW of the basin then crossing the Uddingston Syncline. These panels (Fig. 5.3.5) are orientated SW-NE and E-W. There are four stratigraphical correlation horizons within the borehole panels. These are the base of the Lower Coal Measures, the Castlecary Limestone, the Index Limestone and the Top Hosie Limestone.

The SW-NE panel shows that the succession between the Top Hosie Limestone and the Castlecary Limestone thickens from the margin to the middle of the Central Coalfield. There is no evidence for thickening into the Uddingston Syncline, but general thickening into the Motherwell Basin is observed. The Passage Formation thickens into the Uddingston Syncline, therefore indicating that this is probably a late Namurian fold as interpreted from the seismic data (Chapter 4). However, two major unconformities are present in the Passage Formation in the Motherwell Basin (BGS 1967) which may influence the apparent observed thickening. Minor thickening in the Limestone Coal Formation is observed into the Dechmont fault in this panel. The W-E panel shows the upper Namurian and Westphalian succession across the southern end of the Uddingston Syncline. Though the lack of borehole depth penetration and the modern erosional



level prevents thickening into this syncline being assessed.

5.3.4 Borehole panels across the northern Kincardine Basin and the Forth

Graben

Eight borehole panels have been constructed in the northern Kincardine Basin (Figs. 5.3.6 to 5.3.13), and these are located on Fig. 5.3.0. The borehole panels not only cross the Clackmannan Syncline but also cross the seismically identified Forth Graben. There are five stratigraphical correlation horizons within these borehole panels. They are the base of the Lower Coal Measures, the Castlecary Limestone, the Index Limestone the Black Metals Marine Band and the Top Hosie Limestone.

The WSW-ENE (Fig. 5.3.6), WNW-ESE (Fig. 5.3.8) and NW-SE (Fig. 5.2.10) orientated borehole panels show thickening into the centre of the Kincardine Basin between the Black Metals Marine Band and the Castlecary Limestone. The thickness change from the limb to the centre of the Clackmannan Syncline is ~150 m. This thickness increase indicates that the Clackmannan Syncline was still growing during the Namurian, although not to the same extent that it grew during the Viséan, where the thickness increase identified from seismic data was of the order of several hundreds of metres from seismic interpretations.

Borehole panels 5.3.7 orientated NW-SE, 5.3.9 orientated SW-NE, 5.3.11 orientated N-S, 5.3.12 orientated N-S and 5.3.13 orientated SW-N-SE show thickening into the north Forth Graben bounding fault. This thickening is of the order of an extra 100 m of rock in the hangingwall of the faults between the Black Metals Marine Band and the Castlecary Limestone. However, the maximum








5.3.9 SW-NE panel across the northern Central Coalfield







5.3.12. SW-NE panel across the northern Central Coalfield



Graben fault

5.3.13 W-E panel across the northern Central Coalfield

thickening during the Viséan (~250 m) into the hangingwalls of these faults was observed in seismic data.

5.3.5 Isopach and borehole panel interpretations

Although there are identified changes in thickness across the MVS depocentres evident from borehole isopach data, these do not distinguish between the competing proposed tectonic models (section 1.3).

The major fault and fold orientations identified in seismic data can be correlated with areas of increased thickness in the isopach maps and borehole panels. The borehole panels (Figs. 5.3.1 to 5.3.13) in the Central Coalfield, and the isopach maps (Figs. 5.2.1 to 5.2.7) of the MVS Browne and Monro (1989) increase confidence in seismic interpretations, (Chapter 4). However, not all seismically identified faults can be seen to have an influence on the isopach distribution, which is the result of the spatial nature of the borehole data and the smoothing of the isopach contours during interpretation.

The late Devonian and Viséan isopach maps of the MVS show thickening, of up to 2500 m, Browne and Monro (1989). This major thickening correlates with the major thickening event identified in seismic data below either the Top Hosie Limestone reflector (Chapter 4). The SSW-NNE orientation of these depocentres in Browne and Monro's isopach maps quite closely matches the N-S orientation identified in seismic data. This variation in depocentre orientation is most likely the result of the different scale of data, the seismic data being affected by processing methods e.g. data smoothing, while authors of borehole data tend to have basin models in mind when drawing isolines. The density of data coverage is also important; for example, seismic data is only available within the Central Coalfield with spatial limitations between lines, whereas boreholes and wells are more evenly distributed and there is a greater density of coverage, though depth penetration can also limit this resource.

The isopach maps of Browne and Monro (1989) of the Lower Limestone Formation show that the formation maintains an uniform thickness across the Central Coalfield depocentre; however, this is the result of a lack of depth penetration (Browne *pers. comm.)* as only in the Inch of Ferryton well penetrates the succession. However, a centre to the basin can be interpreted from seismic data in the northern Kincardine Basin and may extend southwards. The isopach map (Fig. 5.2.3) of the Lower Limestone Formation indicates that thickness changes occur around the margin of the Central Coalfield. However, the lack of boreholes in the centre of the Kincardine Basin do not allow for the zone of thickening identified in seismic data around the Central Coalfield margin to be tested (Chapter 4). This isopach map also identifies an area of increased thickness in the Kilsyth Trough; this is interpreted to link with the growth of the Forth Graben in the west of the Central Coalfield.

The isopach maps and borehole panels of the Limestone Coal Formation show thickening in the southern Central Coalfield towards the axis of the Kincardine Basin, and that the succession in the Motherwell Basin also thickens towards the axis of the Clackmannan Syncline. However, on the Browne and Monro (1989) isopach maps in the northern Central Coalfield three distinct areas of increased thickness occur along a WSW-ENE trend into western Fife. These three depocentres occur within the fault-bounded WSW-ENE Forth Graben identified from seismic data. The isopach map of the Upper Limestone Formation shows similar changes in thickness to those in the Limestone Coal Formation. The isopach maps and borehole panels of the Passage Formation show thickening of this formation into the centre of the Kincardine Basin from the east and from the Motherwell Basin in the west, and the thickest area of deposition occurs within the seismically identified Firth Graben. Reads' (1988) isopach maps also shows increased thickening, but only in the Kilsyth Trough. The isopach map of the Westphalian shows generally uniform thickness across the MVS.

Therefore, subsurface information from boreholes and wells in the MVS closely correlates with that obtained from the seismic data. They both show that the Viséan strata above the Clyde Plateau Volcanic Formation show the main effect of tectonism that controlled basin formation in the central MVS. This is especially important to demonstrate in the southern Clackmannan Syncline where there is no seismic data. The borehole data from the Namurian Limestone Coal Formation illustrates that minor thickening, mainly below seismic resolution, is present, and this interval is therefore interpreted to be one of tectonic quiescence. Renewed thickening in the Upper Limestone Formation observed in seismic data was also observed in the borehole panels and isopach maps. The Westphalian, from the borehole data, is interpreted to represent a period of regional subsidence and relatively minor tectonic activity. The isopach maps illustrate that there are great changes in thickness across the MVS, especially around the margin of the Central Coalfield in the seismically identified zone of thickening. However, despite these large changes in thickness the facies variability is limited, emphasising the conclusion (Chapter 2) that deposition in the MVS kept pace with accommodation.

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Chapter 6

Regional tectono-stratigraphic evolution of the Midland

Valley of Scotland

This study has illustrated the importance of a syn-depositional tectonic control on sedimentation (Fig. 6.1.1); including the thinning and thickening into growth folds and syn-depositional faulting on a range of scales and orientations. However, the existing models developed for the tectonic evolution of the MVS, involving either N-S extension (Leeder 1982, Leeder & McMahon, 1988, Fraser and Gawthorpe, 1990) or sinistral strike-slip (Coward, 1993) cannot adequately explain the observed and described orientations of the synsedimentary structures described.

6.1 Summary of fault activity and the generation of accommodation

Although faults display interpreted syn-sedimentary displacement during deposition of the Viséan the precise nature and timing of this mechanism is unclear because of interpertative limitations produced by the lack of correlation within the Dinantian succession, and as such, a satisfactory driving mechanism for this is limited. It is, however, likely that the generally orientated N-S extension across Northern Europe acted upon pre-existing structures within the MVS producing locally controlled depocentres. A second phase of activity in the Yeadonian is identified that influenced the distribution and thickness of the Passage Formation. During the period between these two phases of fault activity (mid-Brigantian to Arnsbergian), accommodation across the Central Coalfield was generated by regional subsidence and continuing syncline growth.



Fig. 6.1.1. Geological map of the Central Coalfield, based upon solid geological map Hamilton, (23); Livingston, (32 W); Kinross, (40); Airdrie, (31 W); Falkirk, (31 E). Important syndepositional (red) and post-depositional (blue) structures interpreted from seismic data. Abbreviations; UCMS, Upper Coal Measures; MCMS, Middle Coal Measures; LCMS, Lower Coal Measures; PGP, Passage Formation; LCF Limestone Coal Formation; LLF, Lower Limestone Formation; ULF, Upper Limestone Formation; SYG, Strathclyde Group; IF, Inverclyde Group. By the Westphalian, the Central Coalfield was undergoing regional subsidence, inversion folding and uplift associated with some faults (e.g. the Salsburgh fault).

An important conclusion of this study is that the E-W-orientated faults, detailed on the geological map sheets and imaged in a number of seismic lines, were not active during the Carboniferous. These faults have previously been included in models for the development of Carboniferous depocentres (e.g. Leeder, 1982). This study, however, demonstrates that these E-W-orientated faults offset folds and faults that clearly formed in the Carboniferous. Therefore, within the Central Coalfield, E-W orientated faults are probably Late Westphalian to Early Permian in age.

6.1.1 Model background

Analogue models of strike-slip basins consistently reproduce similar structures such as growth folds and several orientations of active faults, for example those described from the MVS. The range of these structures were first recognised in experimental clay models and from field examples studied by Tchalenko and Ambraseys, (1970); Wilcox *et al.* (1973) and Bartlett *et al.* (1981). Sylvester (1988) compiled and summarised many of these previous models to produce the currently accepted models for the development of structural features within sinistral and dextral shear bounded basins (Fig. 6.1.2). Later sand box models (Acocella *et al.* 1999; Casas *et al.* 2001) duplicated Sylvester's (1988) models.



Fig. 6.1.2 (A) Plan view of Riedel model with orientations of structures formed in right simple shear along a NE-SW striking faults. Double parallel lines represent orientation of extension. Wavy lines represent orientation of fold axes. Abbreviations: P, P fractures; R¹ and R², synthetic and antithetic shears, respectively; PDZ, principal displacement zone; F angle of internal friction. Plain black arrows = axis of principal shortening; arrows with buffer = principal axis of lengthening (Sylvester 1988). (B) Geologically important structures in the Central Coalfield in a MVS context that influenced the accommodation generation during the Carboniferous with geometric relations among associated structures formed in right simple shear.

6.1.2 Preferred Tectonic Model for the development of the Central Coalfield

The cause of Carboniferous structures within the Central Coalfield is not directly evident from the seismic data boreholes or the geological maps used in this study, because they are all intra-basin datasets. However, by integrating these datasets, and testing the results against published models for strike-slip basin formation, an interpretation of the controlling mechanism can be made. The key assumption for the MVS model presented here is that strike-slip motion was concentrated along the ENE-orientated bounding structures, the Southern Upland and Highland Boundary faults. Movement along these could have produced and controlled the development of synsedimentary structures identified within the MVS based on the models of Sylvester (1988) Figs. 6.1.1 and 6.1.2.

Dextral motion along the Southern Upland fault and Highland Boundary fault would generate maximum compression in an ENE-WSW direction forming the NNE-SSW Clackmannan Syncline. The syn-depositional growth of this flatbased asymmetrical syncline generated the most accommodation in the central MVS (Figs. 6.1.1 and 6.1.2). Seismic lines crossing the edges of the syncline show that there is no evidence for faults beneath syncline margins controlling the growth of this major fold. The syncline margins are therefore not fault propagation folds. The seismic packages interpreted as Carboniferous deposits were observed to thin onto the syncline margins, but there is no direct evidence for unconformities or missing strata and therefore regional subsidence must have contributed to the development of the Central Coalfield depocentre.

The orientation of Namurian and Viséan synsedimentary structures identified from the geological maps, borehole and reflection seismic lines from the Central Coalfield of the MVS are consistent with a predominantly transtensional setting with dextral motion along major bounding structures (Fig. 6.1.2 after Sylvester 1988). Dextral strike-slip along the bounding structures could produce NE-SW to NW-SE orientated faults within the basin, equivalent to the Riedel ¹ shears of Sylvester (1988), and NW-SE to WNW-ESE orientated faults within the basin, equivalent to the Riedel ² shears of Sylvester (1988). The seismic interpretation demonstrates that NE-SW, NW-SE and WNW-ESE orientated faults were active during the Carboniferous, and all had similar displacement histories. These faults are unlikely to be pure normal faults, rather oblique-slip faults that contributed to significant local accommodation variation within the Central Coalfield. Dextral motion on the bounding structures is also consistent with NNW-SSE extension producing ENE-WSW orientated extensional faults, such as those bounding the 25-km-long Forth Graben of the northern Central Coalfield.

In Dinantian times the horizontal principal stresses were low, so the vertical principal stress (the weight of the overburden) corresponded to the maximum principal stress. This led to regional extension with development of new normal faults (cf Anderson, 1951, faulting) (Fig. 6.1.3) (Chadwick, *pers comm.*). Provided that the minimum principal stress was north-south, then the new normal faults would have been oriented east-west. In addition, any pre-existing (Caledonian) NE-SW oriented faults would have suffered a dextral component of displacement (Chadwick, *pers comm.*).

In later Carboniferous times the horizontal stresses increased (in line with Variscan convergence). Importantly, the north-south principal stress remained lower than the east-west principal stress. At some point the east-west stress became the maximum principal stress, with the intermediate principal stress northsouth. This led to regional shortening with development of north-south reverse



'Anderson faulting' model with Ó1>Ó2>Ó3 and ÓV>Ó2>Ó3 thus producing Normal faulting in an E-W direction



Fig. 6.1.3 Theory of change in local stress regime to produce the change in tectonic styles observed in the Dinantian and Westphalian (*sensu* Anderson 1951).

faults and folds (Chadwick, *pers comm*.). As the observed folds affect all of the Carboniferous strata equally, and there is a lack of evidence for thinning of strata onto fold crests it is likely that much of the folding post-dates the preserved succession, i.e. Late Westplalian. As before the pre-existing (Caledonian) NE-SW oriented faults continued to suffer a dextral component of displacement.

The model therefore allows us to switch from early N-S extension to later E-W shortening whilst at the same time maintaining a consistent dextral sense of displacement on the major (NE-SW) basin margin faults (Chadwick, *pers comm.*). The switch moreover requires no radical re-arrangement of stresses – merely a gradual increase in the horizontal confining stress field (Chadwick, *pers comm. And* Fig. 6.1.3).

The N-S orientated listric faults present along the margins of the Clackmannan Syncline developed during the Chokierian to Pendleian but cannot be explained by dextral movement along the bounding structures. However, these faults would be consistent with slumping of the syncline margin during growth of the syncline.

6.1.3 Comparison of the preferred tectonic model with published models

Although sinistral motion, as proposed in the Coward (1993) model, would produce the NE-SW orientated Riedel ¹ and NW-SE orientated Riedel ² shear structures observed in the MVS, the maximum compressional stress direction would be N-S and the maximum extensional direction E-W. These stress directions would therefore have produced E-W orientated fold axes and N-S orientated extensional faults. Structures in these orientations are not identified in the Central Coalfield or the wider MVS and hence sinistral motion along the bounding structures is considered to be unlikely. The sinistral to dextral model of Rippon *et al.* (1996) advocates a change from a Devonian-early Namurian sinistral strike-slip regime (E-W tension), to a dextral strike-slip regime (E-W compression) during the late Carboniferous. Again this model allows for the generation of NE-SW-orientated Riedel ¹ and NW-SE orientated Riedel ² shear structures. There are SW-NE orientated faults present in the Ayrshire Coalfield which also show extensional movement during the Namurian (Eyles *et al.* 1949; Monro *et al.* 1999). However, there is no evidence for E-W fold axes in the Viséan from the seismic data. Ritchie *et al.* (in press) also support the sinistral to dextral model of Rippon *et al.* (1996) based on seismic evidence in the Firth of Forth. Here the authors propose that sinistral movement controlled deposition through a N-S orientated fault (the Mid-Forth fault), and compare this to the proposed Bo'ness fault on the margin of the Central Coalfield, the existence of which has been questioned in this study. Likewise, the existence of the Mid Forth fault has similarly been called in to question by Underhill (*pers. comm.*).

The N-S extensional model, as proposed by Leeder (1982), has some limitations. The orientation and growth of synsedimentary structures in the MVS does not fit and it would be difficult to reconcile the existence of N-S orientated growth folds and the orientations of active faults, observed in the seismic data, with pure extension in a N-S direction. However, when considering the wider driving mechanisms across Northern Europe and the local pre-Carboniferous inherited structures within the MVS a variation of this model could be used to explain the evolution of the MVS.

The dextral model proposed is in broad agreement with those dextral strikeslip models in the MVS from the Viséan-Westphalian (Belt, 1969; Dewey, 1982; Read, 1988). Although there are some key differences, the dextral model

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presented in here (Fig. 6.1.1) still recognises regional subsidence as important but the synsedimentary development of synclines is the key mechanism for accommodation generation in the Central Coalfield and in the East Lothian-Fife depocentre. Read (1988) proposed that the depocentre was predominantly caused by thermal and regional subsidence, with only a minor dextral component, and that the E-W dip-slip faults accommodated subsidence in addition to having post depositional displacement unrelated to dextral motion.

6.2 Evolution of the MVS depocentres outside of the Central Coalfield

6.2.1 The Midlothian-Leven Syncline

The Midlothian-Leven Syncline is an asymmetrical NNE-SSW trending syncline, the southern closure of the syncline arcs to the SW and is offset by the WNW-orientated Roslin-Vogrie fault, (Fig. 6.2.1). The western limb dips more steeply (~60° to 80°) than the eastern limb. The oversteepened western limb is possibly the result of a reversal in movement along the Pentland fault (Cameron and Stephenson 1985). The release of well and seismic data by Conoco and others from the Firth of Forth and the Glenrothes area in Fife provided an opportunity for Ritchie *et al.* (in press) and Underhill *et al.* (in prep.) to examine the major NNE-SSE trending syncline at depth and in three dimensions. Using a similar methodology to this thesis and by integrating the seismic, field, borehole and mining data, the aim of these studies was to constrain the structural development of the MVS (Ritchie *et al.* in press) and to evaluate the hydrocarbon potential of the area (Underhill *et al.* in prep.). The extent offshore of some important onshore



faults, such as the Pentland, Crossgatehall and Ardross faults, and the trace of previously proposed structures like the Firth of Forth Fault (Thomson, 1978) have been tested. The data also provide constraints on the nature of two of the 'marginal' folds to the main Midlothian-Leven Syncline, the Earl's Seat Anticline and the Burntisland Anticline (Underhill *et al.* in prep.).

The seismic interpretations show that the limbs of the Midlothian-Leven Syncline are steeply dipping and predominantly undeformed. However, minor breaks or kinks are interpreted as inward verging folds or small faults (Underhill *et al.* in prep.). The most significant interpretation by Underhill *et al.* (in prep.) is that each of the seismic-stratigraphic packages from the Viséan, Namurian and Westphalian are characterised by internal thickening towards the syncline axis and pronounced onlap towards its flanks, Ritchie *et al.* (in press) only observed this thickening from the Namurian.

The 'complex anticline' structure on the eastern margin of the Midlothian-Leven Syncline is the D'Arcy-Cousland Anticline (Fig. 6.2.1) across which a series of folds are superimposed (Underhill *et al.* in prep.). At depth the anticline narrows, and is cut by upward-divergent, steeply-dipping fault planes that are interpreted to branch from a central zone of deformation (Underhill *et al.* in prep.). These faults may have controlled the development of the eastern margin of the syncline.

There are some significant differences between the interpretations of the seismic data by Underhill *et al.* (in prep.) and Ritchie *et al.* (in press). These are primarily concerned with the interpretation of faults, both in their existence and extent. Ritchie *et al.* (in press) propose the existence of a NNE-orientated fault and associated fold, the *Mid Forth fault* and *Mid Forth Anticline* (Fig. 6.2.2). The

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proposed fault is interpreted to be a WNW-dipping normal fault that was inverted. The Upper Devonian to Dinantian succession is interpreted to thicken westwards into the Mid Forth fault by 0.2 s TWT by Ritchie *et al.* (in press). This fault is then interpreted to die out to the north and terminates against the Inchkeith fault zone (Fig. 6.2.2) in the south (Ritchie *et al.* in press). However, Underhill *et al.* (in prep.) interpret no fault in the area and illustrate thickening towards the syncline axis. Ritchie *et al.* (in press) also propose that the Crossgatehall fault extends offshore (Fig. 6.2.2) into a steeply-dipping fault zone along the mapped trend of the onshore fault. Interpreted movement along the fault has resulted in Dinantian thickness variations between the interpreted footwall and hangingwall blocks. The authors also infer that the Ardross fault may extend to link with the Mid Forth fault (Fig. 6.2.2).

The onshore Pentland fault is thought to form part of a family of faults associated with the Southern Upland fault (Floyd and Stiven 1991; Floyd 1994) and has been interpreted to be a late Carboniferous or younger reverse fault (Mitchell *et al.* 1962; Cameron and Stephenson 1985). Ritchie *et al.* (in press) mapped the fault extent offshore using the seismic data to define the eastern margin of the Inchkeith High.

However, the interpretation of the seismic data by Underhill *et al.* (in prep.) shows no evidence for either the continuation of the Pentland, Crossgatehall or Ardross faults into the offshore region or for the existence of pervasive E-W trending Permian faults within the seismic survey. Furthermore, there now seems to be absolutely no seismic basis for the previously proposed Firth of Forth fault (Thompson 1978) in the area (Underhill *et al.* in prep.; Ritchie *et al.* in press).

Field mapping and field relations similar to those observed in the central



MVS (this study) show that basin formation was complete by the end of the Carboniferous as they are cross-cut by E-W trending Permian dykes and by a suite of E-W trending normal faults and extensional fractures (Underhill *et al.* in prep.).

6.2.2 Evolution of the Midlothian-Leven Syncline

The Viséan-Westphalian (Underhill et al. in prep) or Namurian-Westphalian (Ritchie et al. in press) evolution of the eastern MVS is dominated by syn-sedimentary growth of the Midlothian-Leven Syncline. Underhill et al. (in prep.) propose that Viséan to Westphalian dextral strike-slip movement controlled the timing and geometry of the Midlothian-Leven Syncline. This is similar to the NNE-SSW trending syn-sedimentary growth of the Clackmannan Syncline to the west (Chapters 4 and 5). However, Ritchie et al. (in press) sub-divide the evolution of the eastern MVS into three main stages: 1. Upper Devonian to Dinantian fault-controlled subsidence; 2. Silesian basin-wide subsidence with local structural inversion and growth during the Silesian; 3. Late Silesian dextral transtension and transpressional strike-slip faulting. This differs from the basin evolution interpretations based on observations in the Central Coalfield (Section 6.1) where accommodation generation was dominated by growth into the Clackmannan Syncline from the mid-Viséan to the Westphalian, with faults controlling local distribution. More similarities in interpreted geological structures do seem to appear than differences, however, between the depocentres.

6.3 The Douglas Coalfield

The Douglas Coalfield is the smallest of the MVS coalfields. It is preserved as an outlier of the Carboniferous, separated from the Central Coalfield to the north by Devonian rocks, and from the Ayrshire Coalfield to the west by



Fig. 6.3.2 (A) Sketch map showing the variation in thickness of the Index Limestone and the probable limit of deposition of the Shell Band Limestone (after Lumsden and Wilson 1967). (B) Sketch map showing the variation in thickness of the sandstone above the Index Limestone (after Lumsden and Wilson 1967). The stratigraphic position of the isopached beds are shown on Fig 6.3.1.



Fig 6.3.3 (A) Sketch map showing the variation in thickness of the Ellenora Coal and the probable limits of deposition of that seam and the two coals above (after Lumsden and Wilson 1967).

(B) Sketch map showing the variation in thickness and probable limit of deposition of the Ponfeigh Gas Coal (after Lumsden and Wilson 1967). The stratigraphic position of the isopached beds are shown on Fig 6.3.1.



Fig. 6.3.4 (A) Sketch map showing the variation in thickness of the Gill Coal and the probable limits of deposition of the seam and the thin limestone below the seam (after Lumsden and Wilson 1967).

(B) Sketch map showing the variation in thickness of the succession between the Index and Calmy limestones (after Lumsden and Wilson 1967). The stratigraphic position of the isopached beds are shown on Fig 6.3.1.



Fig. 6.3.5 View to the north across the Douglas Coalifield from the Glentaggert opencast mine. The blue line is a coal in the Lower Coal Measures; the coal is downthrown by 4 m to the NE across a fault zone, the red shaded zone is a fault breccia that is up to 10 m wide, the fault trends NW, internal slickenlines in the fault breccia indicate that it is a dextral strike-slip fault

Silurian and Devonian rocks. It forms a narrow basin along a NNE (Fig. 6.3.1) trend covering approximately 48 km² which widens to the SSW and NNE (BGS 1967). The coalfield is bounded and offset by the Kennox fault along the SE margin of the basin (Fig. 6.3.1).

The Douglas Coalfield consists of a SSW-NNE trending asymmetrical syncline. The SSE limb dips steeply (up to 60°) with a gentler-dipping NNW limb (up to 30°) (BGS 1967). The Lower Limestone, Limestone Coal, Upper Limestone and Passage formations and the Lower and Middle Coal Measures are exposed at the surface. There are several orientations of faults within the Douglas Coalfield which trend approximately E-W, ENE-WSW NE-SW and NW-SE.

6.3.1 Isopachyte maps in the Douglas Coalfield

Lumsden and Wilson (1967) constructed a series of isopachyte maps (Figs. 6.3.2 to 6.3.5) across the Douglas Coalfield. The maps illustrate either the succession between limestones and coals, or represent the thicknesses of individual coals or limestones. The use of individual bed isopachyte maps may need to be considered with care as this study has shown that limestones are often storm-related deposits (Chapter 2). Therefore, thickness distribution may reflect the storm surge or topographic relief rather than tectonic accommodation generation during limestone deposition. Similarly coal thicknesses may need to be considered with care as this is the result of compaction.

The isopachyte map of the thickness of the Index Limestone and the sandstone above (Fig 6.3.2 A & B) show that the limestone is of variable thickness across the northern Douglas Coalfield. Although there is a greater preserved thickness in the centre of the syncline compared to the limbs, the limestone also thickens both to the NW and SE towards the margins of the basin. Above the

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Index Limestone it shows a much more consistent pattern of change and is thickest in the centre of the syncline and elongate along the axis of the fold, and significantly the sandstone also thickens towards the south-easterly bounding structure, the Kennox fault. The isopachyte map of the thickness of the Ellenora Coal and the depositional limit of the two overlying coal seams (Fig 6.3.3 A) show that the thickness of the Ellenora Coal reflects the location of the syncline axis in the area NW of the town of Tower. However, the most significant thickening is again towards the Kennox fault. The isopachyte map of the thickness of the Ponfeigh Gas Coal (Fig 6.3.3 B) shows that this coal does not vary in thickness across the syncline axis. However, a significant nine-fold thickness increase occurs towards the Kennox fault. The isopachyte thickness map of the Gill Coal shows a similar pattern of distribution as the Ponfeigh Gas Coal with thickening towards the Kennox fault (Fig 6.3.4 A). The isopachyte thickness map of the Index to the Calmy limestones also shows a marked thickness increase towards the Kennox fault (Fig 6.3.4 B).

6.3.2 Evolution of the Douglas Coalfield

Analysis of the thickness trends of key intervals in the Douglas Coalfield shows two important features. These are thickening of the succession into the centre of the SW-NE orientated syncline from the Lower Limestone Formation until at least the Middle Coal Measures (Lumsden and Calver 1967; Lumsden and Wilson 1967), and the thickening of the succession into the NE-SW trending Kennox fault on the margin of the coalfield. Therefore, the Douglas Coalfield Syncline and the Kennox fault were active from at least the late Viséan to the early Westphalian.

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The Kennox fault is an extremely steeply dipping to vertical fault that has a wide fault breccia zone (Lumsden and Calver 1967). The fault also changes its sense of downthrow; from Glespin to Kennox Hill the downthrow changes from SE to NW (Lumsden and Calver 1967). This wide zone of fault breccia and the changing sense of downthrow (*sensu* Barnes and Audru 1999) is common to strike-slip faults. Evidence for strike-slip faulting in the Douglas Coalfield has also been recorded in the Glentaggart OCCS south of Glespin. In this site, a NW-SE orientated fault has been recorded in the Lower Coal Measures with a 4 m offset but a 10 m wide fault breccia zone (Fig. 6.3.5). Slickensides within the fault breccia zone indicate that the fault had a dextral strike-slip displacement.

The isopach and field evidence from this study, combined with evidence from surrounding basins, are consistent with the conclusion that the Douglas Coalfield was probably formed by dextral offset along the Kennox fault and deposition occurred into a related NE-SW-orientated syncline and adjacent to the Kennox fault itself.

The growth of the Douglas Coalfield Syncline and thickening into the Kennox fault are similar to the patterns of thickening observed in the Central Coalfield. However a direct comparison of the timing of this thickness is not possible because of the lack of resolution in seismic data compared to the thickening of individual units. There is no evidence for the early development of the syncline in the mid-Viséan as there is in the Central Coalfield. However, thickening is observed in both depocentres from the upper Viséan to the Westphalian. The thickening of the succession into the Kennox fault from isopachyte maps is similar to that observed into NE- and ENE-trending faults in the Central Coalfield.

6.4 The Ayrshire Coalfield

No major fold is identified in the Ayrshire Coalfield, unlike in the Central

Coalfield, the Midlothian-Fife Coalfield and the Douglas Coalfield. The Ayrshire Coalfield is dominated by four major SW-NE-orientated faults with minor related folds. These faults have a more north-easterly orientation than those in the other coalfields and this is interpreted as an inherited Caledonide structure associated with Carboniferous reactivation (Monro 1982). A change in strike of the minor folds adjacent to these faults is thought to be related to the variation in orientation of the faults, as well as to later Variscan events (Monaghan *pers. comm.*). Evidence for the control on deposition by these faults is presented in the isopachyte maps of Browne and Monro 1989, (Chapter 5 Figs. 5.2.3 to 5.2.6) and Read (1988). Deposition in the Ayrshire Coalfield appears to have been periodically controlled by active movement on these faults and by topographic infilling.

6.4.1 Dinantian development of the Ayrshire Coalfield

The Dinantian development of the Ayrshire Coalfield is closely linked to the extrusion of the Clyde Plateau Volcanic Formation, the southern limit of which is formed by the Inchgotrick fault (Monro *et al.* 1999).

The Clyde Plateau Volcanic Formation rests unconformably on rocks of either the Stratheden or Inverclyde groups (Paterson *et al.* 1990; Forsyth *et al.* 1996) and has been linked to a phase of uplift resulting from updoming prior to eruption (Monro *et al.* 1999). The evidence for fault movement on the NEorientated faults in Ayrshire comes from gravity data (Monro *et al.* 1999) and seismic data (Hall *et al.* 1984). These datasets show that the lavas thin southeastwards toward the Dusk Water fault but thicken abruptly on the south-east side of the fault i.e. in the hangingwall. Borehole data around the Dusk Water fault show that there is little evidence for thickness variation in the Lower Limestone



Fig. 6.4.1 (a) Isopachyte and palaeogeography map of the Limestone Coal Formation. (b) Horizontal section showing the variation in thickness and lithology within the Limestone Coal Formation. reproduced from Mykura and Calver (1967).
Formation indicating that any thickening related to fault movement, as observed in the lava pile, had ceased by this time.

Therefore the early Carboniferous accommodation was generated in the Ayrshire Coalfield in response to updoming in the crust to the north (Monro *et al.* 1999). This is evident from changes in thickness of the volcanic formation across major faults and in the sedimentary rocks which overlie the lavas and thicken into the faults (Monro *et al.* 1999).

6.4.2 Namurian development of the Ayrshire Coalfield

The Inchgotrick and Dusk Water faults and the smaller NE trending Annick Water fault (Monro *et al.* 1999) have been shown to influence sedimentation in the Ayrshire Coalfield during the Namurian (Richey *et al.* 1930). The Limestone Coal Formation is occasionally absent or present as a condensed succession, south of the Inchgotrick fault (Fig. 6.4.1). The area covered by the condensed succession is interpreted as a high 'block' area (Monro *et al.* 1999). Immediately south of the Kerse Loch fault in the fault's hangingwall major thickening occurs. The Limestone Coal Formation then thins southwards up the hangingwall dip slope and is absent south of the Dalmellington fault (Mykura 1964; Mykura *et al.* 1967; Fig. 6.4.1).

Sedimentary logs in this study (Chapter 2, Fig. 2.5.1 and Appendix 3) have been concentrated on the succession from the top of the Lower Limestone Formation through the Limestone Coal Formation and into the Upper Limestone Formation, in the east of the Ayrshire Coalfield, to the south of the Kerse Loch fault. These logs illustrate the dominance of marine shelf, restricted marine and deltaic facies associations (palaeogeography maps Chapter 2, Figs 2.5.3 to 2.5.5) present in the western MVS compared to the central and eastern MVS. The sedimentological studies also suggest that the location and orientation of minor channels were controlled by NE-SW orientated faults, as they have been observed in the immediate hangingwalls of these faults. These faults have been recorded in the Viaduct Open Cast Coal Site (OCCS) and Spireslack OCCS and slickensides suggest a probable dextral dip-slip to strike-slip displacement. The Upper Limestone Formation is also present as condensed sections between the Inchgotrick and the Kerse Loch faults, and expands in the hangingwalls of both the Kerse Loch and Littlemill faults (Mykura *et al.* 1967).

The Passage Formation has presented and continues to present correlation problems in the Ayrshire Coalfield. This is because the Castlecary Limestone, defining the base of the Passage Formation, is not recognised in the coalfield, having been removed by erosion (Mykura *et al.* 1967). Therefore, the lower boundary of the formation is placed either at the top of the uppermost coal or at the top of the uppermost shelly horizon of the Upper Limestone Formation. The top of the Passage Formation also presents correlation problems across the coalfield as erosion has removed parts of the formation (Mykura *et al.* 1967). The isopachyte maps of the Passage Formation (Browne and Monro 1989 Chapter 5 Fig. 5.2.6; Read 1988) show a complicated pattern of sediment thickness distribution in the Ayrshire Coalfield. A condensed Passage Formation succession is present on the 'block' between the Inchgotrick and Kerse Loch faults and thick accumulations are present in the downthrown hangingwalls of these faults. This is similar to the distribution of the Limestone Coal and Upper Limestone formations and suggests a persistent influence of the faults.

6.4.3 Westphalian development of the Ayrshire Coalfield

The Lower Coal Measures succession is observed to thicken from the

Inchgotrick fault towards the southeast in a similar pattern to the Limestone Coal and Upper Limestone formations (Mykura 1964; Mykura *et al.* 1967). Isopachyte maps (Mykura *et al.* 1967; Read 1988) also show thickening into the Kerse Loch and Dalmellington faults, and show that deposition in the Middle Coal Measures (Mykura *et al.* 1967) show was confined within grabens with half-graben thickening into the Kerse Loch fault.

6.4.4 Summary of deposition in the Ayrshire Coalfield

The analysis of sediment distribution suggests that deposition in the Ayrshire Coalfield was predominantly controlled by displacement along NE-SW trending faults within an overall pattern of regional subsidence. The main period of displacement is interpreted to have occurred during the Viséan and this phase of movement controlled the distribution of the Clyde Plateau Volcanic Formation. During the Namurian, periodic fault displacement on the SW-NE orientated faults, basin wide subsidence and topographic relief controlled the distribution of the Namurian strata. The Kerse Loch fault appears from isopachyte maps (Mykura et al. 1967) to have been the most significant structure in the coalfield during this time. The Westphalian isopachyte maps (Mykura et al. 1967; Read 1988) show renewed fault activity during the Lower Coal Measures deposition, that had ceased by the Middle Coal Measures times. The exception is where hangingwall thickening of Middle Coal Measures is observed into the Kerse Loch fault. The isopachyte maps (Mykura et al. 1967; Browne and Monro 1989; Read 1988) show that the synclines mapped within the Ayrshire Coalfield are probably later features because there are, for example, no thickness changes towards the centre of the syncline and therefore syncline development does not appear to have had an influence on succession thickness or distribution. The pattern of accommodation



Fig. 6.5.0 Geologically important structures in the Central Coalfield and across the MVS that controlled accommodation generation during from the Mid-Viséan to the Westphalian. Geometric relations among associated structures formed in right simple shear after Sylvester (1988).

in the Ayrshire Coalfield is very different to that in the Central Coalfield. The main difference is that accommodation was generated by displacement along inherited Caledonide structures in Ayrshire, whereas syndepositional synclinal growth was the predominant mechanism of subsidence generation in the Central and Midlothian-Leven coalfields.

6.5 Summary of active Carboniferous structures outside of the Central Coalfield

The orientation of active synsedimentary folds and faults identified from reflection seismic data in the eastern MVS, and from isopachyte maps and geophysical data in the Douglas and Ayrshire coalfields, are all consistent with a predominantly dextral movement along major bounding structures from late Viséan-Westphalian time (*sensu.* Sylvester 1988. Fig. 6.5.0).

Dextral displacement on the MVS bounding structures would cause maximum extensional in a NNE direction with WNW maximum compressional direction. Dextral strike-slip along bounding structures could also reactivate SW-NE lineaments interpreted to be present below the SW-NE orientated faults in Ayrshire (Paterson *et al.* 1998; Dentith and Hall 1990; Rollin, 2003). The reactivation resulted in Carboniferous movement along the Kerse Loch, Inchgotrick and Kennox faults. These NE-SW-orientated faults are equivalent to the Riedel¹ shears of Sylvester (1988) (Fig. 6.5.0) and were probably dip-slip faults. Growth into the downthrown side of the fault indicate that extension occurred across the faults. In the depocentres outside of the Central Coalfield, extensional WSW-ENE and WNW-ESE orientated faults were not recognised, with the exception of the Roslin-Vogrie fault. There are two potential reasons for this; 1. a lack of data at depth for WSW or ESE-trending faults; 2. inherited structures precluded the development of these orientations of faults.

During the late Carboniferous and early Permian, the depocentres were offset by E-W trending faults that were then intruded by an array of dated dykes (Monaghan and Pringle in press). The lack of evidence for continued differential subsidence in the synformal depocentres, in conjunction with the developments of these late stage faults, suggests that dextral strike-slip had been replaced by N-S tension.

6.5.1 Comparisons of observed and documented structures to models of basin formation

These fault and fold structures generating accommodation outside the Central Coalfield illustrate the importance of a syn-depositional tectonic control on sedimentation across the MVS, including thinning and thickening into growth folds and syn-depositional faulting on a range of scales and orientations. However, the existing models developed for the tectonic evolution of the MVS, involving either N-S extension (Leeder 1982, Leeder & McMahon, 1988, Fraser and Gawthorpe, 1990) or sinistral strike-slip movement (Coward, 1993, Phillips *et al.* 1997) cannot adequately explain the observed and described orientations of these synsedimentary structures.

Dextral or sinistral motion on the bounding structures is consistent with NNW-SSE extension producing (Riedel¹) NE-orientated extensional faults, for example those in Ayrshire. However, their orientation is not consistent with the N-S extension model of Leeder (1982). The sinistral motion along the bounding structures of the MVS suggested by Coward (1993) and Phillips (1987) cannot explain the generation of NNE-orientated growth folds because this would produce an ENE-WSW maximum extensional direction and a NNE-SSW maximum compressional direction (*sensu.* Sylvester 1988). However, dextral motion along the bounding structures of the MVS could reactivate inherited lineaments to generate both NE- and NNE-orientated faults. This would also produce an NNE-SSW maximum extensional direction and an ENE-WSW maximum compressional direction. This is consistent with the growth of NNE-orientated growth folds (Fig. 6.5.0).

6.6 Burial history of the Midland Valley depocentres

Using the sediment loading equation one-dimensional tectonic subsidence curves have been constructed to assess the fill of the MVS depocentres.

$$Sw = Ss \left(\frac{pm - ps}{pm - pw}\right)$$

Where Sw is tectonic subsidence, Ss is the total thickness of the sediment column corrected for compaction, pm, ps, pw are mantle, mean sediment column and water densities.

These tectonic subsidence curves use the thickness of the succession and the timing of depositional episodes to recognise periods of rapid tectonic subsidence. The shape of the curve is affected by several factors:

- Changes in palaeobathymetry or palaeotopography
- Sediment compaction
- Timing of sediment compaction
- Water volume of the sediment
- Lithology and initial porosity i.e. sediment density
- Thermal gradient

Palaeobathymetry and palaeotopography are not considered to be major





Compressional foreland









issues because of where the curves were constructed, sedimentological studies suggest deposition was on flat or gentle palaeoslopes. Limited sediment supply may produce an underfilled basin during episodes of major tectonic-controlled subsidence. If a basin is starved of sediment during subsidence and then later filled, the age of the later sedimentary infilling will not reflect the age of basin formation. This is not considered to be a significant problem in the MVS. The sedimentological analysis from this study demonstrates that Carboniferous deposition kept pace with accommodation generation (Chapter 2) and therefore the sedimentation was coincident with the main phase of subsidence. Increased subsidence rates, or rapid infilling of the palaeotopography both produce steeper burial history schematic curves, while slower subsidence (or tectonic uplift), or relative sea-level rise will produce shallow burial history schematic curves (Bertram and Milton 1989; Allen and Allen 1990; Emery and Myres 1996). The timing of sedimentary fill is also important as this affects the shape of the tectonic subsidence curves (Bertram and Milton 1989; Prosser 1993).

The tectonic subsidence curves constructed for the MVS are therefore describing tectonically-generated vertical displacement through time. The profiles can be compared with standard subsidence profiles for various tectonic regimes (Fig. 6.6.1), for example extensional basins conforming to the McKenzie model (Fig. 6.6.1; McKenzie 1978; Emery and Myres 1996) or strike-slip basins (Fig. 6.6.1; Emery and Myres 1996).

Although the initial porosity and water content of the MVS Carboniferous sediments are not known, the tectonic subsidence curves have been decompacted using generalised compaction ratios. For each formation the volume of coal, claystone, siltstone, sandstone, limestone, palaeosol and marl was calculated. The

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volumes of each lithology were derived from the sedimentary logs measured in this study (Appendix 3), as these represent the most accurate record of lithology. Gaps in sections were filled using borehole information and so the sediment volumes are only truly representative of one location. Sedimentary profiles derived from borehole data were used to calculate the volumes of sediment types for the Viséan interval where no exposed sections have been logged. In this study lithologies were assumed to have compacted by the following proportions:

Coal	80%
Claystones and siltstone	30%
Sandstone	10%
Limestone	0%
Palaeosol	30%
Marl	30%

Therefore thickness of the groups or formations increased by the proportions:

Strathelyde Group	122%
Lower Limestone Formation	154%
Limestone Coal Formation	192%
Upper limestone Formation	123%
Passage Formation	160%
Coal Measures	128%

The tectonic subsidence curves (blue lines) are presented with both the compacted (black line) and decompacted (red line) data. Therefore, the black burial curve represents the total amount of accommodation generated while the



Fig. 6.6.2 Location of the tectonic subsidence curves (red dots) constructed in this study in the Midland Valley.

red uncompacted burial curve represents the amount of sediment deposited. The tectonic subsidence curves were constructed by calculating the depth to formation boundaries from seismic data (Chapter 3 depth conversion), or by measuring the depth to formation boundary from borehole data. These depths to formation boundaries were plotted against time. The absolute dates were obtained from the volcanic age dating by Monaghan and Pringle (in press). The tectonic subsidence curves disregard the statistical errors applied to the radiometric dates and use a single date.

6.6.1 Tectonic subsidence curves in the Central Coalfield

Three tectonic subsidence curves have been constructed in the central MVS. These are located in the centre of the Clackmannan Syncline south of the Ochil fault from seismic line TOC82-V201 (Fig. 6.6.2), on the axis of the Salsburgh Anticline from the Salsburgh Borehole and in the Motherwell Basin from seismic line SAX84-02(VIB) (Fig. 6.6.2).

The tectonic subsidence curve for the central Clackmannan Syncline (Fig. 6.6.3) illustrates the succession from the Clyde Plateau Volcanic Formation to the base of the Lower Coal Measures. The age of the Clyde Plateau Volcanic Formation reflector is given as an age range as the exact age of this reflector is not known. The tectonic subsidence curve has a steep gradient from the Clyde Plateau Volcanic Formation to the Top Hosie Limestone, suggesting a tectonic subsidence rate between c.140-450 m/Myr. The tectonic subsidence curve shallows from the Top Hosie Limestone to the Lower Coal Measures, suggesting a decrease in the sediment accumulation rate to c.75 m/Myr.

The tectonic subsidence curve located on the axis of the Salsburgh Anticline (Fig. 6.6.4) shows the burial history from the mid-Viséan to the late



Fig. 6.6.3 Decompacted sediment red, sediment column black and tectonic subsidence blue curves for the Clackmannan Syncline. The curve was constructed from seismic lines TOC82-V201



2000m -

Fig. 6.6.4 Decompacted sediment red, sediment column black and tectonic subsidence blue curves for the Salsburgh Anticline. The curve was constructed from the Salsburgh Borehole



Fig. 6.6.5 Decompacted sediment red, sediment column black and tectonic subsidence blue curves for the Motherwell Basin. The curve was constructed from seismic lines SAX 84-02(VIB) in the downthrown side of one of the NE orientated faults.



Fig. 6.6.6 Decompacted sediment red, sediment column black and tectonic subsidence blue curves for the Douglas Coalifield. The curve was constructed from the Happendon Borehole (NS 8510,3383) in the centre of the Douglas Coalifield Syncline.



Fig. 6.6.7 Decompacted sediment red, sediment column black and tectonic subsidence blue curves for the Midlothian-Leven Syncline. The curve was conctructed from the seismic interpretation of Richie *et al.* (in press) and BGS velocity data.

Namurian. The tectonic subsidence curve has a steep gradient from mid-Viséan to Top Hosie Limestone times indicating a tectonic subsidence rate. This is comparable to same interval in the Clackmannan Syncline curve (Fig. 6.6.3). The gradient shallows from the Top Hosie Limestone to the Castlecary Limestone indicating a slower tectonic subsidence rate of c.100 m/Myr.

The tectonic subsidence curve calculated for the Motherwell Basin (Fig. 6.6.5), from seismic line SAX84-02(VIB) (Fig. 6.6.2), illustrates the tectonic subsidence from the Clyde Plateau Volcanic Formation to the base of the Upper Coal Measures. The curve again has a steep gradient from the Clyde Plateau Volcanic Formation to the Top Hosie Limestone suggesting an accumulation rate between c.150-600 m/Myr. comparable to the rate calculated for tectonic subsidence in the Clackmannan Syncline (Fig. 6.6.3). The gradient shallows between the Top Hosie Limestone and the base of the Upper Coal Measures suggesting a reduced tectonic subsidence rate of c.25 m/Myr, much slower than that calculated for either the Clackmannan Syncline or across the Salsburgh Anticline.

6.6.2 The Western and Eastern MVS

The tectonic subsidence curve located in the centre of the Douglas Coalfield (Figs. 6.6.2 and 6.6.6) shows the tectonic subsidence from the Top Hosie Limestone to the mid Lower Coal Measures. The tectonic subsidence curve has a steep gradient from the Top Hosie Limestone to the Index Limestone that rapidly shallows to the Lower Coal Measures suggesting a sediment accumulation rate of c.30 m/Myr. It then steepens dramatically to the middle Lower Coal Measures.

The tectonic subsidence curve located in the Midlothian-Leven Syncline

(Figs. 6.6.2 and 6.6.7), calculated from the seismic interpretation of Ritchie *et al.* (in press), illustrates the tectonic subsidence from an interpreted intra-Devonian reflector to the base of the Upper Coal Measures. However, because the base of the Carboniferous has not been interpreted on the seismic lines there is no means of identifying the initiation of syncline growth. Therefore, the curve between the intra-Devonian and Top Hosie Limestone reflector is unrepresentative of depositional timing. It is suggested that the curve would have been similar to those in the other depocentres were the data available. The gradient of the tectonic subsidence curve is steep between the Top Hosie and Index limestones indicating a sediment accumulation rate of c.600 m/Myr. The curve shallows from the Index Limestone to the base of the Middle Coal Measures suggesting a sediment accumulation rate of 350 m/Myr.

In the Ayrshire Coalfield no suitable borehole was available to use in the construction of a tectonic subsidence curve. In addition the graben and halfgraben structure characteristic of the Ayrshire area would not produce a tectonic subsidence curve that was representative of the entire coalfield.

6.6.3 Summary of Midland Valley schematic burial curves

The tectonic subsidence curves derived from the MVS show the most rapid sediment accumulation during the Viséan. The exception to this is the Midlothian-Leven curve because of the lack of data. In all the depocentres the Namurian-aged intervals are represented by shallower gradients, interpreted as a decrease in the tectonic subsidence rate. This general slowing of tectonic subsidence in the Namurian is likely to result from a decrease in the subsidence rate and corresponds to the interpretations made from seismic data where fault activity became increasingly periodic and syncline growth was interpreted to have slowed (Chapter 4).

The Westphalian tectonic subsidence curves vary depending on the depocentre. In the Central Coalfield, tectonic subsidence rates continued to slow through the Westphalian but in the Douglas and Midlothian-Fife coalfields the tectonic subsidence rate accelerated. This difference may reflect longer-lived tectonic activity in these areas or renewed periods of activity along fault and fold structures. Underhill (*pers. comm.*) invokes renewed activity to explain the late Carboniferous observed tightening of the Midlothian-Leven Syncline. Any changes in late Carboniferous accumulation rates may not be observed in the Central Coalfield because the Lower Coal Measures is rarely fully preserved and even less so in the Middle and Upper Coal Measures.

The different rates of tectonic subsidence between the Central, the Midlothian-Fife, Douglas and Ayrshire coalfields are difficult to reconcile, as no single explanation is valid for all coalfields. It is more likely that a combination of several factors controlled the varying rate of accommodation, namely location of:

- inherited structures
- contemporaneous faults and folds
- volcanic activity and its timing.

Each of the coalfields inherited a variety of Caledonian structures, which may have facilitated the development of some depocentres and hindered others. The propagation of faults and folds within each of the coalfields would have varied depending upon the amount of stress placed upon them. Also the proximity of active volcanism may have contemporaneously slowed the tectonic subsidence along the syncline margins and accelerated it in the centre of the synclines by uplifting the margins. Therefore, each depocentre would have subsided differentially.

Leeder and McMahon (1988) constructed tectonic subsidence curves for four Carboniferous basins in England; the Northumberland, Bowland, Stainmore and Alston/Durham basins. These tectonic subsidence curves show subsidence of:

- c.1.1 km in Northumberland Basin during the Dinantian
- c.1.6 km in the Bowland Basin from the Dinantian to the mid Namurian
- c.0.8 km in the Stainmore Basin during the Dinantian
- *c*.0.3 km in the Alston/Durham during the Dinantian.

These periods of active extension are followed by an interpreted phase of thermal subsidence from either the base- or mid-Namurian to the Stephanian of:

- c.0.3 km in Northumberland Basin
- c.0.35 km in the Bowland Basin
- c.0.35 km in the Stainmore Basin
- c.0.5 km in the Alston/Durham area

In both the MVS and these English basins the main period of subsidence or sediment accumulation, suggesting subsidence, was during the Dinantian. This is followed by slower accommodation generation in the Silesian, which Leeder and McMahon (1988) interpret as a prolonged period of thermal subsidence. However, the tectonic subsidence curves of the MVS from the Namurian do not look like the thermal subsidence curves of Leeder and McMahon (1988) or Emery and Myers (1996). These differences in the rates of subsidence and the generation of thermal subsidence are suggested to be related to the varying orientations of fault and fold structures between the depocentres.

The periodic reactivation of faults and continuation of syncline growth observed in seismic data also suggests that the MVS was not dominantly controlled by thermal subsidence but by movement on the bounding structures. However, thermal subsidence in the MVS cannot be completely discounted because the evidence for it may have been overprinted by the tectonic signal.

6.7 Igneous activity related to the evolution of the Central

Coalfield

The volcanic history of the MVS is significant for accommodation generation in the MVS and must be considered in the context of the dextral model proposed in this study. Large volumes of igneous material have been extruded and intruded into the MVS (Francis 1991b). These have been referred to often in this study but have not been considered in detail or in terms of their influence on basin formation and development. This section therefore aims to draw some generic conclusions about the origin and influence on basin formation and development of the igneous rocks in the MVS.

The NE-SW orientation of the vent systems in the Clyde Plateau Volcanic Formation indicate that extrusion was possibly controlled along lineaments at depth parallel to the bounding structures of the MVS (Cameron and Stephenson 1985). The orientation of these vent systems, if controlled by lineaments, is consistent with dextral motion on the bounding structures.

The early Viséan extrusion of the Garleton Hills and mid- to late-Viséan

extrusion of the Clyde Plateau volcanic formations are contemporaneous with the main phase of syn-tectonic accommodation generation in the MVS. Palaeogeography, sedimentology and onlap relationships suggest the volcanic areas in the MVS formed relative highs, allowing little or no deposition in the early Viséan within the Central Coalfield. However, during the mid Viséan, deposition of sediment, onlapping onto the volcanic rocks, indicate that subsidence affected the margins of the Clyde Plateau Volcanic Formation. Therefore, volcanism had some temporal and structural control on the distribution of sediments.

The volcanism that formed the Bathgate Hills occurred contemporaneously with late-Viséan to mid-Namurian sedimentation, and formed a relative high area on the eastern margin of the Clackmannan Syncline. The N-S orientation of the Bathgate Hills Volcanic Formation does not appear to be aligned with any inherited structural trends, in contrast to the Clyde Plateau Volcanic Formation. The volcanic rocks are orientated along a similar trend as the axis of the Clackmannan Syncline, the Midlothian-Leven Syncline, the Burntisland Anticline and the D'arcy-Cousland Anticline. These structures are interpreted to have developed because of dextral motion on the bounding structures of the MVS (this study; Read 1988; Underhill *et al.* in prep.). Therefore, the coeval development of folds and volcanism along similar trends could imply that both were linked with periods of dextral motion on the bounding structures.

Evidence from seismic interpretation (Chapter 4) implies that the Clackmannan Syncline had already begun to form prior to extrusion of the Bathgate Hills Volcanic Formation. In addition, the extent and location of the volcanics is restricted to \sim 15 km of the eastern limb of the \sim 55 km preserved

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length of the Clackmannan Syncline margin. Therefore, volcanism in this area was unlikely to have controlled the generation of the Clackmannan Syncline but may have controlled sediment input into the Central Coalfield by acting as a high area along the eastern margin of the syncline.

6.8 Relative sea-level change in the Carboniferous succession

The relative sea-level in the Carboniferous had an important influence on the environment of deposition within the MVS. During this period, global sealevel is estimated to have varied by 60 ± 15 m (Crowley and Baum 1991). This is reflected in the abundant flooding surfaces preserved as marine mudstones and limestones. The sedimentary fill of the MVS is characterised by cycles of transgression to emergence. During the deposition of the Lower Limestone, Limestone Coal and Upper Limestone Formations minor transgressive events could create regional marine flooding and drowning of the alluvial plain, because of the relatively flat plain on which were deposited. Regional marine flooding events are observed as limestones and mudstones within the MVS.

These successions are interpreted to be the result of the filling of accommodation space. However, there is no evidence for major incision in the MVS during these periods of emergence unlike in other Carboniferous basins, where channel sandstone bodies with 25-30 m of incision can be traced 20-30 km perpendicular to palaeo-strike (*sensu*. Hampson 1998; Davies *et al.* 1999).

During the deposition of the predominantly fluvial Passage Formation, incision in the order of 20-30 m has been observed (Lumsden and Wilson 1967; Mykura *et al.* 1967; Read 1988; Rippon.1997). This has resulted in two unconformities in the Ayrshire and Douglas coalfield (Lumsden and Wilson 1967; Mykura *et al.* 1967) and erosion of the Castlecary Limestone in the Central Coalfield (Read 1988; Rippon *et al.* 1997). Read (1988) interpreted this incision to be the result of a relative sea-level fall. The tectonic subsidence curves suggest that during the deposition of the Passage Formation sediment accumulated at its slowest rate, suggesting that subsidence was also slow. Therefore, incision resulting in unconformities may be the result of both a relative sea-level fall, suggested by Read (1988), and a low subsidence rate (this study).

Brettle (2001) compared the sea-level curve for the Pennine Basin of Church & Gawthorpe (1994) that of the Quaternary (de Boer & Smith 1994; Chappell & Shackleton 1986; Pillans *et al.* 1998). He suggested that eustatic modulation at magnitudes and periodicities were similar between the Quaternary and the Namurian. Eustatic modulations in both the Quaternary and the Namurian (Veevers & Powell 1987) are interpreted as the product of glacio-eustatic fluctuations (Brettle 2001). The similarities between Quaternary and Namurian relative sea-level modulations suggest that Milankovitch orbital forcing may have controlled the extent of Namurian polar ice, and therefore eustatic sea-level in the MVS (Read 1988).

6.9 Is the MVS a unique basin?

There are few similar basins to the MVS around the world formed in either dextral or sinistral, transtensional or transpressional settings. The MVS is not a typical strike-slip basin in the sense of Crowell's classic notion of a slide- to pull-apart basin along a bend in a major strike slip fault (Crowell 1974). The uniqueness of the MVS resulted from a combination of variations in orientation of structures, relative to the bounding structures, styles of accommodation generation and facies´s deposition. Therefore, examples of similar basins are included and comparisons with other strike-slip and Carboniferous basins are made in this section.

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Fig. 6.9.1 (A) Map of the main structural elements of the Piaui Basin, the antiformal highs composed of volcanics (in red) and the synformal depressions in the light shade from Zalen et al. (1985). (B) Midland Valley reorientated to compare to the Piaui Basin and (C) Plan view of Riedel model with orientations of structures formed in right simple shear along a NE-SW striking faults. Double parallel lines represent orientation of extension. Wavy lines represent orientation of fold axes. Abbreviations: P, P fractures; R1 and R², synthetic and antithetic shears, respectively; PDZ, principal displacement zone; F angle of internal friction. Plain black arrows = axis of principal shortening; arrows with buffer = principal axis of lengthening after Sylvester (1988).



6.9.1 The Cretaceous Piaui Basin, Brazil

The Cretaceous Piaui Basin, Brazil has been examined by a limited number of seismic lines and wells (Fig. 6.9.1; Zalan et al. 1985). The basin formed between ENE-orientated dextral strike-slip and trends ENE-WSW for 150 km, approximately parallel to the north coast of Brazil (Fig. 6.9.1; Zalan et al. 1985). Shallow marine shales, sandstones and limestones and terrestrial fluvialdeltaic, coals and marls were deposited during an 18 Myr period of active tectonism (described as rifting) in depocentres that formed as a series of NNEorientated synclines (Fig. 6.9.1). The synclines formed between NNE-orientated anticlines that are interpreted to be formed and modified by contemporaneous volcanic and intrusive complexes (Fig. 6.9.1). The orientation of the synclines, with respect to the bounding structures of the Piaui Basin, closely matches orientations of those relative to the bounding structures in the MVS (Fig. 6.9.1). These igneous highs are comparable to the Clyde Plateau and Bathgate Hills volcanic formations in the MVS. In the Piaui Basin the contemporaneous igneous rocks are suggested to have controlled the sediment distribution into the growth synclines and possibly had a structural influence on their development. The extrusion and intrusion of these igneous rocks were suggested to be related to the strike-slip tectonism (Zalan et al. 1985). The Piaui basin underwent widespread subsidence (described as post-rift), marked by marine transgressive deposits which was either related to a thermal subsidence phase or continued diachronous continental separation (Zalan et al. 1985). Although the study of the Piaui Basin is limited by the data available, the general appearance and orientation of synclinal depocentres formed between anticlinal highs intruded by igneous rocks is very similar to the MVS. The formation of these structures between dextral strike-slip



Fig. 6.9.2 Cross-section of the East Ventura Basin and the Piru Syncline from Yeats *et al.* (1994) to illustrate the similarities to the MVS. Abbreviations; Tf, The Fernando Formation; Tt, Towsley Formation; Tm, Modelo Formation; Qs Sagus Formation; Ts Sespe Formation and Te, marine Eocene.

faults also suggests that there are similarities between the Piaui Basin and the MVS.

6.9.2 The East Ventura Basin, California

The East Ventura Basin in California began to form its present structure during the Miocene (Yeats *et al.* 1994) and is located between two reversed strikeslip faults, the Santa Susana and the Holster faults, orientated WNW-ESE and E-W respectively (Yeats *et al.* 1994). To the south of the basin lie the Santa Monica Mountains, composed of Oligocene/Miocene volcanic rocks. Within the East Ventura Basins and between the reversed strike-slip faults, an E-W-orientated synform, developed the Piru Syncline (Fig. 6.9.2). The syncline is ~10 km wide and ~25 km long and up to 4 km of Miocene sediment has been deposited within it. The succession is dominated by a shallow-marine facies association (Yeats *et al.* 1994). The synclines display thickening of the Miocene succession into the syncline centre (Fig. 6.9.2).

Although the East Ventura Basin was formed in a transpressional setting, compared to the transtensional setting of the MVS there are similarities in the presence of marginal faults and in the scale of the growth syncline depocentres. The Piru Syncline formed between faults on the margins of the syncline while no faults have been interpreted on the margins of the Clackmannan Syncline. However, Underhill *et al.* (in prep.) have interpreted upward-verging faults on the western margin of the Midlothian-Leven Syncline.

6.9.3 The Maritimes Basin, Canada

The MVS is perhaps more similar in its tectonic and stratigraphic evolution to other Carboniferous basins e.g. the Maritimes Basin of eastern Canada. The Maritimes Basin contains a number of distinct sub-basins, a feature in common with the MVS, and also has a complex polycyclic history of extension, regional subsidence and inversion. In common with the eastern MVS, the main phase of broadly extension-related fault activity occurred during the Tournaisian forming a series of NE-trending half-grabens (Pascucci et al. *et al.* 2000) but by the late Viséan, regional subsidence dominated basin evolution. A major Namurian-Westphalian unconformity developed across the entire Maritimes region during a period of uplift, folding and erosion. Following this sognificant phase of basin inversion, thermal subsidence is then considered dominant from the Westphalian B into the Stephanian (Pascucci et al. *et al.* 2000). This contrasts with continued subsidence in the MVS during this period and with unconformities being developed as a result of relative sea-level fall during the deposition of the Passage Formation (Read 1988).

Intrusive and extrusive igneous activity is also an important component of some sub-basins within the Maritimes area (e.g. Dunning *et al.* 2002; Koukouvelas *et al.* 2002). Although the tectonic evolution of this region has been described, the main driving mechanisms are not fully resolved. However, Langdon and Hall (1994) proposed a dextral strike-slip motion on marginal master faults similar to the model proposed for the MVS in this study.

6.9.4 UK Carboniferous depocentres

The Carboniferous basins of northern England, like the MVS, were partially controlled by inherited Caledonian structures (Fraser and Gawthorpe 2003; Corfield *et al.* 1996). In the Solway and Northumberland basins, Chadwick *et al.* (1995) recognised a major extensional phase beginning in the early Tournaisian. However, from the early Asbian onwards, extension across the





basin-bounding structures diminished and by the end of the Viséan, anticlines were developing in the Solway Basin. There is a clear switch in these UK Carboniferous depocentres from Dinantian subsidence to Westphalian basin inversion.

The sedimentary thickness per given time interval can be compared for the MVS, Solway Basin and Northumbria Trough (Fig. 6.9.3). The Holkerian-Courceyan deposits from the Solway Basin and Northumberland Trough comprise 59% and 65% of the preserved basin fill respectively, and this contrasts with only 45% of the fill of the Central Coalfield deposited during the same period. Therefore, the Solway Basin and Northumberland Trough are suggested to have begun subsiding earlier than the MVS.

The Namurian Stainmore Group in the Solway Basin is observed to thin over anticlinal structures and unconformities are also recognised both on seismic and in outcrop at the Namurian-Westphalian boundary (Chadwick *et al.* 1995). A major NE-SW depocentre, identified from thickness maps of Namurian and Westphalian strata, is the dominant feature in the Solway Basin, and contrasts with the very clear graben or half-graben geometry in Northumberland (Chadwick *et al.* 1995). Chadwick *et al.* (1995) attributed the development of the synclines and anticlines and associated unconformities to a proposed phase of dextral transpression. The basin evolution of the Solway Basin therefore has a number of key similarities with central and eastern MVS in terms of syncline and anticline development and the thinning of strata over developing anticlines.

Inherited Caledonian structures imparted a strong NW-SE and NE-SW tectonic grain into basins in England (Fraser and Gawthorpe 2003). However, the fill of these basins is distinctly different to the MVS. In England, Carboniferous

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basins were starved of sediment during the Dinantian. During the Pendleian clastic sedimentation began to outpace subsidence, and deposition was largely controlled by eustatic sea-level changes (Fraser and Gawthorpe 2003). By the early Westphalian, 'delta top' sediments were deposited across England (Fraser and Gawthorpe 2003).

6.10 Implications for Carboniferous depocentres UK

The most widely quoted model for the evolution of the Northumberland-Solway and Pennine basins involves Dinantian rifting as N-S extension reactivated NE and NW Caledonian structures and later in the Carboniferous, active extension gave way to thermal subsidence. (Leeder 1982; Fraser and Gawthorpe 1990). Aspects of this simple model have been questioned by a number of studies including Waters *et al.* (1994).

If dextral motion is invoked for the development of Carboniferous depocentres within the MVS, this may have some implications for the Solway and Northumberland basins to the south including the possibility that some lateral displacement occurred along faults and that the development of synclinal depocentres may not be the simple product of N-S extension. Waters *et al.* (1994) proposed an important dextral strike-slip motion along faults in the Staffordshire area during the Westphalian. The different styles of basin formation between the MVS and Carboniferous basins to the south may be the result of contrasting inherited structures and variations across the Southern Upland terrain. However, the proposed dextral evolution of the MVS may add constraints on the timing of tectonic activity and question the interpretation of simple thermal subsidence in Carboniferous depocentres to the south.

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6.11 Implications for strike-slip basins in general

If the dextral strike-slip model is accepted for the MVS, there are several features that have been observed that may be applicable to complex intracontinental strike-slip systems:

- The strong control by inherited lineaments on the distribution of fault and fold structures controlling accommodation
- Long-lived inherited lineaments controlled the location of major synsedimentary faults, and restricted the location of syncline growth within the MVS. This is suggested to be the reason why the MVS responded to regional stress in a strike-slip manner.
- The spatial control these inherited lineaments exerted on the distribution of volcanics.
- The development of a complex series of intra-basinal faults and folds related to stress on the bounding structures.
- The variation in accommodation space created by the complex local fault and fold structures

Chapter 7

Conclusions

This study represents the first integrated analysis and interpretation of the onshore seismic profiles with borehole data and field observations from the Central Coalfield. Based on the interpretation of this comprehensive dataset, a well-constrained tectonic model is proposed for this depocentre that has implications for the tectonic setting and evolution of the wider MVS.

Accommodation was predominantly generated by the syn-depositional evolution of the NNE-SSW orientated Clackmannan Syncline. The main phase of syncline growth occurred during the mid- and late-Viséan. The syncline continued to grow during the early to mid Namurian. During the late Namurian and Westphalian, regional subsidence across the entire Midland Valley area was accompanied by more limited syncline growth. There is no evidence that the syncline developed between upward propagating faults on its margins.

A number of different fault populations are recognised from seismic data across the Central Coalfield. Using seismic data those faults active during the Carboniferous could be distinguished from post-depositional faults that did not influence sedimentation. Small-scale (2-7 km long) syn-depositional faults with a range of orientations (predominantly NW, NE and ESE orientated faults) contributed to minor, local variations in Carboniferous accommodation. The largest fault-bounded structure recognised is the ENE-trending Forth Graben in the northern Central Coalfield. The graben is interpreted to extend for some 25 km along strike and thickness changes between the hangingwall and footwall on the order of c.170-350 m are recognised. The main period of tectonic activity and evolution of both the synclines and faults occurred from the mid-Viséan to the beginning of the Namurian. During the Namurian, limited displacement on faults and widespread subsidence across the MVS suggest a period of relative tectonic quiescence with minor tectonic-related accommodation dominant. The greatest period of folding occurred during the tightening of the synclines during Late Carboniferous, for example the Uddingston Syncline in the Motherwell Basin and the Midlothian-Leven Syncline. However, little evidence for this can be seen in the Clackmannan Syncline because of the amount of erosion. The syncline and some of the Carboniferous faults were later offset by E-W faults that are attributed to late Westphalian-early Permian tension Read (1988).

The control on syncline initiation and growth and the development of faults is not directly evident from the seismic data or the geological maps used in this study. However, the presence of inherited Caledonian structures and lineaments are suggested to have played a key role in the distribution of Carboniferous folds and faults and the distribution of volcanic rock.

The careful documentation of the timing and orientation of all syndepositional structures within the Central Coalfield, and combination of this information with analogue models (e.g. Sylvester 1988), suggests that a dextral transtensional model can be proposed. The other basins within the MVS, e.g. the Ayrshire, Midlothian-Fife and Douglas coalfields, contain syn-depositional structures, including synclines and anticlines, that are also consistent with dextral strike-slip movement on bounding faults. In this model, the Highland Boundary and the Southern Upland faults are proposed as the basin-bounding structures accommodating dextral motion.

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The sedimentary and stratigraphy of the MVS reveal some unique characteristics among the British Carboniferous basins. Sedimentation in the MVS was restricted between topographic highs of volcanics and within topographic lows created by syncline growth. Temporal and spatial facies changes are minimal; depocentres were dominated by shallow-marine, deltaic and alluvial environments and no Carboniferous alluvial fans are recorded along basin margins. Therefore deposition appeared to have kept pace with accommodation generation.

In contrast, thick marine Dinantian and Namurian sediments are preserved in the basins of central and northern England, reflecting underfilled depocentres and in the Northumberland Basin, for example, thick successions of alluvial fan conglomerates characterise fault-bounded margins.

Sedimentary facies variations across the MVS are suggested to have been controlled by the implied rate of subsidence. For example, the incision documented in the Passage Formation is suggested to have been the result of a slowing of the rate of subsidence.

7.1 Future Work

This study has identified areas in which future work could be directed:

 The present chronostratigraphic constraints for the MVS are based upon relatively few dates. It is recommended that more work be undertaken to date both the depositional fill and igneous extrusions. This would provide a better constrained stratigraphic framework to allow a more concise spatial and temporal model to be developed.

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 The continuation of mining activity exposing new sections within the MVS will allow ongoing and potentially further testing of the dextral tectonic model proposed in this study. Continued data collection from new opencast coal sites will add more detail for palaeogeographic reconstructions. It is therefore recommended that fieldwork forms an integral part of any future examination of the MVS.

Appendices

Appendix 1. Interpreted reflection seismic lines

The interpreted reflection seismic lines are enclosed on the CD-ROM. Labelled

Appendix 1. Archive of seismic lines.

The CD-ROM is accessible using a PC with 128 MB of ram and a CD-ROM

reader. The software required to view the reflection seismic lines is Corel Draw 9 or higher.

The seismic lines are also available from the public access UK Onshore Geophysical Library (UKOGL). http://www.lynxinfo.co.uk/ The lines are:

UKOGL Seismic

LINE_NAME	FIRST_CDP	LAST_CDP	TOTAL_KM	OPERATOR	VINTAGE
BRK-85-02	101	871	11.64	BERKELEY	85
E86B-16	463	810	7.36	ENTERPRISE	86
E86B-19	700	1085	7.66	ENTERPRISE	86
SAX-84-02HYD	101	469	3.72	SAXON	84
SAX-84-02VIB	101	1199	21.75	SAXON	84
SAX-85-01	100	535	8.73	SAXON	85
SAX-85-02	101	463	7.19	SAXON	85
SAX-85-03	101	700	11.96	SAXON	85
SAX-85-04	101	744	12.82	SAXON	85
SAX-85-05	101	893	15.8	SAXON	85
SAX-85-06	101	597	11.18	SAXON	85

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SAX-85-08	101	625	10.45	SAXON	85
SAX-85-09	101	406	6.1	SAXON	85
SAX-85-37	101	478	7.54	SAXON	85
SAX-85-38	101	839	14.74	SAXON	85
SAX-85-39	101	837	14.79	SAXON	85
SAX-85-40	100	827	14.55	SAXON	85
SAX-85-41	101	641	10.76	SAXON	85
TER85-01	75	705	7.92	TEREDO	85
TER85-02	80	480	5	TEREDO	85
TER85-03	110	787	8.45	TEREDO	85
TER85-04	90	533	5.53	TEREDO	85
TER85-05	100	673	7.16	TEREDO	85
TER85-06	110	432	4.02	TEREDO	85
TOC-82-V01	4	130	3.17	TRICENTROL	82
TOC-82-V02	10	156	3.7	TRICENTROL	82
TOC-82-V03	10	467	11.64	TRICENTROL	82
TOC82-V201	100	926	20.69	TRICENTROL	82
TOC82-V203	100	723	15.68	TRICENTROL	82
TOC82-V204	100	330	5.79	TRICENTROL	82
TOC82-V205	100	660	14.07	TRICENTROL	82
TOC82-V206	100	420	8.04	TRICENTROL	82
TOC82-V301	100	1162	26.54	TRICENTROL	82
TOC82-V302	100	369	6.66	TRICENTROL	82
TOC82-V304	100	490	9.79	TRICENTROL	82
TOC82-V306	100	497	9.9	TRICENTROL	82
TOC82-V308	100	503	10.13	TRICENTROL	82
TOC82-V309	100	588	12.22	TRICENTROL	82

SAX-85-07

9.28 SAXON

TOC82-V311	100	1183	27.12	TRICENTROL	82
TOC82-V312	100	670	14.31	TRICENTROL	82
TOC82-V313	100	470	9.28	TRICENTROL	82
TOC83-V207	100	391	7.3	TRICENTROL	83
TOC83-V209	100	328	5.7	TRICENTROL	83
TOC83-V210	100	333	5.84	TRICENTROL	83
TOC83-V212	100	308	5.22	TRICENTROL	83
TOC83-V31	100	674	14.39	TRICENTROL	83
TOC83-V315	100	425	8.16	TRICENTROL	83
TOC83-V316	100	551	11.29	TRICENTROL	83
TOC83-V317	100	448	8.67	TRICENTROL	83
TOC83-V320	100	1117	25.48	TRICENTROL	83
TOC83-V326	100	423	8.15	TRICENTROL	83
TOC85-V211	100	360	3.28	TRICENTROL	85
TOC85-V213	100	400	3.77	TRICENTROL	85
TOC85-V215	100	880	9.84	TRICENTROL	85
TOC85-V216	100	600	6.28	TRICENTROL	85
TOC85-V324	100	1120	12.78	TRICENTROL	85
TOC85-V326	100	540	5.53	TRICENTROL	85
TOC85-V327	100	520	5.22	TRICENTROL	85
TOC85-V328	100	520	5.18	TRICENTROL	85
TOC85-V329	100	620	6.52	TRICENTROL	85
TOC85-V330	100	680	7.27	TRICENTROL	85
TOC86M101	1	285	3.98	TRICENTROL	86
TOC86M102	1	289	4.03	TRICENTROL	86
TOC86M103	1	655	9.16	TRICENTROL	86
TOC86M104	1	571	7.98	TRICENTROL	86
TOC86M105	1	666	9.31	TRICENTROL	86
TOC86M106	1	202	2.81	TRICENTROL	86
<i>هــــــــــــــــــــــــــــــــــــ</i>					

TOC86M107	1	232	3.24	TRICENTROL	86
TOC86M108	1	444	6.2	TRICENTROL	86
TOC86M109	1	328	4.58	TRICENTROL	86
TOC86M110	1	227	3.17	TRICENTROL	86
TOC86M111	1	836	10.5	TRICENTROL	86
TOC86M112	1	1588	19.88	TRICENTROL	86
TOC85-V212	100	1445	16.96	TRICENTROL	85

Appendix 2. Borehole and Well Archive used in this study

The list below contains the names and locations of boreholes and wells used in the study of the Central Coalfield, Douglas Coalfield and the Ayrshire Coalfield. No information on the depth to horizons as this represents the BGS sellable data source.

Bore name	Sheet	Grid Reference Easting	Grid Reference Northing
66NE/6	NS	6840	6999
75NE/136	NS	7813	5802
Addiewell Fm	NS	9867	6281
Auchenheath	NS	8021	4528
Auchmeddan	NS	8435	3959
Auchtee head	NS	8727	5500
Aucthuhead No 1	NS	8976	5474
Baads 11	NS	9833	5836
Baads 12	NS	9835	5824
Baads 3	NS	9994	5872
Baads 4	NS	9980	5887
Baads Mine	NS	9973	6099
Balornoch	NS	6234	6875
Bardykes Shaft	NS	6751	5886
Bargeddie 1	NS	9318	4649
Barumullock Fm	NS	6289	6813
Baton Coll.	NS	8603	6137
Beatties Bakery	NS	6186	6513
Bellyhole Fm	NS	8516	3543
Belmont	NS	8841	5849
Benty Hillocks	NS	8863	5379
Benty Hillocks No 2	NS	8747	5412
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Birkshaw	NS	7672	4879
Birniehall 1	NS	9051	5418
Birniehall 11	NS	9203	5405
Birniehall 2	NS	9177	5426
Birniehall 29	NS	9217	5392
Birniehall 3	NS	9000	5367
Blackfaulds	NS	9347	6058
Blackness	NS	10537	7953
Blair Mains	NS	9712	8604
Blantyre Fm.	NS	6839	5994
Bloodmire	NS	8406	3193
Bnow	NS	8783	5567
Boglesholedyke	NS	6413	6157
Bogslde 1	NS	6432	6842
Bowridge Fm	NS	8504	4162
Brackenhlll Fm	NS	8229	5250
Braldholm Pit	NS	8092	4508
Brightknowes	NS	9570	5530
Broomelton	NS	7429	4996
Brownhousebog	NS	8513	5877
Brownlee	NS	8079	5172
Browntod	NS	7055	4994
Browntod	NS	7098	4983
Browshot	NS	9393	5100
Burnhead	NS	7953	4656
Burnside	NS	7862	3372
Cairnie	NS	5945	6336
Cambuspeath		7924	5070
		7054	5273
Campusneath 1	NS	7851	5278

Cambusnethan	NS	8109	5546	
Canderrigg	NS	7736	4597	
Canderrigg Quarry	NS	80,18	4629	
Cardown	NS	6706	6876	
Cardown Coll.	NS	6665	6836	
Carscallan	NS	7220	5115	
Castlehill	NS	8664	5272	
Castlehill	NS	8446	5283	
Castlehill Coll.	NS	8395	5205	
Castlehill Iron wks.	NS	8394	5173	
Climpy	NS	9264	5487	
Clyde 4	NS	8033	5105	
Clyde Bridge	NS	7380	5621	
Cornhills Fm.	NS	7040	5205	
Cotcastle	NS	7366	4545	
Craighead 1	NS	8267	6212	
CrofthIII 2	NS	9815	5274	
Crofthill 3	NS	9775	5279	
Crofthill 4	NS	9775	5279	
Crown Brewery	NS	6131	6477	
Cuthill	NS	9859	6367	
Dale's Fm	NS	9671	6489	
Dalmarnock	NS	6118	6272	
Dalmarnock Power Station	NS	6159	6276	
Darlsclyde	NS	8572	5633	
Douglas 5	NS	8627	3696	
East Badallan	NS	9218	5952	
Eastfield Paper Mill	NS	6227	6230	
Eggerton	NS	8504	3171	
		0004	0171	

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Fence Coll. Lesmahgow	NS	8092	4591
Fence Coll. Lesmahgow	NS	8090	4588
Forth 1	NS	9358	5462
Forth 3	NS	9364	5475
Gallow Knowe	NS	8388	3117
Garderner's Hall	NS	9879	6452
Garnkirk	NS	6757	6989
Garrlongill Overton Coll.	NS	8006	5273
Gartarrytoll	NS	9313	9126
Garthamlock 5	NS	6576	6620
Gillfoot	NS	8284	4760
Gillhead	NS	8178	5352
Glenavon	NS	7658	4917
Glenbervie	NS	8651	8388
Grasshill 1	NS	7408	2996
Grasshill 1A	NS	7408	2996
Grasshill 5	NS	7413	2999
Grasshill 7	NS	7416	2982
Greenhead 4	NS	8130	5496
Greenrigg 1	NS	9111	6254
Greenrigg 2	NS	9136	6249
Handax	NS	9578	5775
Handaxwood	NS	9463	6037
Handaxwood	NS	9524	5754
Handaxwood estate 2	NS	9534	6084
Hanestonhills	NS		
Happendon	NS	8510	3383
Hartfield	NS	8536	5710
Harthill	NS	9060	6279
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Hartwood Mine 6	NS	9902	5826
Hartwoodhili 3	NS	8537	5980
Harwood Mine	NS	9936	5845
Heads estate	NS	7196	4896
Henshieldwood	NS	9466	5201
Huntershill	NS	6087	6959
Hyndshaw	NS	8429	5274
IGS Alexandra Parade	NS	6177	6566
IGS Drumpark	NS	7055	6426
IGS Maryhill	NS	5717	6855
IGS Stoneyknowes	NS	8817	3570
Inch of Ferryton	NS	9077	9015
Jersey Bridge	NS	8300	6086
Kilnhill 4	NS	7214	5118
Kincardine Bridge	NS	9164	8716
Kingshill	NS	8939	5512
Kingshill Coll.	NS	9048	5495
Kingshill Coll. 1	NS	8516	5833
Kingshill Coll. 1 pit	NS	8563	5707
Kingshill Coll. 2	NS	8560	5710
Kingshill No 3	NS	8690	5436
kingshill Pit	NS	8525	5828
Kirkwood pit 2	NS	7135	6414
Kirkwood pit 2	NS	7135	6414
Knowton	NS	8987	5837
Lady Mary's Pit	NS	8690	3545
Land of Dura	NS	9032	5669
Lanniesmuir	NS	8214	5324
Leavenseat 1	NS	9423	5960
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Limekiln Burn	NS	7072	5029
Limekiln Burn 3	NS	7072	5080
Loganlea Coll.	NS	9775	6197
Longford	NS	9815	5956
Longford 355	NS	9822	5792
Longford 430	NS	9837	5770
Lord Dunglass's Pit	NS	8688	3542
Mainshill	NS	8578	3252
March pit	NS	7477	6298
March pit	NS	7477	6298
Milton 2	NS	6274	6779
Mortanblow	NS	9829	5755
Mosshat	NS	9973	5584
Mossneuk	NS	8723	8609
Mount Vernon	NS	6685	6356
Mounthillblow	NS	9766	5787
Mulchon	NS	9330	5911
Mulchon	NS	9166	5746
Murdiston	NS	8372	5822
Murdostoun	NS	8349	5710
Netherfield	NS	7278	4524
Newhouse 2	NS	8031	6237
Newlands	NS	5667	6058
No 1 bore Bogside Fm	NS	8586	5278
No 1 bore Hill of			
Westerhouse	NS	8863	5314
No 1 bore No 2 pit			
Dechmont Coll	NS	6649	5912
No 1 Gain Fm	NS	8619	5343

No 2 Gair Bore	NS	8652	5266
No 3 Pit Bothwell Castle	NS	6861	5877
No 4 Birniehall	NS	8961	2376
North Mains	NS	6712	6670
On Westfield	NS	8834	8706
Orchard Fm	NS	7434	6250
Overton	NS	8006	5294
Overton 1	NS	8005	5281
Overton 2	NS	8008	5279
Overton Fm	NS	8071	5317
Overton Threepwood Quarry	NS	8145	4816
Polkemmet	NS	9342	6404
Porat	NS	9730	5520
Queenhill	NS	8666	5423
Queenslle 1	NS	6630	6603
Queenslie 2	NS	6590	6491
Queenslie 3	NS	6755	6490
Queenslie 5	NS	6608	6213
Queenslie 6	NS	6813	6523
Raw 18	NS	8536	3814
Rimmon	NS	8850	6109
Robroyston 1	NS	6342	6890
Rosehall estate	NS	7255	6171
Roshiehill	NS	9624	5972
Rowantee	NS	8849	5508
Salsburgh 1	NS	8167	6487
Salsburgh 2	NS	8211	6385
Shotlinn	NS	7096	4878
Soltness	NS	9076	6147
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Springfield Fm	NS	8964	5352
Starryshaw 1	NS	9073	6112
Starryshaw 2	NS	9050	6096
Stictly	NS	8704	5355
Stoneheap	NS	9649	6194
Stonehouse	NS	7689	4577
Swinhill	NS	7769	4844
Tannockside	NS	7100	6135
Thankerton Fm.	NS	7671	6134
Tippethill	NS	9330	6495
Titwood	NS	5694	6264
Tuliyalian	NS	10382	8682
Unthank Fm	NS	7424	6048
Viewpark	NS	7068	6070
Viewpark 1 Pit	NS	7068	6070
Vinegar Hill	NS	6171	6473
Watstonmids	NS	8407	5448
Wellshot Brewery	NS	6323	6097
West Badallan	NS	9170	5892
West Forth	NS	9398	5265
Whitrigg	NS	9671	6457
Wilsontown	NS	9518	5563
Wilsontown 1	NS	9403	5429
Wilsontown coll	NS	9330	5658
Wilsontown Shaft 3	NS	9413	5561
Windyhill	NS	9386	8901
Wishaw	NS	7918	5420
Woodmuir	NS	9644	5991
Woodmuir 1	NS	9600	5807

Woodmuir 2	NS	9681	5984
Woodmuir 300	NS	9666	5777
Woodmuir 4	NS	9607	5899
Woodside pit	NS	79,26	4887
Woolfold 5	NS	9965	5759
Woolfolds	NS	9880	5740
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Appendix 3 Sedimentary logs recorded in the Midland Valley of

Scotland

The Sedimentary logs recorded in the MVS were logged in various opencast coal mines and from natural sections. The logs are enclosed on the CD-ROM. Labeled

Appendix 3. Sedimentary Logs.

The CD-ROM is accessible using a PC with 128 MB of ram and a CD-ROM

reader. The software required to view the reflection seismic lines is Corel Draw 9

or higher.

The CD-ROM contains three folders:

- Key to all logs
- All sedimentary logs in a spatial and temporal framework
- Individual logs

The sedimentary logs were recorded at:

OCCS or section	easting	northing
Wester Mosshat	9794	5635
Climpy New	9220	5459
Climpy Old	9225	5472
Rashiehill	9651	5914
Viaduct	7300	2963
Gasswater	6300	2370
Muirkirk	6923	2522
Burntfoot Moor	6875	2733
The Gasswater	6290	2329
Dalquhandy	7891	3382
Watsonhead	8367	5516

Morningside	8271	5504
Damside	8858	5799
Spireslack	7478	2911
Drumshagie	7852	6758
Medowhill	9722	9410
House of Water	5528	1185
Blinkbonny	13493	6237
Oxonford	13585	6696
Kirkaldy	18971	9237
Joppa	13172	7346
Colton	10919	9024
Glentaggert	1200	6900

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