Characterisation of fluid-flow systems for Irish Lead-Zinc deposits

A thesis submitted for the degree of
Doctor of Philosophy

by

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ABSTRACT

The lead-zinc sulphide deposits of central Ireland are hosted primarily in Lower Carboniferous strata of the Midland Basin. The ores are thought to be approximately contemporaneous with their sedimentary hosts, but the mode of their formation is a subject of dispute. The mineralisation is variously regarded as having either a predominantly sedimentary-exhalative, or a predominantly MVT-type of genesis. The ores are hydrothermal, so the interpretation of mineral genesis is strongly linked to the interpretation of the fluid-flow system that generated the deposits. This thesis investigates the structural setting of the deposits, particularly in relation to faults, on both the regional and more local scales, and the nature of the fluid-flow systems that could have provided the mineralised fluids.

The structural setting is established by reconstructing the geometry of the Midland Basin region, and restoring it to several stages in its Early Carboniferous development. The reconstruction and restorations identify a style of basin development dominated by the movement (mostly subsidence) of fault-bounded blocks of basement, with superjacent sedimentary rocks. The restorations reveal a spatial relationship between ore deposits and fault-block corners. This spatial relationship is proposed to have significance for exploration.

The flow systems which could have been active in the Midland Basin and its surrounds (including the Munster Basin) are investigated using both mass balance, and numerical simulations of heat- and fluid-flow. The mass balance study shows that most of the suggested flow systems could have produced adequate metals, but tens to several thousand fluid pore-volumes are required to deliver these metals to the sites of deposition, thus eliminating compaction as a driving mechanism, and severely limiting the applicability of some of the other putative causes of fluid flow.

When the results of the mass-balance and the numerical models are combined, they show that: regional flow systems could not have developed in central Ireland during the Carboniferous; gravity-driven flow is cold, shallow and only very local; but local convective systems that penetrate deep into the fractured basement not only develop in this setting, but are very stable. Convective circulation of hydrothermal fluids is the most likely cause of the Irish lead-zinc mineralisation.

Thesis Declaration

The material presented in this thesis is the result of research carried out between January 1990 and October 1995 in the Department of Geology and Applied Geology, University of Glasgow, under the supervision of Prof. M.J.Russell.

This thesis is based on my own independent research and any published or unpublished material used by me has been given full acknowledgement in the text.

Helen Lewis

September 1995

We certify that Helen Lewis has undertaken the bulk of the work involved in this thesis, specifically, background geology, data collation and analysis, and computer modelling. We have assisted with advice and help of a general, technical, conceptual nature, as would be expected in the course of normal Ph.D supervision. Helen Lewis has written the thesis herself, and is responsible for its content.

M. J. Russell

G.D. Couples

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CHAPTER 1

INTRODUCTION

The lead and zinc sulphide mineralisation of central Ireland is hosted primarily in the Lower Carboniferous carbonate and clastic sedimentary rocks of the Midland Basin. Because of their economic importance, these deposits have been the subject of extensive study over the past forty years, encompassing: regional geological setting (Phillips and Sevastopulo, 1986), sedimentation history (Philcox, 1984), ore morphology and paragenetic sequence (Hitzman and Large, 1986), and ore deposit genesis (Russell, 1968; Hitzman and Large; 1986; Ashton et. al., 1986). The ores are hydrothermal, and they are the product of the mixing of hot, acid, fluids with cool, saline, alkaline fluids. They are generally believed to have been deposited either during sedimentation or fairly soon thereafter. The known deposits are mostly widely spaced (Fig. 1), and generally each covers an area of less than 10 km^2.

The present-day Midland Basin is a shallow depression (less than 3km in depth), containing a number of sub-basins separated by minor uplifts of uncertain age. The ores appear to be located near faults that bound the basin or its sub-basins, but the control of structure on both the position and the development of the deposits has not been systematically investigated In particular, the fluid-flow systems that provided the metals, water and energy needed to create the deposits need to be investigated to determine which possible systems provide viable explanations for this hydrothermal mineralisation.

The primary goal of this research is to investigate the fluid-flow system(s) that provided the raw materials and the energy which are required for creating the ore deposits. The investigation uses numerical simulations of the fluid- and heat-flows, which, in turn, require analysis of the geometry of the fluid-rock system. The development of the lead/zinc deposits is evaluated by:

(1) characterising the structural/tectonic setting of the ore deposits through a basin reconstruction to the present-day configuration, and restoration to several stages in the Early Carboniferous;

(2) investigating, through numerical modelling and mass-balance calculations, what fluid-flow systems may have been active within the constraints provided by the chosen

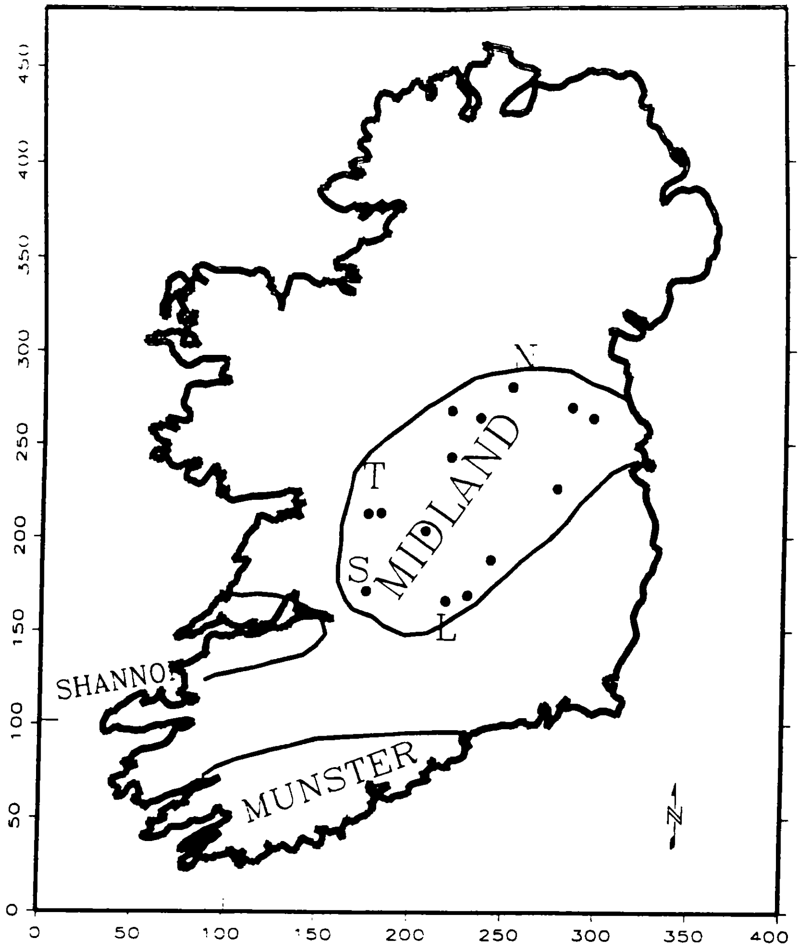


Figure 1.Map showing approximate positions of Midland Munster and Dublin Basins and Shannon Trough. Letters give locations of key deposits:
N= Navan; T = Tynagh; S = Silvermines; L = Lisheen
Map displays Irish National Grid at 20 km intervals

structural/tectonic setting; and (3) assessing the fluid-flow systems which could have been active for their suitability as the source of the hot mineralised fluids which were delivered to the mineralised sites.

1:1 GEOLOGIC SETTING

The geology of Ireland, which is presently at the western margin of the Eurasian landmass, has been heavily influenced by repeated opening and closing of the "Atlantic" from at least the Precambrian. The Ox Mountains in north-central Ireland are probably a remnant of the Grenville orogeny, attributed to such a closure (Cope et al., 1992b). The Caledonian Iapetus suture boundary, together with other major Caledonian tectonic boundaries of northern Britain, is also present in Ireland. The southern portion of Ireland shows the effects of the Variscan orogeny, while the Tertiary volcanics of the Giant's Causeway are a product of the most recent oceanic opening.

Ireland's exposed geology can be considered in two sections: its centre, and its margins. The geology of the margins is variable, with the western margin in Connemara containing the main part of exposed Precambrian and earliest Phanerozoic rocks. Devonian sediments of the Munster Basin are exposed on the southern margin. The Leinster Granite, abutting the eastern coast, is a late Caledonian intrusive body, and Tertiary volcanics, associated with the most recent opening of the Atlantic, occur at the northern margin.

The central portion of Ireland is dominated by surficial deposits, but these are underlain by Carboniferous carbonate and clastic sedimentary rocks. The sedimentary rocks of the Midland Basin, the primary study region, overlie metamorphosed rocks of the Caledonian orogeny. They were deposited in a shelf setting, with deeper waters to the south. Sedimentation in the Midland Basin began with the mainly fluvial Devono-Carboniferous Old Red Sandstone. The dominantly shallow-marine carbonate rocks of the Lower Carboniferous succession constitute the bulk of Midland Basin strata, and they are followed by Upper Carboniferous fluvial sediments and coal measures. Permo-Triassic siliciclastic rocks are preserved in a few locations. Figure 2 shows the main stratigraphic divisions of the Lower Carboniferous and their ages,figure 2a showing the divisions used by Hitzman (1992a), modified slightly to match the terminology adopted in this thesis (see section 3:2:1:3), and figure 2b showing some of the formal terminology used for the Midlands Lower Carboniferous rocks

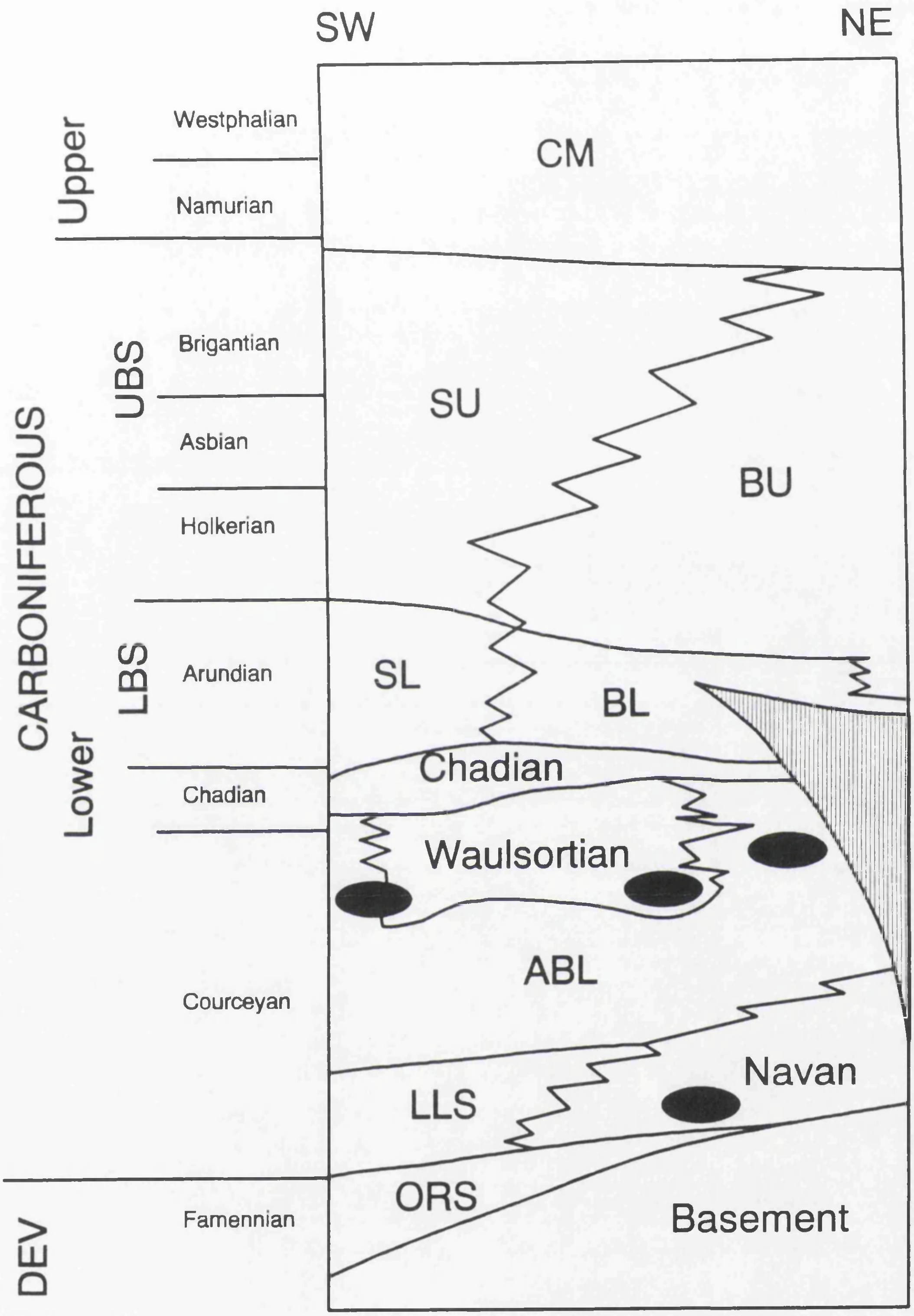


Figure 2a. Simplified Stratigraphic Succession of Irish Midlands Showing Position of Deposits as Ovals (after Hitzman, 1992a). ORS = Old Red Sandstone; Navan = Navan Unit; LLS = Lower Limestone Shale; ABL = Argillaceous Bioclastic Limestone; Waulsortian = Waulsortian Limestone; Chadian = Chadian Unit; SL = Lower Shelf Deposits; BL = Lower Basinal Deposits; SU = Upper Shelf Deposits; BU = Upper Basinal Deposits; CM = Coal Measures; LBS = SL + BL; UBS= SU+ BU

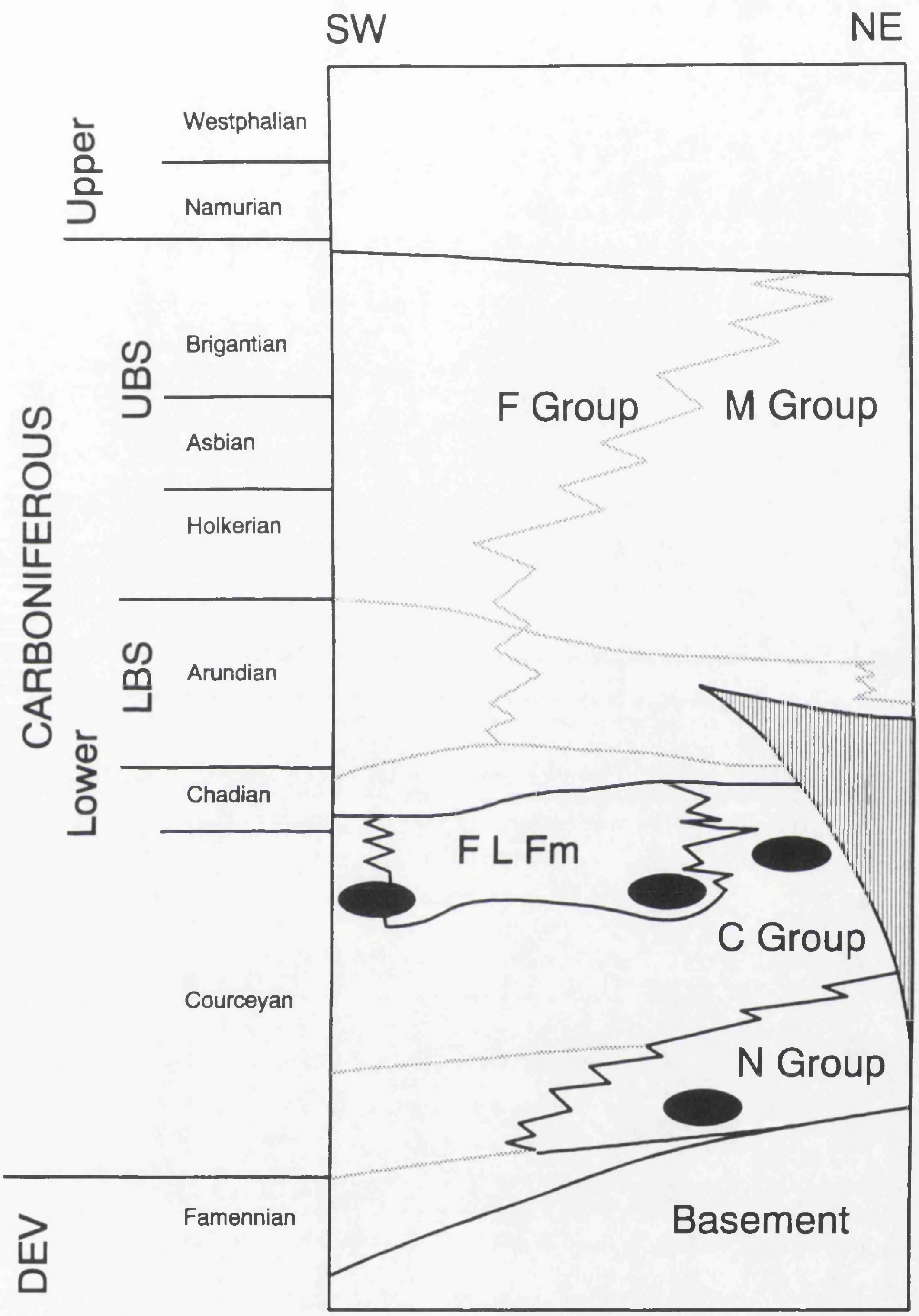


Figure 2b. Simplified Stratigraphic Succession of Irish Midlands Showing Formal Nomenclature (After Jones and Earls, 1994). N Group = Navan Group; C Group = Cruicetown Group; M Group = Milverton Group; F Group = Fingal Group; F L Fm = Feltrim Limestone Formation; B L Fm = Ballysteen Limestone Formation Outlines of Figure 2a Shown in Grey; Deposits Shown as Ovals

During the Early Carboniferous Ireland was at tropical latitudes and had an arid climate (Cope et al., 1992a). It was probably at the margin of a sheltered coast or interior seaway (King, 1990). The landmass to the north, which extended eastward to Central Europe, provided some siliciclastic sediment to the uppermost Devonian and lowermost Carboniferous Old Red Sandstone, which is primarily fluviatile. This same northen landmass may or may not have been the prime source for the thick accumulations of clastic sediment in the rapidly subsiding Munster Basin of southern Ireland (MacCarthy and Gardiner,1987).

Clastic sedimentation during the early development of the Midland Basin region was replaced in the middle Courceyan by the northward onlap of a mixed clastic and carbonate succession, producing a sequence of limestones and shales. By the latest Courceyan and earliest Chadian there was a transgression across the Irish Midlands, accompanied by the development of the Waulsortian Limestones of Sevastopulo (1982). By this time the northern supply of clastic material appears to have diminished greatly, being replaced by a dominantly carbonate system. Variability of sediment type increased in the Chadian: there were also minor volcanics in the Midland Basin during this time. During the Arundian the diversity of deposit types diminished (probably due to a diminishment of tectonic activity) in the Midland Basin, with the primary sediment type being regularly-bedded, bioclastic limestones. By the Asbian and Brigantian the distinction of a Midland Basin seems to have disappeared, to have been replaced by the fault-bounded Dublin Basin (Jones et. al., 1988), in which turbiditic shales and limestones are overlain by black shales. Mixed sediments dominate the remainder of the old Midland Basin region, and include bioclastic limestones around the Leinster massif area, and cyclical limestones.

The detail of the development of the Carboniferous sedimentary sequence of Ireland is not well understood. The general outline given above hides much (acknowledged) complexity. Sevastopulo (1981) warns that "within the generally shallow-water region there were marked lateral changes of facies and thicknesses" and that "the facies varied not only with space but with time". Stratigraphic units, such as the distinctive Waulsortian Limestones, are notably diachronous. Macrofossil and microfossil availability is generally quite good, but the complexity of the environment requiring interpretation presently exceeds the resolution of the available fossil information.

1:2 PREVIOUS WORK: THE DEPOSITS

The major orebodies of the Irish Midland are hosted in the Navan Beds and in the Waulsortian Limestones (Fig. 2a). The lead and zinc deposits occur predominantly as sulphides (primarily sphalerite and galena), and are accompanied by iron-bearing minerals, barite, and by subordinate copper (Hitzman and Large, 1986). The known deposits are of small areal extent and are generally separated by 17 km or more (Fig. 1). Only a few deposits have been regarded as commercially viable, but these include the world-class Navan deposit, estimated to have originally had ore-in-place of 69.9 Mt, grading to 10.1% Zn and 2.6% Pb (Ashton et al., 1986). The next-largest deposits, at Lisheen and Silvermines, have estimated reserves of 15 Mt (Hitzman, 1992b) and 17.7 Mt (Andrew, 1991), respectively. Smaller deposits make up the remainder of the 11.3 Mt of zinc and 2.8 Mt of lead estimated for the Irish Midlands (cf. Hitzman and Large, 1986).

Most of the deposits are stratiform, and they usually consist of several orebodies separated by small vertical or lateral distances. In addition, smaller orebodies are hosted (generally as veins) in the Lower Palaeozoic metasediments which underlie the Midland Basin Carboniferous sequence.

The syngenetic, diagenetic or epigenetic nature of the deposits has been a subject of much controversy (Hitzman and Large, 1986). Basement-hosted deposits, such as the K zone at Silvermines (Andrew, 1986) are clearly epigenetic. Some deposits, such as Lisheen, appear to have mineralisation concomittant with or post-dating dolomitisation of their Waulsortian hosts (Hitzman, 1992b). Other deposits have a position and form consistent with formation at the surface during host-rock sedimentation, but these are variously interpreted to be syn-sedimentary, diagenetic or epigenetic (Russell 1983; Large, 1980; Rizzi, 1993). Still others appear to show features of more than one mineralising environment (Andrew and Ashton, 1985).

It is generally agreed that the ores are the product of hydrothermal systems in which a warm or hot, acid, mobile fluid (which bears the metals) mixes with a local, cool, saline, mildly alkaline fluid containing sulphur which is about 85% bacteriogenic in origin. Fluid temperatures as high as 270^{o}C at the site of deposition have been reported (Samson and Russell, 1987). Russell and Skauli (1991) estimate that 10^{18}g of fluid were required to produce the known ore deposits.

1:3 PREVIOUS WORK: FLUID FLOW SYSTEMS

Several fluid-flow systems have been suggested as being responsible for the Irish Pb-Zn mineralisation, either formally in the literature, or more informally. Lydon (1986) proposes a fluid-flow system in which the ore-forming solutions are modified saline formation waters occupying the Old Red Sandstone of the Midland Basin. In his model a combination of compaction-driven flow, a seal overlying the Old Red Sandstone, and high heat flow, are responsible for delivering warm, metal-laden fluids to the deposit sites. Williams and Brown (1986) propose that the fluids (and presumably their partitioned metals) originated in the Midland Basin, and that mineralisation was driven by episodic dewatering at various stages of sediment compaction. Their de-watering process includes the development of growth faults at the basin margins. Russell (1968; 1978) suggests the operation of a hydrothermal convection system where Carboniferous seawater penetrated to depths of 10 km or more, partitioning metals during hydrothermal metamorphism (Bischoff et al., 1981). Other authors have suggested, often by implication rather than directly, that the mineralising fluids were heated and driven by the Variscan orogeny, which reached as far north as southernmost Ireland in the Upper Carboniferous (Cope et al., 1992a).

1:4 THE DEBATE

A great deal is known about the geology of the Lower Carboniferous of Central Ireland in general, and about the geology of the ore deposits in particular, but the genesis of the lead-zinc deposits is hotly debated. That they are the products of hydrothermal systems is generally agreed, as is their approximately mid-Dinantian age. Beyond this the concensus breaks down: suggested mechanisms of formation range from epigenetic deposits, formed at a depth of about 1km from Midland Basin-derived, compaction-driven, connate waters, to sea-floor precipitation where cool local saline brines mix with hot hydrothermal fluids delivered by an upper-crustal convection system.

This study is not concerned directly with the details of the time or depth of ore formation, but it shares a concern for the nature of the fluid-flow system which produced the raw materials. It is the premise of this thesis that available knowledge, such as the quantity of metals required, the temperature constraints, and the information with which the local and regional structural setting of the deposits can be derived, have not yet been fully used to assess the viabilty of proposed fluid-flow mechanisms.

Such an assessment (using a reconstruction and restoration of the region, numerical models and mass balance) is performed as an integral part of this research, and provides constraints on possible fluid systems. Proposed flow systems that cannot satisfy these constraints can be discounted as the source of the Irish lead-zinc deposits.

1:5 STUDY GOALS AND OUTLINE

This study investigates the palaeo-geometries of the Midland Basin region and its underlying basement during the Carboniferous in order to derive the setting in which the mineralising fluid-flow systems developed. By combining the lessons learned about the potential fluid-flow systems with a reconstruction of basin geology and geometry, it should prove possible to identify both the characteristics of likely sites of mineralisation within Ireland, and characteristics of convective systems which could have been active elsewhere (and at other times).

Chapter 2 addresses the reasons for the debate over the genesis of the deposits, and the use of mass balance calculations of both metal and fluid to select viable flow systems for ore formation; Appendix A details the equations used in the mass balance calculation. Chapter 3 addresses the reconstruction of the palaeo Midland Basin region, and its restoration to several stages in its development in the Early Carboniferous. The theory behind geometric representation by grids is contained in Appendix B. Chapter 4 addresses the geological aspects of the reconstruction and restoration and their implications for the evolution of the region and the development of the deposits. Appendix C contains the larger maps refered to in Chapters 3 and 4. This is followed by a description of the fluid- and heat-flow modelling (Chapter 5). The remainder of the document discusses the completed work, and considers how the lessons learned here can be applied elsewhere (Chapter 6). Conclusions of the work are contained in Chapter 7.

CHAPTER 2

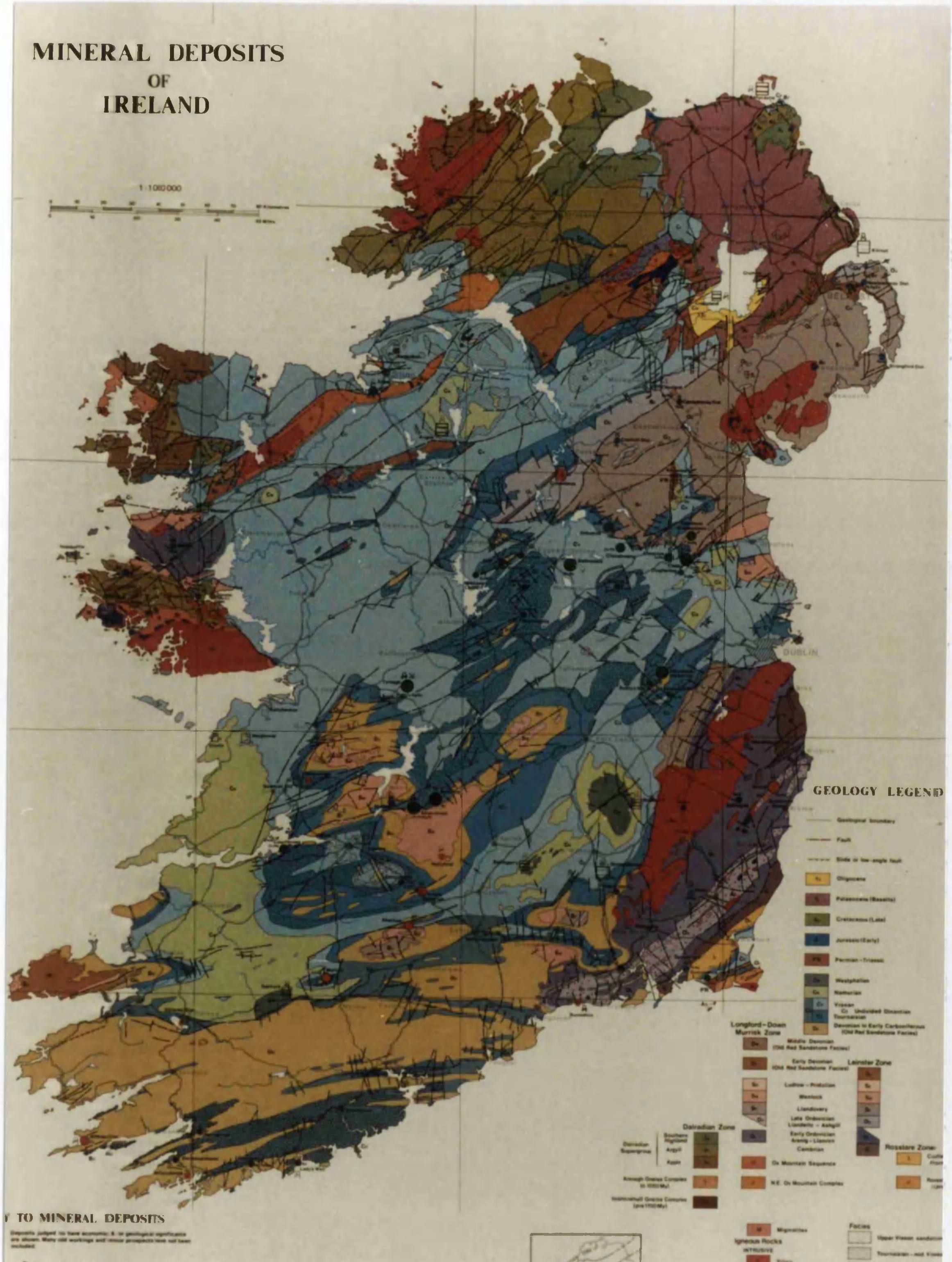
A MASS BALANCE INVESTIGATION

The lead and zinc deposits of Ireland occur primarily as sulphides hosted in the Lower Carboniferous sediments of the Midland Basin (Fig. 3). There are numerous mineralised sites widely spaced over this region, and each is quite localised. The age of mineralisation is generally thought to be mid-Dinantian (Andrew, 1991) but the mode of formation is a matter of dispute. Most of the deposits are stratiform to stratabound, usually consisting of several orebodies separated by small vertical or lateral distances. In addition, the Lower Palaeozoic metasediments, which underlie the Carboniferous sequence, contain smaller deposits (generally in veins).

The major orebodies are hosted in the Navan Beds and in the Waulsortian Limestones (Fig. 2a,), part of the Navan and Waulsortian units as defined in Chapter 3:2:1:3. The largest known deposit, at Navan (Fig. 1), is estimated to have originally had ore-in-place of 69.9 Mtonnes, grading to 10.1% Zn and 2.6% Pb (Ashton et. al, 1986). Smaller deposits make up the remainder of the basin's estimated 11.3 Mtonnes and 2.8 Mtonnes of zinc and lead, respectively (Hitzman and Large, 1986; Andrew, 1991).

This study initially assumes that the deposits are of Early Carboniferous age, and is also initially limited to the Midland Basin region. The study in performed with due regard for the following facts: that the Midland Basin is a geographical term; that, depositionally, it represents only part of a predominantly shelf setting (in which the Dublin Basin developed); and that the Munster and Shannon depositional centres developed outwith the Midland Basin's geographic limits (Fig. 1). The study is later expanded, in both time and space, to investigate the involvement of the Munster Basin sedimentary rocks (Fig. 1), and the potential for fluid flows driven by the action of the Variscan orogeny and its associated highlands, which is of approximately mid-Westphalian age in southern Ireland.

Although there is a debate surrounding the genesis of the deposits (Large, 1980; Russell, 1983) it is generally agreed that they are the product of hydrothermal systems in which a hot, acid, mobile fluid (which bears the metals and about 15% of the sulphur) mixes with a local, cool, saline, mildly alkaline fluid containing bacteriogenic sulphur which constitutes the remaining 85% of the sulphur in the deposits (Anderson et. al, 1989; Boyce et. al, 1993) Interpretations of the deposits' geneses are linked to the inferred size of the fluid-flow systems, and the inferred driving energy.


MINERAL DEPOSITS
OF
IRELAND
DUBLIN
GEOLOGY LEGEND
TO MINERAL DEPOSITS

This chapter reports the results of a mass-balance study designed to assess: (i) whether the rock masses of the proposed fluid-flow systems can provide sufficient metals to source the deposits; and (ii) how many pore volumes of fluid are needed to transport the metal. The characteristics of the proposed fluid-flow systems are established first, and, from these, four system types are derived which are used as templates for the mass-balance calculations. The role that mass-balance plays in testing a fluid-flow system, is then discussed, the parameters used in the calculations are described, and the nature of the mass-balance calculation engine is outlined. This is followed by a summary of the results of the investigation, and a discussion of their power in discriminating between hypotheses for the mineralisation of the Irish Midlands. The driving mechanisms and heat distributions for the two flow systems that survive the analyses are considered: (1) crustal-scale convective flow, and (2) Munster and Midland Basin flow driven by the Variscan orogeny.

2:1 CHARACTERISTICS OF POTENTIAL FLUID-FLOW SYSTEMS

Several fluid-flow systems have been suggested for the Irish Pb-Zn mineralisation, either formally in the literature, or more informally. Lydon (1986) proposes a fluid-flow system in which the ore-forming solutions are modified saline formation waters occupying the Old Red Sandstone of the Midland Basin. In his model a combination of compaction-driven flow, a seal overlying the Old Red Sandstone, and very high heat flow, are responsible for delivering warm, metal-laden fluids to the deposit sites. Williams and Brown (1986) propose that the fluids (and presumably their partitioned metals) originate in the Midland Basin, and that mineralisation is driven by episodic dewatering at various stages of sediment compaction. Their de-watering process includes the development of growth faults at the basin margins during extensional growth of the basin. Russell (1968, 1978) suggests the operation of a hydrothermally-driven convective system where Carboniferous seawater penetrated to depths of 10 km or more, partitioning metals during hydrothermal metamorphism (Bischoff et.al, 1981), and returning hot mineralised fluids to the near-surface. Both a topographic drive from highlands, and flow caused by the tectonic loading of the Munster (and possibly Shannon) Basin sediments by the advancing Variscan front, have been suggested informally by a number of workers and formally by Hitzman (1995a), and these possibilities also need to be examined.

2:1:1 Limits of the Flow Systems

Each of these potential source regions for metals has been considered in establishing the size and boundaries of the systems which is examined by mass balance. In each case the systems' dimensions are chosen to honour the requirements of our mass-balance calculations: that is, the extent of the **rock mass providing the metals** defines the physical size of the fluid-flow system. However, the origin of the aqueous phase itself does not affect the size of our system as defined here. If water enters the "system" carrying metals from elsewhere, then those rocks (providing the metal) must be part of the complete system; but non-metal-bearing waters may exchange across the boundaries of the system, i.e. in this respect the system is open. Thus it is the dimensions of the metal "source-rock" that is of paramount importance in this definition of the system.

2:1:2 Categories of Flow Systems

Having stated the criteria for establishing the system boundaries, the method of categorising the three proposed source-rock regions must be considered. The candidate systems are (i) the southerly clastic-filled Munster Basin; (ii) the sediments of the Midland Basin (and its extensions beyond the present erosional edge); and (iii) the basement underlying the Midland Basin. (Note that the same mass-balance arguments can be applied to the Shannon Basin as to the Munster Basin.) At the most basic level, these possible source models can be divided into two categories: basin-only and basin-plus-basement. The fluid-flow systems under investigation also fall into two basic categories: local to the deposit and regional. Using these components, the possible flow systems are simplified into: basin-only *versus* basement-involved, and local (to the deposit) *versus* regional systems. This classification produces four generic systems. Each requires assignment of appropriate rock types and dimensions, and geochemical parameters based on prototypes from the Irish Midlands. The viability of each case is then assessed *via* mass-balance techniques.

2:1:3 Rock and Fluid Properties

The ranges of rock- and fluid-property values permitted in the mass-balance calculations (Table1) are taken from observations of relevant parts of natural examples,

	Sedimentary Rocks	Metagreywacke Basement	Gneissic Basement
"Local" Diameter (km)	10-40	10-40	10-40
"Regional" Diameter (km)	160-320	160-320	160-320
Thickness (km)	0.5-2	2-4	4-7.5
Initial Pb Concentration (ppm)	15-25	15-25	15-25
Initial Zn Concentration (ppm)	90-130	90-130	90-130
Participating Rock Proportion (%)	20-66	4-8	---
Avg Porosity of Participating Rock (%)	10-25	8	---
Vertical Fracture Spacing (m)	---	1-100	1-100
Horizontal Fracture Spacing (m)	---	100-1000	100-1000
Half-Width of Alteration Zone (cm)	---	0-50	0-50

Table 1. Parameter ranges for each rock type. Lead and zinc concentrations from Rusell (1968) and Morse and Mackenzie (1990). Average porosity estimated from observation of rocks.

although in some cases a single value must represent a wide range of values in the natural system. The four generic systems (above) contain only three rock types: sediments, metagraywacke basement, and gneissic basement. Of these the sediments are the best characterised, but also have the widest variation in properties.

2:1:3:1 The Basinal Rocks

The dominant lithologies of the Lower Carboniferous sequence are carbonates, carbonaceous mudstones, and mudstones at various stages of compaction, although arenites dominate the lowermost parts of the sequence. The range of porosity values at any one time could have been extremely large, with uncompacted, unlithified Waulsortian Limestones providing the highest values, possibly up to 50%. The carbonate mudstones are likely to have compacted very soon after sedimentation (Shinn and Robbin, 1983), and will therefore have a much lower porosity (perhaps as low as 5%): the limey mudstones and arenites will have intermediate values. Though there was undoubtedly some open fracturing at the time of mineralisation, it is anticipated that flow was concentrated in the connected higher-matrix-porosity units. To acknowledge the likely concentration of flow in the higher-quality units, a porosity cut-off value is used: only rock with porosity above the cut-off is considered to be participating in the flow system. Fracture densities like the basinal rocks are used (see section 2:1:3:2).

In the absence of any published values for trace-element compositions in the carbonate sediments of the Irish Midlands, the approach of Morse and Mackenzie (1990) is followed and typical (pre-mineralisation) shale trace-element values are used. The fluids are assumed to have properties typical of those within shallow basins of this nature.

The thickness of the basin sequence at the end of the Lower Carboniferous could well have been quite variable throughout the Midland Basin region. Estimated thicknesses range from a few hundred metres, to perhaps 2.5 km in both the incipient Dublin Basin and possibly in some parts of the northeast/southwest trending depositional troughs. This configuration is in rough agreement with geophysical interpretations of present-day depth to the base of the sedimentary rocks (Williams and Brown, 1986). Chapters 3 and 4 address the present-day configuration of the region, and agree with this range of thicknesses.

The temperature distribution in the sedimentary rocks, and of their contained fluids, must also be considered. The majority of the information available comes from the deposits and their immediate surrounds, and mainly from fluid-inclusion analysis and conondont alteration indexes, but even this is open to diverse interpretation. Samson and Russell (1987) and Banks and Russell (1992), suggest that fluid temperatures had reached ~250°C at Silvermines and Tynagh (Fig. 1), though Probert (1983) reports that ore deposition at Tynagh occured at temperatures between 140 and 190°C. Hitzman et. al

(1992) report that mineralisation took place between 100 and 200°C at Lisheen (Fig. 1). Fitzgerald et. al (1994) suggest that there has been an influx of Variscan, or immediately pre-Variscan, hot fluids (at about 350°C) in the west Clare region, to the west of the Midland Basin region. Rock temperatures are investigated by Clayton et al. (1989) who determine thermal maturation levels in the Devonian and Carboniferous sedimentary rocks across Ireland. Their thermal index map of Ireland shows moderately high peak temperatures throughout the Midland Basin region, though these authors neither differentiate between rock temperatures within and outwith deposits, nor attempt to assign the peak temperatures to any specific event.

While there is room for further research on this topic, it is provisionally concluded that: (i) flow rates are likely to have been low enough (through most of the region) that rock and fluid temperatures were generally in equilibrium; (ii) that temperatures at the deposits are probably in the range of 150 to 250°C, and (iii) that the maximum fluid temperatures at the deposits, (a mixture of the hot mobile fluid and the colder local fluid) is the best indicator of the temperature of the mobile (and mineralising) fluid, and the lowest temperature of this fluid mixture is probably the upper limit for the temperature achieved by the local fluid. These values may or may not have any direct relationship with the fluid and rock temperatures outside the deposits: if the flow system which produces the deposits produces a local thermal spike, the spike value tells us little about the surrounding temperature field. In the absence of more concrete thermal information a temperature distribution calculated from a normal to slightly elevated heat-flow rate is used to estimate fluid temperatures, adapting these temperatures as appropriate for the fluid-flow model under consideration.

2:1:3:2 Metagreywacke Basement

The uppermost part of the basement, exposed at a number of places within the Midland Basin region, consists of metamorphosed greywackes, shales, mudstones (now slates) and siltstones, together with andesitic extrusives and minor intrusives. No published porosity or permeability data for these rocks are known to me, but visual inspection suggests porosity values in the 2 to 5% range. The rocks are invariably fractured in outcrop (mostly vertically) on a spacing of tens of cm to occasionally tens of metres. Such fracturing is likely during basinal extension, and this range of fracture spacings is permitted in the metagreywacke unit in the mass-balance calculations, and later, in the fluid- and heat-simulations reported in Chapter 5.

Russell (1968) reports lead and zinc analyses of the metagreywackes, calculating mean values of 22 ppm and 109 ppm with 16 ppm and 53 ppmvariance, respectively. These values are not atypical for such rock types, but it is unknown if these samples had been subjected to the hydrothermal metamorphism that produced the lead-zinc deposits.

Murphy (1952) suggests a metagreywacke thickness of approximately 3 km, while Williams and Brown (1986) interpret a present-day 3 to 4 km depth to the seismic refractor which represents the top of Precambrian granulite-facies rocks. This seismic-based interpretation is supported by its rough coincidence with the deep sources of magnetisation within the Midland basin region (Williams and Brown, 1986).

2:1:3:3 Gneissic Basement

No gneissic basement is exposed in the Midland Basin region, though some gneissic xenoliths have been found in Viséan volcanics (Strogen, 1974), so its general nature is unknown. However it seems reasonable to suggest that: the metagreywackes are underlain by gneisses similar to those exposed in other parts of the Caledonides; that they have a very low matrix porosity; are generally fractured; and have minor-element abundances typical of such rocks.

2:1:3:4 Fluid Chemistries and Temperatures

The lead- and zinc-sulphide ores are the product of the mixing of hot, acid, mobile fluids with local, cool, saline, mildly alkaline fluids containing biogenic sulphur. Fluid-inclusion studies at several deposits suggest that the hot mineralising fluid is both saline and acid. Samson and Russell (1987) report salinities ranging from 8 to 28 equiv. wt. percent NaCl at Silvermines, with the higher-temperature fluids towards the lower end of this range, while Banks and Russell (1992) report a high-temperature fluid (240°C) with 12 equiv. wt. percent NaCl at Tynagh. As the fluids produced by the flow system have to be at least as hot as the fluids at the deposits (after a correction for adiabatic expansion), the temperature at the deposit and in the source rocks is assumed to be the same, and the solubilties used are chosen accordingly.

The nature of the mineralising fluid before it reached the deposit, and its ability to uptake metal, is investigated by Bischoff and co-workers (1981) They use an experimental approach, heating greywacke samples from central Ireland to 200°C and 350°C in the presence of both seawater and a brine. Their results show that the seawater is changed very little, but that brines are significantly changed, losing all their Mg and gaining Ca, K and CO_2. The brines also gain significant concentrations of heavy metals, which could not be reprecipitated without the addition of another component.

There is a strong link between mineralising brines held responsible for the formation of MVT deposits and oilfield brines, and a number of workers have used data on the metal solubilities in oilfield brines (Sverjensky, 1984) in assessing the metal solubilities of the fluids sourcing the Irish deposits (see, for example, Lydon, 1986). If the data of Russell et. al (1981) are appropriate, fluid temperatures associated with the solubilites of lead and zinc reported by Sverjensky (1984) are in the range of 100 to 150°C.

2:1:3:5 Compactive Fluids

Fluids which are produced by the progressive compaction of sediments resulting from burial are likely to be cold, and to be moved directly upward (Bethke, 1985) rather than being focused to sites of mineralisation. The volume of fluid produced over a given time period is dependent on, at least: the original volume of the pore fluids; the nature of the sediments' framework grains; and the rate of accumulation of overburden. The rate of fluid expulsion from new sediments can be very rapid: Shinn and Robbin (1983) report a 50% reduction in porosity for an experimentally simulated burial depth of 300 metres, followed by minimal further decrease in porosity during simulation of more than 3000 m of burial. This range of values is supported by the decompactions reported in Chapter 3. of this study The volume of fluid expelled by compaction of a thickening basinal sequence may vary markedly through time as the rate of sedimentation and the type of sediments which are deposited changes.

2:1:3:6 The Munster Basin

One of the driving mechanisms which has been informally suggested by a number of workers is flow induced by tectonic loading of the Munster Basin's Devonian and Carboniferous sediments by a tectonic overlap produced during the Variscan orogeny. Regional paleogeographic reconstructions (Cope et. al, 1992) suggest that this event occurred at about Westphalian B time, so the sedimentary section used in our mass-balance calculations must include the rocks through this age. The Munster Basin sedimentary rocks (mostly clastics) are estimated to have an average thickness of about 6 to 8 km (Graham, 1983), and that the basin had a surface area of about 9,000 km^2 . Lacking comprehensive palinspastic reconstructions of the Upper Carboniferous it is estimated that the Midland Basin **average** sedimentary column thickness should be increased by values in the range 0.25 to 0.75 km.

2:2 MASS-BALANCE METHOD

2:2:1 Evaluating a Fluid-Flow System

There are many tests that a proposed fluid-flow system must pass before it can be regarded as viable: (1) The rock mass providing the metals must be of sufficient size, and have a suitable mineralogy and geochemistry, to be an adequate source of metals; (2) There must be sufficient rock surface area (in the form of pores and fractures) to allow fluid/rock interaction; (3) The fluid must have a chemistry and temperature suitable to have partitioned and transported the metals; (4) The flow system must be able to provide fluids at least as hot as evidence at the orebody demands; (5) There must be a viable source of sulphur (as sulphate or sulphide) present at the site of deposition; (6) There must be a flow path from the supply to the deposit, and a focusing mechanism; (7) There must be a driving mechanism (or mechanisms); (8) The fluid-flow system must be able to produce the required volume of fluid; and (9) There must be a set of conditions which initiate the flow system, and, by implication, a rational explanation for its ordering.

Here the focus is on items 1 through 3, and 8, but, in the discussion, comment is made on corollary factors when they affect the viability of fluid-flow systems that have passed the mass-balance tests. These corollary factors include the temperatures the fluids can achieve, the efficiency of the putative driving mechanisms and the likelihood of the conditions required for their development being met, and the ability of the flow systems to focus fluids to the sites of ore deposition.

2:2:2 Mass-Balance Calculations and Required Parameters

The mass-balance study is a forward approach and is designed using a commercial spreadsheet. In essence, it calculates the fluid required **at the deposit**: from: (i) the lead and zinc mass deposited, and (ii) the solubilities of lead and zinc in the fluid at the point of deposition. It then calculates **for the flow system:** (i) what mass of lead and zinc can be produced from the rocks encompassing the flow system, and (ii) the volume of fluid required to do this. These basic calculations can be used to determine, **for each set of assumed deposit conditions and flow system character:** (i) whether the rocks can provide the metal mass present in the deposit, and (ii) how many times the pore fluid must be replaced to provide that much metal. Figure 4 is a flow diagram of these calculations, showing both the input parameters, and the products of the calculations.Simplified versions of the equations used are given, in logical order, in Appendix A, and are referred to in the following sections.

The purpose of using a spreadsheet is to permit easy investigation of the effects of different parameter values. To make these calculations useful, reasonable ranges of values for each input parameter need to be established. The first quantity needed is the metal mass deposited at each site (see equation **1** of Appendix A). The starting point is the published ore-in-place (Andrew, 1991) which is corrected for: the efficiency of deposition (given as a percentage); the size of the mineralisation halo; and deposit erosion (these latter are combined and expressed as a percentage of the deposit size). This "originally" deposited

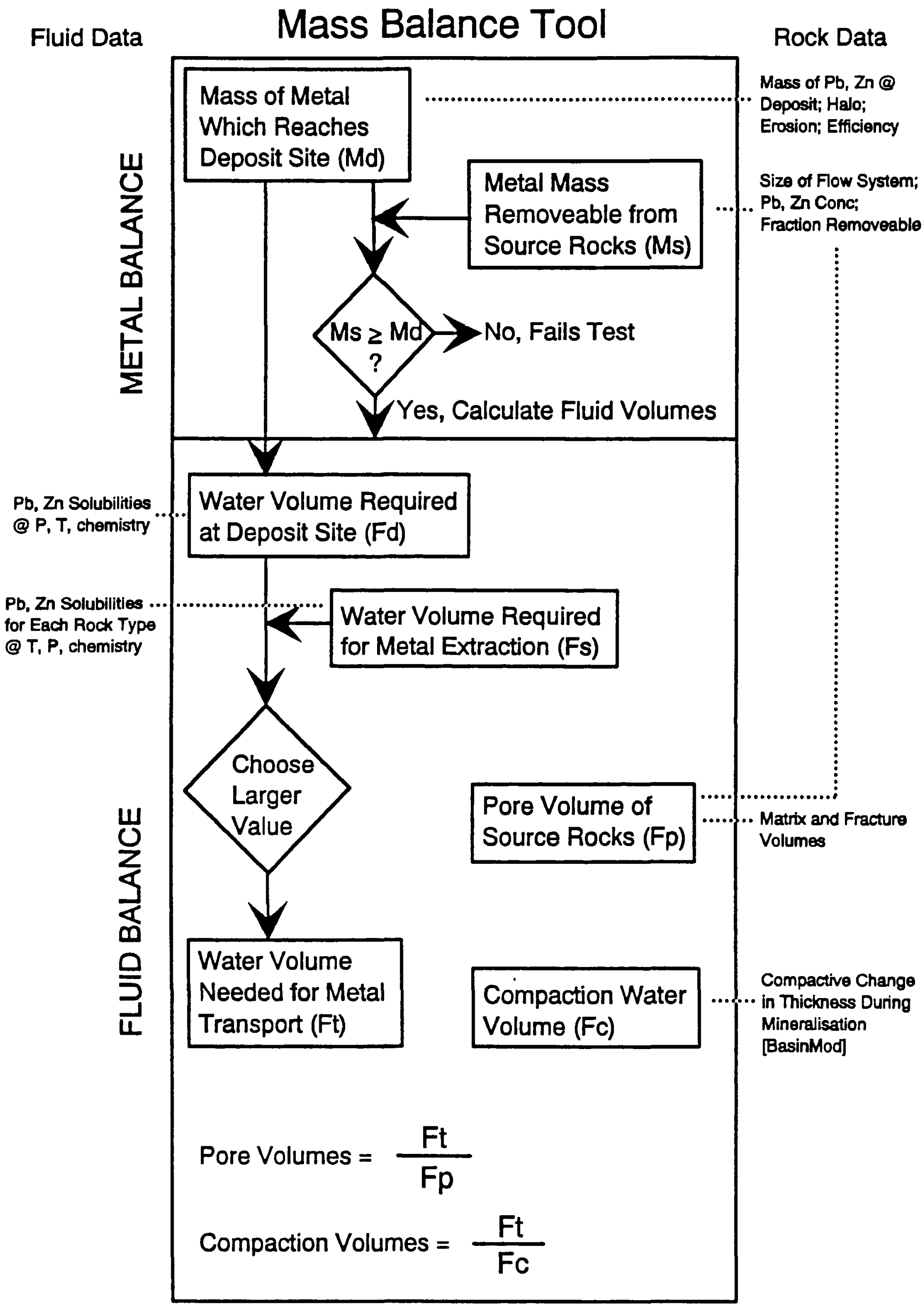


Figure 4. Flow Chart of Mass Balance Calculations. See Lewis et al. (1995).

metal mass is then used to calculate the water mass required to deliver the metals to the site of deposition (see Appendix A, equation **3**).

Metal masses are taken from published original tonnages. Efficiency of deposition values of 10%, 50% and 100% are used, while the "halo" factor is estimated at 10 to 20% of the original tonnage, with 40% being estimated for Navan (Fig. 1), where a pre-Arundian submarine erosion surface trancates large sections of the mineralised Courceyan and Chadian succession (Ashton et. al, 1986) Lead and zinc solubilities at ore deposition of 4 ppm lead and 7 ppm zinc, and 20 ppm lead and 100 ppm zinc, are taken from Sverjensky (1984) and Russell (1978) respectively. *Extremum* values of 200 ppm lead and 1000ppm zinc have also been used.

2:2:2:1 Metal Masses Produced

The majority of the mass-balance calculation is devoted to determining the metal mass which can be produced by the candidate flow systems. The procedure requires both the definition of the volume of the rock mass which contains the flow system and the properties of its rock and fluid constituents. The input values for each rock type are: (1) total rock volume (as defined in the "Limits of the Flow System" section above); (2) initial lead and zinc concentrations in the rock mass, and the portion which can be removed; (3) percentage of the rock which is used by the flow system and its average porosity; (4) fracture density (in the form of fracture spacing); and (5) width of the fluid/rock interaction zone. Calculation of the metal masses is given (in simplified form) by equation **2** of Appendix A, and Table 1 summarises the input parameters assigned to each of the three rock types.

The size of the flow system is represented by a cylinder of equivalent diameter and thickness: this simplification is for the purpose of calculation only and implies nothing about the geometry of the putative flow system. Assigned thicknesses are **average** values across the system's extent. Average sedimentary section thicknesses in the range 0.5 to 2 km are used: basement-involved flow systems are also given average thicknesses of 2 to 4 km (metagreywackes), and 4 to 7.5 km (gneisses). The local flow systems are assigned diameters in the range of 10 to 40 km, and the regional systems are given diameters in the range 160 to 320 km.

Not all porous rock will participate in flow -- some rock has bulk permeabilities which are too low, and the calculations account for this. A porosity cut-off is used to reflect the participation of only the better-quality rock in the flow system: this allows expression of porosity in terms of the percentage of the effective rock volume (that which is participating in the flow system), and the average porosity of that portion. Because of the anticipated large range of porosities within the basin sediments (from less than 5% to

50% or greater), participating rock percentages in the range 20 to 66% are accompanied by porosities of 10 to 25%.

The metagreywackes are treated in a similar way, although the variation in their matrix porosity is probably quite low. Participating percentages of 4 to 8% are used, and are accompanied by average porosities of 8%. The gneisses are assumed to have no matrix porosity.

Initial lead and zinc concentrations in the source rocks are given values from 15 to 25 ppm and 90 to 130 ppm, respectively: the fraction of this initial value which can be removed can reach 0.2. The same removable fractions apply to both matrix and fracture calculations. The metal mass removed from the rock matrix is given by equation **2a** of Appendix A.

Both the metagreywackes and the gneisses are assumed to possess fractures. Three orthogonal (two vertical and one horizontal) fracture sets are incorporated. Fracture spacings in the vertical sets can vary between 1 and 100 m, and the horizontal fractures are spaced 100 to 1000 m apart. Where fluids penetrate along fractures, the width of the zone of alteration must be specified. As the fractures are all planar, the alteration zone's half-width is given: these half-width values range up to 50 cm. The metal mass removed from fracture walls is given by equation **2b** of Appendix A.

Partitionable metal, from both matrix and fracture calculations, can then be summed. The total lead and zinc provided by the source rocks is then compared with that required to create the targeted deposit size. An initial match is rarely obtained, necessitating the adjustment of the flow system values within the specified limits. If a match <u>can</u> be obtained within the limits, the candidate system and its parameters are regarded as valid, and the associated rock- and fluid-flow system is viable from a metal mass-balance viewpoint. That is: the system has satisfied conditions 1 through 3 of the criteria listed in "Evaluating a Fluid-flow System". The ability of the source to provide 95% of the required metal is regarded as a success, whereas a result yielding 75% or less of the necessary metal is regarded as a failure of the proposed system. Failure prompts re-investigation of the limits placed on the input parameters, or rejection of the particular system under investigation.

2:2:2:2 Fluid Volumes

Once a viable 'metal-balanced' fluid-flow system is found, the ratio of the water required by the mineralising process to the volume of pore space which contains mobile (mineralised) fluid is calculated. This ratio is actually expressed as the number of pore volumes of fluid. Unity implies that the mobile fluid volume which is resident in the flow system equals that required at the ore deposit(s); a ratio of 0.5 implies that only half the potentially mobile fluid is required to produce the ore deposit(s); and a ratio of 10 implies that the mobile fluid volume is insufficient, and the "original" fluid must have been replaced 9 times by "new" fluid. For a flow system to be physically reasonable, it must be able to provide at least the calculated number of pore volumes, as described in condition 8 of "Evaluating a Fluid-flow System", as well as satisfying conditions 1 through 3, as previously described.

The equation for calculating the volume of the matrix pore space which is participating in the flow system is given in equation **4a** of Appendix A, and the volume of fluid which is contained in open fractures is calculated from the fracture surface area and the fracture apertures (equation **4b** of Appendix A). Average fracture aperture can reach 0.5 mm.

To allow for the effects of different temperatures and fluid chemistries on metal solubilties in the various rock types, the water volume required in removal of the metal from the rock is also calculated (equation **5** of Appendix A), and the larger of the deposit-site and metal-removal water volumes (equation **6** of Appendix A) is calculated. This larger fluid volume is used as the numerator in subsequent pore-volume calculations (equation **8** of Appendix A).When the relevant denominator is the compactant fluid volume (equation **6** of Appendix A), the sediment thickness decrease is derived using BasinMod,^{TM} a one- or two-dimensional code for simulation of compaction and fluid flow. The number of compactive fluid volumes is calculated using equation **9** of Appendix A. A final (top Lower Carboniferous) thickness of the sedimentary section of 1.25 km is used, and it is assumed that mineralisation was continuous from the beginning of Carboniferous Limestone sedimentation through the deposition of the Waulsortian Limestones. Using a Sclater and Christie (1980) porosity-depth relationship, BasinMod^{TM} a sophisticated simulator of compaction in basinal rocks, predicts a decrease in thickness for the basin sediments over this time period of approximately 100 m. Shorter time periods for mineralisation will result in smaller thickness decreases, and so smaller compactive pore volumes.

2:3 RESULTS

Two questions have already been raised: (i) can the volumes defining the proposed fluid-flow systems provide sufficient metals to source the deposits?; and (ii) can the flow systems produce sufficient mobile fluids (number of pore volumes) to transport the metal-saturated solutions? It is also useful to ask what can be achieved, in terms of metal balance and the number of pore (or compactive fluid) volumes, in *extremum* cases. Given the large number of parameters required in an analysis, that each parameter may take any value within its specified range, and that there are several dozen deposits for which tonnages are available, the suite of possible cases is quite large. Table 2 reports typical results for each of the four basic types. It includes, as appropriate: (i) the approximately mid-range parameter values required for mass balance and the number of fluid volumes required to achieve it; (ii) results at extremum conditions; and, (iii) for the basin-only systems, parameter values when only one compactive fluid volume is allowed.

2:3:1 Local Cases

Metal balance is achieved for all examples using parameter values falling within the chosen limits, although the Navan deposit requires use of limiting values for a number of parameters (Table 2). The Silvermines deposit (Fig. 1) is used to illustrate both the basin-only and the basin-with-basement cases. Its estimated deposit size, expressed as 1.14 Mtonnes of zinc and 0.45 Mtonnes of lead, is taken from Andrew (1991). Generally metal balance is easily achieved for the local basin-only examples, and very easily achieved when basement (total flow system depth 10 km) is included. The basin-only cases fail to reach metal balance when the most pessimistic (but permissible) parameter values are chosen: metal balance is always achieved when basement is included in the flow system. The metal-balanced basin-only examples require 500 to 1000 fluid replacements, using the pore space within the basin. When basement is included, the number of required replacements drops to 100 to 200 (Table 2). Because compactive flow has been proposed, the possibility of achieving metal balance using a single compactive fluid volume is also investigated. One way of achieving this balance is to both increase the lead and zinc solubilities (in the basin and at the deposit) by an order of magnitude, and increase the size of the flow system by 16-fold. But both these actions severely violate the established limits. These results also suggest that local compactive-driven flow requires a minimum deposit separation of 50 to 70 km, which is considerably wider than minimum deposit separations in the Midland Basin region. Moreover, in these calculations a 100% depositional efficiency and a minimal halo size are used.

2:3:2 Regional Cases

Estimated total metal masses for the Midland Basin region of 12 Mtonnes zinc and 3.5 Mtonnes lead (Andrew, 1991) are used to assess the regional flow system scenarios. In general, metal balance is easily achieved with and without basement involvement (Table

System Type	Comments	Metal Balance	Solubilities @ Deposit Site		Rock Type[1]	Size of System		Participating Rock		Fraction Removed		Fracture Spacing		½-Width of Zone (m)	Pore Volumes
			Pb (ppm)	Zn (ppm)		Diam (km)	Thickness (km)	Proportion (%)	Porosity (%)	Pb	Zn	vert (m)	horiz (m)		
Navan, local, w/ bsmt	At limit of some params	Yes	20	100	seds	20	1.25	66	14	0.2	0.1	---	---	---	600
					gr-wke	20	2.5	5	8	0.1	0.1	5	100	0.2	
					gneiss	20	6.25	--	--	0.05	0.05	5	100	0.2	
Generic, local, no bsmt	Mid-range values	Yes	20	100	seds	20	1.25	20-40	10-20	0.2	0.1	---	---	---	500-1000
Generic, local, w/ bsmt	Mid-range values	Yes	20	100	seds	20	1.25	20-40	10-20	0.05	0.05	---	---	---	100-200
					gr-wke	20	2.5			0.05	0.01	10	1,000	0.2	
					gneiss	20	6.25			0.05	0.025	10	1,000	0.2	
Generic, local, no bsmt	One compactive fluid vol	Yes	200	1,000	seds	65	2	66	20	0.002	0.001	---	---	---	1 comp[2]
Generic, reg, no bsmt	Mid-range values	Yes	20	100	seds	200	1.25	20-40	10-20	0.02	0.01	---	---	---	40-80
Generic, reg, no bsmt	One compactive fluid vol	Yes	200	1,000	seds	320	2	66	20	<0.001	<0.001	---	---	---	1 comp
Generic, reg, w/ bsmt	Mid-range values	Yes	20	100	seds	200	1.25	20-40	10-20	0.01	0.075	---	---	---	15-30
					gr-wke	200	2.75	5	8	0.004	0.001	10	100	0.1	
					gneiss	200	6	---	---	0.005	0.0025	10	1,000	0.1	
Midland+ Munster, no bsmt	One compactive fluid vol	Yes	20	100	Mid seds	200	2.25	20-40	10-20	<0.001	<0.001	---	---	---	5-10 comp
					Mun seds	150x60[3]	8			<0.001	<0.001	---	---	---	

[1] seds = sedimentary rocks, gr-wke = greywacke basement; [2] compactive volume; [3] length x width of rectangular area

Table 2. Parameters for Cases Described in Text

2). The required pore-fluid-volume replacements are, predictably, fewer than for the local scenarios, needing 40 to 80 replacements for the basin-only system. The basement-involved example requires 15 to 30 pore-volume replacements. Again the conditions required to produce a regional flow system which consists of only one compactive fluid volume are investigated. Increasing the basin size to its limits is insufficient, so the solubilities again have to be increased by an order of magnitude.

The viability of tectonic loading of the Munster Basin rocks (Fig. 1) can be assessed by incorporating this basin into the flow system. Any tectonic loading will have occured in about Westphalian times, so the thickness of the Midland Basin region sedimentary rocks is increased to allow for the Upper Carboniferous sediments that would have been present at the time. As might be expected when a system's size is greatly increased, but its ore metal is not, metal balance is very easily achieved. Table 2 shows that use of mid-range values result in the need for only 5 to 10 compactive pore-fluid volumes to be mobilised.

2:4 DISCUSSION

2:4:1 The Mass-Balance Tool

The mass-balance calculation is not a sophisticated tool; for example, it does not allow integration of the metal removed across an alteration zone, but simply uses an average value. Other parameters also take the form of bulk values, rather than spatially- or temporarily-variable properties. In addition, some of the values used in this study are quite poorly known, including the lead and zinc trace-element concentrations in the source regions, and the portion of this metal which may be removed by the mobile fluids. The metagreywacke is a possible exception to this, in that Russell (1968) provides trace-element analyses, and Bischoff et. al (1981) experimentally investigate the reaction of crushed (<100 mesh) metagreywacke with brine and with seawater. Their results indicate that almost all the lead and 50% of the zinc can be removed from particles with diameters of 1 mm or less, but this does not allow determination of either how deep the zone of alteration would be in intact rock, or what portion of the metals could have been removed from it.

Is it important to tightly constrain the lead and zinc trace-element abundances in the source rocks and the removable proportions, or are approximations adequate? Use of the mass-balance spreadsheet shows that there is generally more than enough metal available in the flow systems investigated, so that rough estimates of the trace-element abundances, and the removable portions, are probably adequate for the evaluation of flow-system types by metal mass-balance.

The mass-balance study also shows us that relatively small changes in the putative solubilities of lead and zinc, both at the deposit site and within the source rock, make quite a difference to the fluid volume required to produce the metal mass at the deposit. Solubility is normally highly dependent on the temperature of the fluid(s) but the palaeo-temperature field in the Midland Basin region (basin and basement) is poorly known. The pore-fluid of the region has also been interpreted to have widely different chemistries in the different rock types. For example, Lydon (1986) suggests a scenario for the Old Red Sandstone which would imply very different fluid chemistries to those produced experimentally for the metagreywackes by Bischoff et. al (1981). Lydon's scenario also contrasts with the fluid-inclusion chemistries at Tynagh and Silvermines (Banks and Russell, 1992; Sampson and Russell, 1987)

2:4:2 Hydrogeologic Arguments

In terms of differentiating between candidate fluid-flow systems, the part of the mass-balance analysis involving metal masses has been of limited value. All but the most pessimistic, local, basin-only scenarios are able to provide sufficient metals to produce the known deposits' masses. However, when the number of required pore-fluid (or compactive-fluid) volumes, is considered together with other aspects, such as the proposed or implied fluid-flow driving mechanisms, conclusions can be reached regarding the viability of candidate fluid-flow systems.

2:4:2:1 Local Cases

The requirement for at least hundreds of replacements of the pore-fluid volume in local basin-only scenarios makes the compactive flow of connate brines an untenable hypothesis. Compactive fluids would also be both cold and unfocussed rather than being localised to sites of mineralisation (Bethke, 1985) Another possible **local** driving mechanism is a topographically-caused head which requires a fairly **local** highland. This situation would still produce cold fluids, and it would be re-supplied by rainwater, rather than seawater. Lewis et. al (1994), show that very localised hydraulic flow is possible in the presence of a highland, but that the outflow remains cold. This work is also presented in more detail in Chapter 5. Williams and Brown (1986) suggest that sediment compaction could be accompanied by fluid expulsion as a result of faulting. Though this possibility has not been specifically investigated, it is expected that faulting-induced fluid-expulsion would not greatly change the volume of (cold) fluid produced, though it may well focus the fluids. Cold fluids not only fail to meet the requirement that mineralising fluid temperatures reached at least 150°C (and quite probably 250°C), but they also carry very considerably less metal, if any, than do hotter fluids, thus requiring much more fluid to produce the same size deposit. Therefore, local, basin-only flow systems are very unlikely sources of the mineralising fluids for individual deposits.

The local, basement-involved flow systems, where fluids penetrate to 10 km, can also easily provide sufficient metals, but they still require a few hundred pore-volume recharges (or circulations) to produce the deposits. These multiple pore volumes cannot, by the definition of local used in this study, have brought in metals from other (adjacent or distant) rock masses. Therefore, the replacement of fluid must either have been by recirculation through the same rock mass, or by replenishment from a "fresh" source, such as the sea or by rainwater. Dixon et al. (1990) have shown that the lead-isotope compositions of the ores are consistent with cycling of Carboniferous seawater through the basement. Bischoff et. al (1981) note that, in their extraction experiments, changes to the bulk chemistry of the greywackes were minimal, and that the alteration product did not precipitate. Therefore circulating fluids can retain their ability to remove metals after their first passage.

Combinations of flow systems are possible. Compactive, topographic, or tectonic (seismically pumped) driving mechanisms cannot be considered as the sole mechanism for the local-scale mineralising system, and the first two mechanisms cannot be responsible for movement of fluid through the fractured basement. These mechanisms can, however, be active as components of the flow system, albeit rather ineffective ones because of their low fluid temperatures. This topic is also addressed in Chapter 5.

2:4:2:2 Regional Cases

The sedimentary rocks of the Midland Basin region as a whole (i.e. without basement) are a viable source for the metals required by all the known deposits. However, fifty to a hundred pore-volume replacements (or 40 to 80 compactive fluid volume replacements) are required to carry the metals, showing that connate brines could not have been the only fluids involved, and that compaction cannot have been the only driving mechanism.

Flow that is confined to the sedimentary rocks, but in a system that includes the deep, more southerly Munster Basin (and a thicker Midland basin region section), is balanced from a metal viewpoint, and such a system requires only 5 to 10 pore-volume replacements. Considering the degree of uncertainty in many of the input parameters, this low pore-volume replacement number **might** allow a single volume of compactive fluid, at least from a fluid-balance perspective. Therefore, any flow mechanism, such as compaction or basinal fluids driven by the advancing Variscan tectonic front (either topographically-driven flow or tectonic loading), is acceptable for the Midland-plus-Munster basin-only case, at least from a mass-balance viewpoint.

However, compaction-driven flow would involve a generally cool fluid, and so this hypothesis must be discounted. Regional topographically-driven flow is an unlikely explanation, at least for Lower Carboniferous mineralisation. There is little or no evidence for significant emergence of land above sea-level during the Early Carboniferous, either within the sediment-starved Midland Basin region or in the region between the Midland and Munster Basins. By Westphalian times, or thereabouts, the Variscan tectonic front was approaching southern Ireland, and may well have provided a large highland region. However, numerical models of topographically-driven fluid flow (Garven and Freeze, 1984) show that regional flow is present where there is a regional surface gradient (ie, a sloping groundwater table) but that regional flow rarely extends far outside the sloping area. This topic is also addressed in Chapter 5. Therefore any topographically-driven flow is either local to the highland, or requires a continuous aquifer channel overlain by a continuous aquitard. Regional reconstructions of the bathymetry of the Midland (see Chapters 3 and 4) and Munster Basins suggest the opposite situation, with widespread marine conditions prevailing, many active faults, and frequent, local changes in (subsea) slope (Lewis et al, 1994) The fluids must also be hot by the time they reach the sites of deposition yet topographically-driven fluids in the Midland-Munster basins configuration will have been too cold.

A tectonic drive (probably in the form of fault-emplacement of a thick rock section over the Munster Basin rocks), with or without an associated hydraulic head, could be investigated using numerical modelling (Cathles and Smith, 1983; Garven and Freeze, 1984b; Ge and Garven, 1994) but an understanding of these hydrogeologic mechanisms suggests that they could not have provided fluids hot enough for ore deposition in the Midland Basin (also see Chapter 5). However, there is field evidence for regional heating of southern and central Ireland (Clayton et. al, 1989) Fitzgerald et. al (1994) calculate paleo-temperatures of 340 to 370°C in west Clare, which they assign to fluid-advective heating which pre-dates Variscan folding. It is clear from evidence such as this, that there has been at least one regional heating event which probably loosely corresponds to the Variscan orogeny. What is not clear is whether this event records the movement of hot fluids through basinal sediments, and so could have been responsible for the formation of the ore deposits. Note that any mineralisation resulting from Variscan events would be of approximately Westphalian age.

When the basement underlying the Midland Basin region is included in the supply-side calculations, there is both sufficient metal to supply the known deposits, and a fairly small requirement of 10 to 30 pore-volume replacements. In addition, fluids which have penetrated to 10 km depth can easily achieve 250°C fluid temperatures. However, understanding of the driving mechanism of such a fluid-flow system (or systems) is incomplete.

If regional convection were possible it would almost certainly involve the basement in the flow system, but it is anticipated that a single convective system with a 200 km lateral extent would need to extend very deep into the crust (Combarnous and Bories, 1975: Lapwood, 1948) and this condition seems untenable. If convection operates, the cell sizes must be smaller --- or in the terms used here, local. Chapter 5 shows that local upper-crustal (8 to 12 km deep) convection is a robust flow system that develops in preference to either regional basinal flow or regional convection.

2:5 SUMMARY

Mass-balance calculations allow assessment of the capacity of different rock masses to be the source of the metals for the known deposits. None of the existing models can be ruled out purely on their ability to provide metals, since all seem to be at least adequate sources of metals. However, nearly all realistic cases require numerous pore-volume replacements, and this aspect of mass-balance does discriminate between different models, or more particularly their flow systems. Of the scenarios considered here, only local, upper-crustal (i.e. basement-involved to about 10 km) fluid circulation, and possibly a Midland-plus-Munster Basin flow system, are viable from a mass-balance viewpoint as general models suited to the range of known Irish mineral deposits.

Consideration of fluid-driving mechanisms, and the temperature of the hydrothermal waters they produce, further discriminates between the possible models. This approach has been taken in Chapter 5, and the topic is revisited after the potential fluid-flow systems have been examined. The mass balance portion of this study suggests that the Irish lead-zinc deposits are the product of a series of upper-crustal, local convective systems.

CHAPTER 3

RECONSTRUCTION OF THE MIDLAND BASIN REGION AND RESTORATION TO THE EARLY CARBONIFEROUS

In order to both evaluate the structural setting of the deposits, and to understand the fluid-flow system that produced them, the shape of the basin at the time of mineralisation must be determined. Although the Irish lead-zinc deposits are variously regarded as syndepositional to epigenetic, there appears to be general agreement that they are approximately early Carboniferous in age (Andrew, 1985). Therefore it is necessary to establish the configurations of the Midland Basin region as it developed through the Carboniferous.

A basin reconstruction to a present-day (uneroded) shape, and restoration to several times in the early Carboniferous is performed to: (i) determine the present-day setting of the ore deposits; (ii) to investigate the development of the basin; and, (iii) to determine whether syn-sedimentary faulting is important in basin-formation, thereby both controlling the accumulation of sediments (which host the ores), and potentially localising mineralised hydrothermal flows. The restored basin geometries, including the identified active faults, are used to guide fluid- and heat-flow modelling (Chapter 5). Chapter 5 is primarily concerned with early Carboniferous configurations, but it also uses an approximately Westphalian palaeo-geometry. However, no Upper Carboniferous units are reconstructed and no Late Carboniferous restorations are performed because there is virtually no thickness information for the Upper Carboniferous rocks in the region.

Reconstruction of the Midland Basin region to its un-eroded present-day shape, and restoration to its former geometries at several times during the early Carboniferous is challenging. The available data is not ideally suited to the task, and it is too sparse in some areas to fully constrain the results. However, one must start somewhere, so the reconstruction and restoration are undertaken with the expectation that they will identify areas (or times) of interest, and so prompt further data collection and analysis.

Section 1 of this chapter describes: the approach taken; a general overview of the mathematical and mapping techniques and the software which is used (together with the problems encountered). Section 2 lists the information available and discusses the geological units chosen to represent the basinal sequence. Section 3 addresses the structural style of the region, and the method of (re)construction, both in the subsurface and above the erosion surface, of the top-basement surface, Section 4 describes the reconstruction of the units within the basin sequence, and Section 5 discusses the restoration of the Midland Basin region to several times in the early Carboniferous. The geological significance of the results, particularly their role in understanding the evolution of the region and the deposits' structural setting, and the fluid-flow systems responsible for mineralisation, are discussed in the following chapter.

3:1 SECTION 1: APPROACH

3:1:1 Reconstruction

The first step in performing the reconstruction is to establish the structural style; this style is used to interpolate between data points or to extrapolate into areas of no data. The next step is to create a structural interpretation (a contour map) of the basement/sedimentary rock interface. Surface and subsurface elevation data for the present-day top of the basement (and for several horizons in the basin), are used to create a map of all faults offsetting the top of the basement level (to a resolution of about a 50 m vertical displacement); this map is then used in developing a structure-contour map on this horizon. Because of the nature of the data, the reconstruction of the basinal sequence proceeds by first generating faulted isopachs of each sedimentary unit, and then sequentially adding these isopachs to the top-basement structure contour map. The result of this reconstruction is a complete, uneroded, 3-D interpretation of the Midland Basin region sequence from top of basement through rocks of Brigantian age.

3:1:2 Restorations

The reconstructed geometry is then used to restore the Midland Basin region to its probable shape at several "times" in the early Carboniferous: end-Brigantian; end-Chadian; end-Waulsortian; end-ABL; end-Navan; and end-ORS. Some of the units used are quite diachronous and the choice of both stratigraphic and time units is discussed in Section 2 of this chapter. At each "time" point, the decompacted stratigraphic sucession is "hung" beneath the appropriate palaeo-surface, so generating a series of basin geometries representing the evolution of the Midland Basin region.

Figure 5 is a flow diagram of the steps in the reconstruction and restorations. Appendix B contains the larger maps generated in the reconstruction and restorations.

3:1:3 Computer-Aided Mapping

The reconstruction and restoration require manipulation of rock volumes and their bounding surfaces. Even though reconstruction of the geometry of any rock body and its restoration to earlier geometries can theoretically be done by hand, it is a complex exercise in all but the most trivial cases. Not only does the geometry of the rock bodies have to be defined, but the consequences of any changes of interpretation on, for example, depth of burial must also be considered. Because of the complexity, and the inevitable requirement for multiple iterations, an approach that relies on computer-aided mapping is chosen. This choice allows representation of rock volumes by mathematical grids of the surfaces that bound them, and so allows decompaction and sequential basin restoration by operations on those grids.

3:1:4 Theory of Repesenting Volumes by their Bounding Surfaces

Rock units have shapes and they occupy volumes. The units of interest here are layered sedimentary sequences, and so a major simplification can be made. This simplification involves representing the boundaries (top and bottom only) as surfaces, so that a unit is treated as occupying the space between its two bounding surfaces which are located in space. This approach allows ***either*** specification of the unit's volume in terms of the position of its boundaries, ***or*** a specification of it's thickness. Where units have undergone deformation they may be segmented (wholely or in part) by faults. This adds a further complication to their representation by bounding surfaces because the position and orientation of each fault plane must also be specified.

Generally, geological surfaces cannot be represented as tractable analytical functions, but are instead represented by a regular grid in the XY(horizontal) plane, to which the elevation of the surface is appended as a Z value. Appendix C addresses the theory of representing rock volumes by grids of their boundaries. If the thickness of the unit is to be mapped, the Z values at each grid node (XY location) of the top and bottom surfaces are subtracted to produce an XY,thickness grid. Appendix C also addresses some of the difficulties in working with isopachs. In practice, surfaces are (computer) gridded using data in the form of digitised contours, digitised spot elevations, and digitised fault planes, together with control data (used to control the extrapolation of the generated grid outside the area of interest) and using externally generated data files. Grids can also be

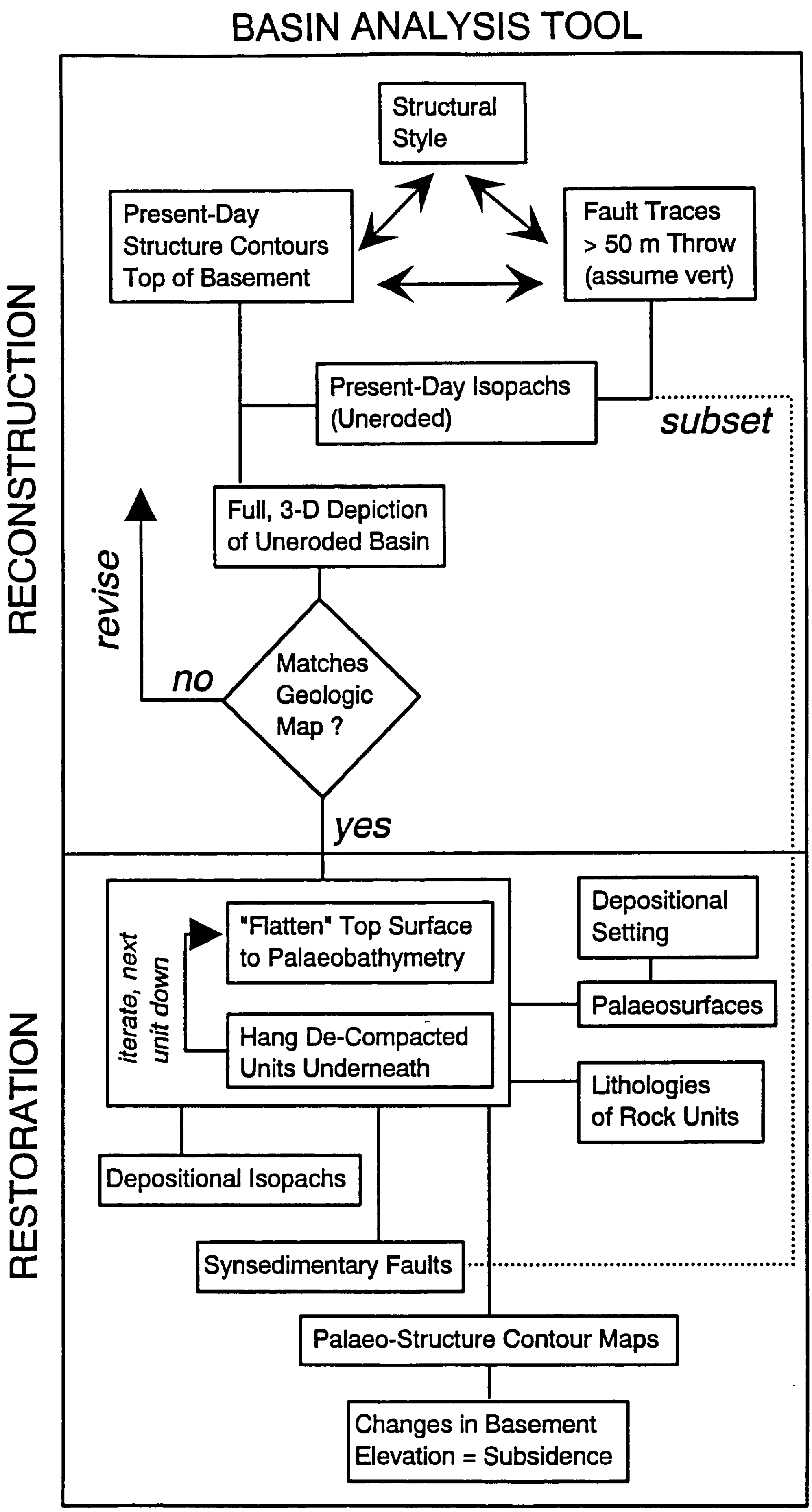


Figure 5. Flow Chart for Reconstruction and Restoration

created by algebraic operations on other grids. In this project, this work has been undertaken using the CPS3™ digitising and gridding package.

3:1:5 Software

CPS3™ is used in this study to generate and manipulate grids of both geologically-defined surfaces and isopachs of the units bounded by those surfaces. It is a digitising, gridding and mapping package designed to allow calculation of volumes of hydrocarbons in a reservoir, and is capable of using faults (vertical or inclined) in its gridding procedures. CPS3™ allows: digitisation of XYZ data of various types, including structure-contours, well depth information, seismic information, and faults (as lines or polygons). It performs several different types of gridding; operates on the resultant grids so as to produce other grids; and calculates volumes between any two specified horizons (either of total rock volume, or of a function of rock volume, which includes factors such as porosity and water saturation).

CPS3™ generates high-quality graphic images of (2-D) maps, and can simultaneously display any input, digitised, or calculated XYZ data (including grid values), and contours of grids, where the values are displayed either using conventional contours or coloured regions. It can also be used to display cultural information (in this project the locations of the deposits). The maps can be plotted at any scale, and can be written to a variety of plotters or printers. CPS3™ can also be used to produce a 3-D isometric (framework) plot of a given surface. It is not cabable of displaying multiple surfaces, nor of distributing vertically variable properties through volumes.

CPS3™ is used in this project as a repository for raw and manipulated depth and positional information for the: top Basement; top Old Red Sandstone; top Navan unit; top Lower Limestone Shale; top and base Argillaceous Bioclastic Limestone unit; and top and base of the Waulsortian Limestone unit. (See Section 2 of this chapter for the types and sources of data used in this project and the naming convention adopted.) It has also been used to generate and store files of the position of faults. Fault displacements have been stored separately from fault position because displacement at each horizon is potentially different. CPS3™ cannot accept orientation (eg dip and strike) data directly. It is the geologist's task to convert such data into a format which can be used as input. This is discussed in Appendix C. Table 3 summarises the information stored by CPS3™, an includes: drilled depths; unit thicknesses; digitised contours and spot elevations; digitised fault positions; grids of surface elevations and unit thicknesses; and digital forms of the maps generated. Many of these files are far too large to be printed as part of this study: Table 3 gives typical sizes of these files.

Type of File	Name of Example File	No. files (approx)	Typical Size (KB)
Drilled depths	rtzwelldata_m_tvtnvn	25	15
Digitised contours	hnw_dig_ed2	25	2
Digitised fault traces	nvnbvs4_f_dig	20	10
Surface elevation grid	topnvnbvs_1grid	40	400
Isopach grid	tvtnvnbvs_1grid	12	400
Digital map	nvnrest_topbas	60	1,250

Table 3. Types of computer data files and their typical sizes.

The original plan was to display the sequential basin geometries via the 3-D visualisation tool SGM™, and to add isochronous surfaces to the displays. Isochronous surfaces are deemed necessary because some of the units are markedly diachronous (see Section 4 of this chapter). This method should have permitted redisplay "hanging" the display on time lines, in much the same way as seismic information is displayed in (two-way travel) time or in depth. Unfortunately this approach has proven impractical because of limitations of the available computer hardware, so the 2-D maps are displayed with time lines superposed where useful.

3:2 SECTION 2: INFORMATION BASE

3:2:1 Data

The available information can be categorised as surface and subsurface data.

3:2:1:1 Surface

Surface data takes the form of geologic maps at various scales and level of detail, which have been created for a variety of purposes. All-Ireland maps have been produced by both the Irish Geological Survey and the Irish Association for Economic Geology (Browne and Reid, 1984). The latter locates mineralised provinces, and names individual deposits. There are also many late-1800s to early-1900s Institute of Geological Sciences one inch to the mile maps (see for example, James, 1857).

The maps of most use to this project are the Bedrock Geological Map Series of the Carboniferous of Central Ireland, complied by Murray W Hitzman (Hitzman, 1993), with a correlation of geological units across Central Ireland. This map series is used extensively in this project for the construction of the top-basement map, and as control for the generation of the environment-of-deposition maps and associated isopachs (see Sections 4 and 5 of this chapter). However Hitzman's map series is not suitable for deriving structure-contour maps on any one horizon, and so is not suitable for derivation of the structural style of the region.

Other maps which are used include the Devonian (Bluck et. al, 1992), Carboniferous (Cope, 1992) and Permian (Smith and Taylor, 1992) series of palaeo-geographic reconstructions of Britain and Ireland published in the Atlas of Paleogeography and Lithofacies (Cope et. al,1992). The Ordnance Survey of Northern Ireland 1:250,000 topographic (metric) maps (Ordnance Survey of Northern Ireland, 1989) are also used in converting drilled depths to subsea depths.

3:2:1:1 Subsurface

The available geophysical information takes the form of Bouger gravity maps and magnetic surveys, and their interpretations. The earliest reported geophysical surveys and their interpretations are the work of Murphy and his co-workers (Murphy, 1962; Murphy, 1960; Murphy, 1955; Murphy, 1952; Thirlaway, 1951) of the Dublin Institute for Advanced Studies, and their surveys have formed the basis of most gravity interpretations. Williams and Brown (1986) use both gravity and magnetic interpretations to develop a genetic model for the Irish lead-zinc deposits, and these authors maps have also been used in this study. Most of the more recent geophysical interpretations are based on more sophisticated interpretations of the older geophysical survey data.

Wellbore information (in the form of drilled depths to the tops of horizons) is available both in the literature, and as a proprietary database assembled and contributed to this project by Riofinex North Ltd. Figure 6 is a map of the Midland Basin region showing the locations of the core information, from both public and proprietary sources, used in this study. These data are used to control and check the elevations of the of chosen geological horizons, and are also used in the generation of the database of geological unit thicknesses.

3:2:1:3 Rock Succession

The only surface which is both unmistakable (although faulted) and continuous across the region is the top-basement. The tops and bases of the overlying sedimentary units are often somewhat indistinct and the lithological types vary quite significantly laterally. For example, Philcox (1984) identifies three provinces in the area covered by this study, each of which has a rather different Lower Carboniferous sucession. In addition, in the absence of adequate chronostratigraphic information, it is quite difficult to determine age equivalents. In practice most correlations have been made using identifiable local units (Jones and Earls, 1995), though many of the locally defined units are acknowledged to be diachronous, generally younging northwards.

Philcox's (1984) division of the Central Ireland region into four sub-provinces illustrates the difficulty of developing a useful correlation system. His classification is adopted in large part by Andrew and Ashton (1985) for the area around the Navan mine. Andrew (1986) records the most commonly used stratigraphic nomenclature for the Courceyian stage for both the Munster Basin and Central Ireland. Strogen et al. (1990) establish a formal nomenclature for the North Dublin Basin, formalising the nomenclature of Philcox (1984) below the Feltrim Limestone (Waulsortian), which was itself formalised by Jones et al. (1988). Strogen et al. (1990) provide a new formal nomenclature from the Feltrim Formation (Waulsortian Limestone) up through rocks of Brigantian age. These authors also interpret chronostratigraphic correlations for the North Dublin Basin, while

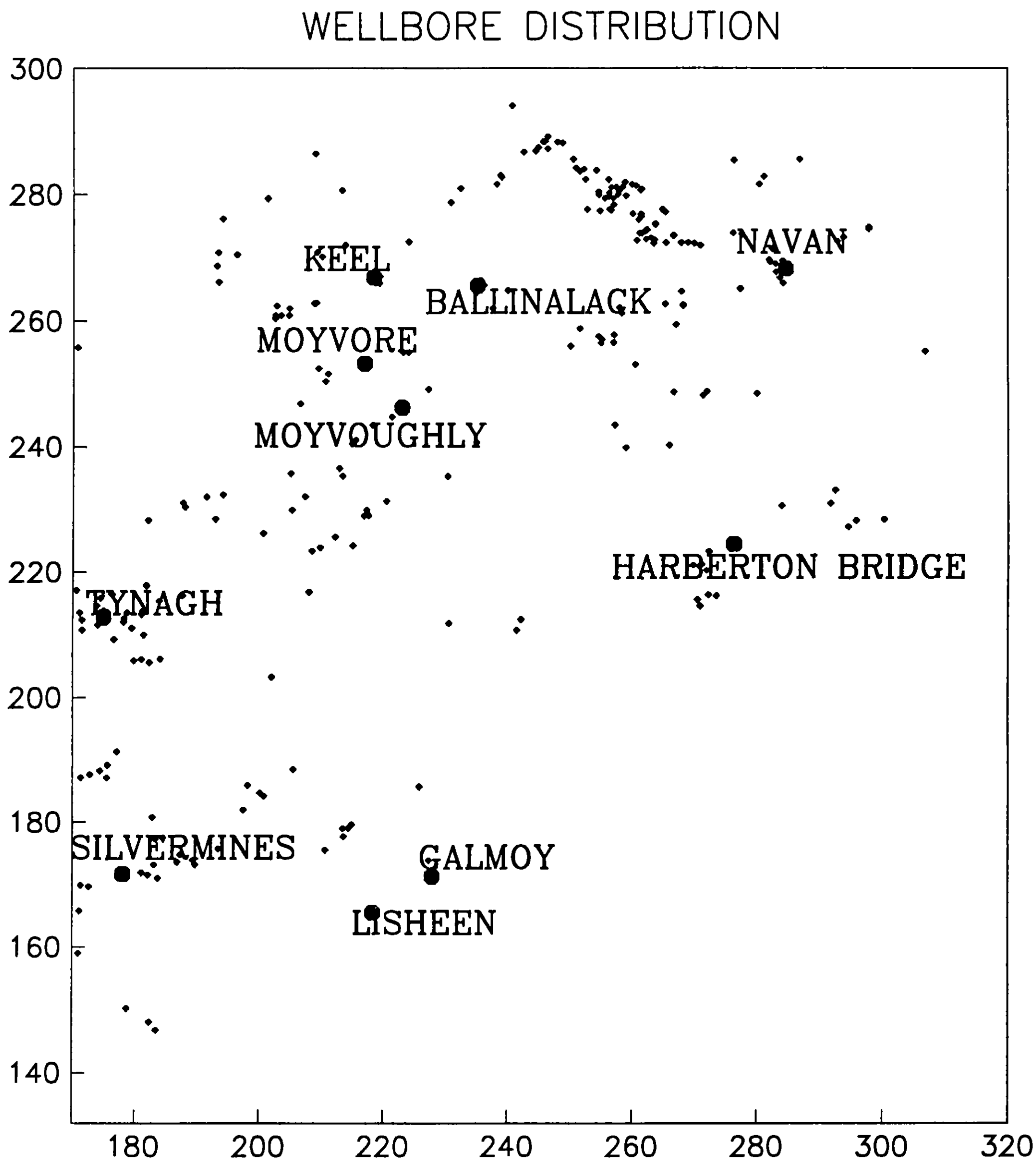


Figure 6. Location of subsurface data contained in database Wellbore Locations as diamonds. Irish National Grid used on x and y Axes. Each Axis Increment is 20 km

Higgs et. al (1988) interpret such correlations for the Tournasian rocks of Ireland. However, this information is insufficient to provide chronostratigraphic units for this study.

Hitzman's (1993) choice of units allows correlation across the region, though it uses locally-defined and diachronous units. Hitzman (1993) combines the uppermost Devonian and lowermost Carboniferous clastics (identified by Philcox as the Basal Sandstone) into one unit, named ORS. He also combines all units between the top of the ORS and the top of the Ballyvergin Shale into one unit, the Lower Limestone Shales (LLS), and uses time units above the Waulsortian Limestones.

To keep this project to a manageable size, regionally correlated units are required, ideally units correlated in time. However, the regional chronostratigraphic units are not well enough defined to be useful in this study, and most of the available surface and subsurface information uses the local, informal (lithologic-type based) nomenclature. It was decided that the ability to correlate regionally was the most important factor in choosing units for the restorations. Accordingly Hitzman's (1993) units are adopted in a slightly modified form (see figure 2a). His regional correlations have proven particularly useful, in part because they contain divisions within the Arundian to Brigantian section, both in time, and by environment of deposition. His units are also very similar, but not identical, to those used in the proprietary database made available for this study.

This choice of units still presents two big problems. Firstly, Hitzman's (1993) Navan unit is confined to the nothern area, and his Lower Limestone Shale only occurs to the south, and limited lithochronological information demonstrates that these are not true lateral equivalents. Secondly, most of his lower units are diachronous, some strongly so, and this makes restoration to several stages in the early Carboniferous difficult. It was intended that this second problem would be mitigated by adding approximate time planes to the 3-D images of the reconstructed early Carboniferous restorations, but this has proven impractical because of computer hardware problems that developed during the project.

In order to keep the problem tractable, the reconstruction uses the following units adapted from Hitzman (1993) (brackets contain abbreviations used in this study): basement; Old Red Sandstone (ORS); Navan Group (Navan); Argillaceous Bioclastic Limestone (ABL); Waulsortian Limestone or Feltrim Limestone(Waulsortian); Chadian Facies Mosaic (Chadian); late Chadian to Arundian limestones (LSB); and Holkerian to Brigantian limestones (USB). These units are shown in Figure 2a. The LLS unit is combined with the Navan unit (see below), and, -- for most purposes -- the LSB and USB units are combined. The database uses the top of the: basement; ORS; LLS; Navan; ABL; Waulsortian; and where data is available, the Chadian; LSB; and USB units.

These units are generally suitable for creation of isopachs. However, difficulties arise in treating the Navan and LLS units. The isopachs are intended to approximately represent stages in the creation of the basinal sequence (see Section 5 of this chapter), in part to allow identification of faults active during each stage of basin development. While it is acknowledged that the units chosen are generally diachronous, the large difference in thickness beween the LLS and Navan units, and the likelihood that (while the start of deposition is approximately synchronous) the Navan unit represents a much longer period of deposition, presented problems. In an attempt to alleviate this problem, the lowermost part of the ABL unit (which overlies the LLS , Figure 2a) is assigned to the Navan unit. Its thickness is estimated using information from the area of transition from the Navan to the LLS unit. It is fully recognised that this is, at best, only a very rough approximation to a synchronous unit, but this approach is deemed better than retaining a wildly diachronous unit.

The geological significance of the isopachs of each of these units is addressed in the following chapter (Chapter 4).

3:2:1:4 Data Distribution

The density and reliability of both XYZ data, sensu stricto, and the information used to generate XYZ data is greatest in the north and west of the area, and decreases to the southeast, to the extent that the far southeastern corner of the area is virtually unconstrained in the subsurface (Figure 6). Also, the Lower Carboniferous units crop out quite frequently in the north and west of the area; to the south and east the exposures are dominated by Upper Carboniferous units. This variability of information inevitably causes problems in deriving an interpretation of consistent quality throughout the area. Data quality will be noted as appropriate in the subsequent sections.

3:3 SECTION 3: TOP-BASEMENT STRUCTURAL STYLE AND RECONSTRUCTION

The basic form of a basin is an expression of its structural style, or styles if it has been subjected to more than one event. A structural style proposed for the Midland Basin region in the Carboniferous must pass two tests: it must be reasonable in light of the tectonic setting of the region in the Carboniferous; and it must provide a good fit to the early Carboniferous geometry. The Midland Basin region has not experienced much deformation since the Carboniferous, and so a good match to the present-day geometry is an adequate test of a style. Once the tectonic style has been determined the present-day faulted geometry of the top of the basement can be constructed. A style dominated at basement level by fault-bounded, tilted blocks has been suggested by several workers (see, for example Brown and Williams, 1985), and this agrees with this analysis of the geology of the central region of

Ireland. This section describes the derivation of the structural style of the Midland Basin region and the creation of a top-basement, faulted, structure-contour map.

3:3:1 Tectonic Setting and Structural Style in the Early Carboniferous

The Caledonian Orogeny in Ireland was completed by the end of the Silurian (Bluck et al., 1992). The rocks which form the basement to the Carboniferous and Devonian-age basins of south and central Ireland reflect the Caledonian Orogeny in that they are often highly folded, and have all been metamorphosed to some degree. The late Caledonian Leinster Granite was emplaced at about 408 Ma (Bluck et al., 1992), and by the end of the Silurian, the degree of deformation in the region had greatly diminished. The Variscan Orogeny, which approached Ireland from the south, was being felt in south-central Ireland by about Westphalian times (Cope et. al, 1992). What, then was the tectonic environment of Ireland during the Carboniferous?

Bassett et al. (1992) suggest deposition of alluvial plain and deltaic sediments in southern Ireland during the late Silurian (Mid Pridoli, c 412 Ma), and Bluck et al. (1992) propose the deposition of similar sedimentary sequences across southern and central Ireland during the early Devonian (Lochkovian through early Emsian, c. 408 to 400 Ma), though no early Devonian sedimentary rocks are known in the Midland Basin region. Bluck et al. (1992) also suggest widespread deposition of primarily floodplain deposits across Ireland during the Late Devonian. These deposits are most abundant in the deep, fault-bounded Munster Basin (Fig. 1), which is developing to the south of the Midland Basin.

By the start of the Carboniferous, Ireland is at the northern margin of a marine shelf (Cope et. al, 1992), with an emergent landmass to the north and to the east (Saint George's Land). As the Carboniferous progresses, the Midland Basin region is subjected a marine transgression, with fluvial deposition being replaced by carbonate shelf sedimentation, and, by late Chadian time, by some basinal sedimentation: all of these are accompanied by some syn-sedimentary faulting. During the time of this deposition, there is also extensional tectonic activity in what is now the Rockall Trough, to the northwest of Ireland (Haszdeldine, 1988); there is also smaller-scale block faulting throughout Northern Britain (Haszeldine, 1989).

During the early part of the Carboniferous, the Midland Basin region appears to have been in a relatively quiet tectonic setting on a continental margin, within a region of fairly widespread, incipient, rifting. While the causes of this tectonism are not fully clear, this setting appears to be suitable for the development of a structural style dominated by fault-bounded, tilted blocks.

The style is determined from the configuration of the top of the basement. This surface is chosen because it is geometrically simpler than the basinal horizons, which are potentially partly eroded, or may have areas of non-deposition. Several areas, particularly Slieve Bloom (Irish Grid reference 220-250, 190-210) and the area of outcropping basement south of Silvermines (Irish Grid reference 175-200, 140-180) are used to construct detailed structure-contour maps of the basement / ORS unconformity -- here called the top-basement. All available dip information from the ORS unit is used, with greatest confidence being placed in measurement from the lowest parts of the sequence; dips from the basement rocks (below the unconformity) are ignored.

These maps reveal that, in general, faults bound regions which have very similar dips and dip directions, and that the primary structural style at the top-basement is of tilted fault-bounded blocks separated by high-angle faults.

3:3:2 Top-Basement Surface

The regional top-basement map interpretation is based on the assumption that an originally planar top of the basement has been rotated due to movements on faults. Post-Caledonian folding of the basement rocks is assumed to be negligible. While remaining aware that the top of the basement is highly unlikely to have been absolutely planar when ORS deposition began, the simplifying assumption is made that the primary cause of localised elevation changes in the basement (at least those changes large enough to be determined with the available data) is faulting.

3:3:2:1 The Fault Map

Given this approach, the first step in generating the structure-contour map of the top-basement is creation of a map showing all faults. The primary data available for identifying faults offsetting the top-basement are the published bedrock geological maps at various scales, surface dip data, and drilled depths. Drilled depths are screened for the effects of faulting and structural dip, and these effects are noted. Various sources of secondary data are used, most commonly the depths to basement calculated by extrapolation from drilled depths of the top of sedimentary units. Geophysical maps are also used as guides to the general shape of the top-basement surface. Although most faults are steeply-dipping normal faults, at the map scales used in this study, this distinction is unnecessary and the faults are treated as if they are vertical.

The first step is to identify the larger faults by identifying locations where large (often interpreted) elevation changes occur at top-basement. Existing (surface or subsurface) geological maps are then used to identify changes in dip and dip direction; such changes indicate that a fault separates the two areas, and, therefore, serves to identify possible fault locations. Not all faults in the sedimentary section necessarily continue into the basement, and basement faults can be expressed as folds in the overlying sedimentary rocks.

When the larger displacement faults have been identified, smaller displacement faults are located by a similar process, such that (hopefully) most faults with a vertical displacement exceeding 50 m are identified. It is also recognised that this method of identifying faults will tend to "lump" smaller faults together, particularly where data is sparse, but no better alternative is available. Faults in the areas of outcropping basement are taken from published information (see for example, Ashton et al, 1986; Slowey, 1986, Hitzman, 1993).

In some areas, the major faults, and the majority of the minor faults, are identified with confidence. This is particularly true in those areas where the basement approached or reached the present-day surface. In addition, the map and subsurface information in the north, west, and central areas seem of at least acceptable quality. Neither surface nor subsurface information is particularly good in the southeast of the region, and confidence in the fault interpretation in this area is poor.

In order to produce the level of detail required, the fault interpretation is initially made at a scale of 1:100,000. This requires that the area be broken into six regions, plus two overlap regions, to provide continuity. The identified faults are then digitised using CPS3^{TM}, and the resulting files are merged (after corrections are made for paper stretch), and edited, to produce a set of polylines representing the top-basement fault set (see Table 3). Figure 7 shows the faults which cut the top-basement surface.

3:3:2:2 The Top-Basement Structure-Contour Map

The generation of the regional top-basement structure contour map is effectively an extension of the method used to identify the tilted fault-block structural style, except that subsurface rather that surface information is also used. The creation of the structure-contours involves deriving a tentative dip and dip direction from three (normally subsurface) data points (if available) at the top-basement surface in each of the fault-bounded blocks illustrated in Figure 7, and checking this orientation against any other elevation or orientation data, including outcrop information. If orientations are available for the sedimentary rocks they are also considered, since sedimentary rock dips are probably very like those at the top-basement surface (away from fault zones). Where there are less than three elevation points in a fault block, any suitable dip information from surface maps is used. In the absence of any orientation data, outcrop patterns are used to provide the best guess of top-basement orientation.

The structure-contours so produced provide the input for the gridding process. Accurate gridding of the planar-segment geometry of the fault-block style requires that all fault blocks be digitised with at least two contours, and that contours are everywhere quite

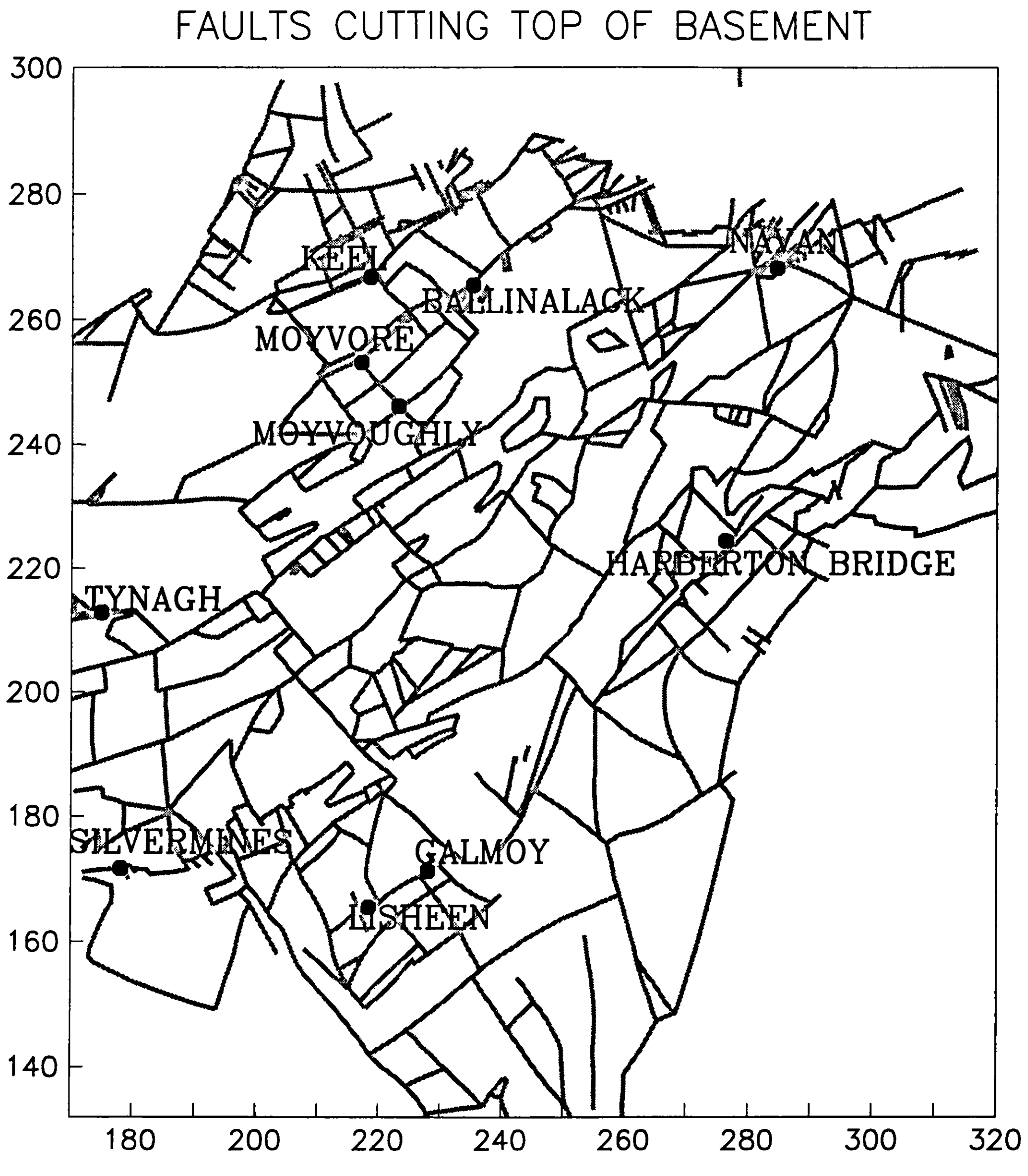


Figure 7. Faults cutting top of Basement - Restoration

closely spaced. At a scale of 1:100,000 this requires contours to be spaced no more than 2 cm apart resulting in the digitisation of unusual contour line elevations. This tends to render the digitised contours unsuitable for displaying the surface geometry.

The digitised contours are gridded using a convergent algorithm (see Appendix C) at a one km grid spacing. This spacing was chosen as the best compromise between the degree of detail required for a useful analysis and the size of file that could be readily processed. The gridding is performed for each of the eight maps, and the grids are corrected for problems induced by overlap problems and paper shrinkage. They are then complied into one data set. Some considerable manual editing of values in smaller fault blocks and at the margins of the region is required. Figures 8a and 8b are a coloured map and 3-D view of the contoured grid values for the top- basement surface. Figure 1 of Appendix B (Fig. B1) is a 1:350,000 map of the same information. This process of fault and structure contour map generation is iterative through all stages of the process, requiring one major and several minor revisions before a satisfactory top-basement structure-contour map is produced.

3:4 SECTION 4: SEDIMENTARY UNITS RECONSTRUCTION

This section considers the approach taken in constructing the present-day geometry of the sedimentary rock units through the Brigantian age rocks, and reconstructing them where they have been subjected to recent erosion. The section describes both the environments in which deposition takes place and the methods used to isopach these units and to identify syn-sedimentary faulting. It then details the method of sequential addition of the faulted isopachs' grids to the top-basement elevation grid, creating the reconstructed present-day geometry.

The reconstruction of the Lower Carboniferous basinal units requires a different, and more complex, approach from that used in reconstructing the top-basement surface. The accumulation of the sedimentary units is a result of a number of factors, including variations in sediment supply and changes in sea-level, deposition on a potentially complex surface. The units have also undergone compaction and possibly erosion. Even though the data available for the top-basement surface and for the boundaries of the basinal units is very similar, because of extra complexities in the shape of the basinal units, and because of the expectation that faults at top-basement level could become folds up-section, the basement's structural style could not be applied directly to the basinal units. Consequently the elevation and outcrop data, even with an approximate structural model available, proved inadequate to create acceptable structure-contour maps for any of the basinal horizons. There is also

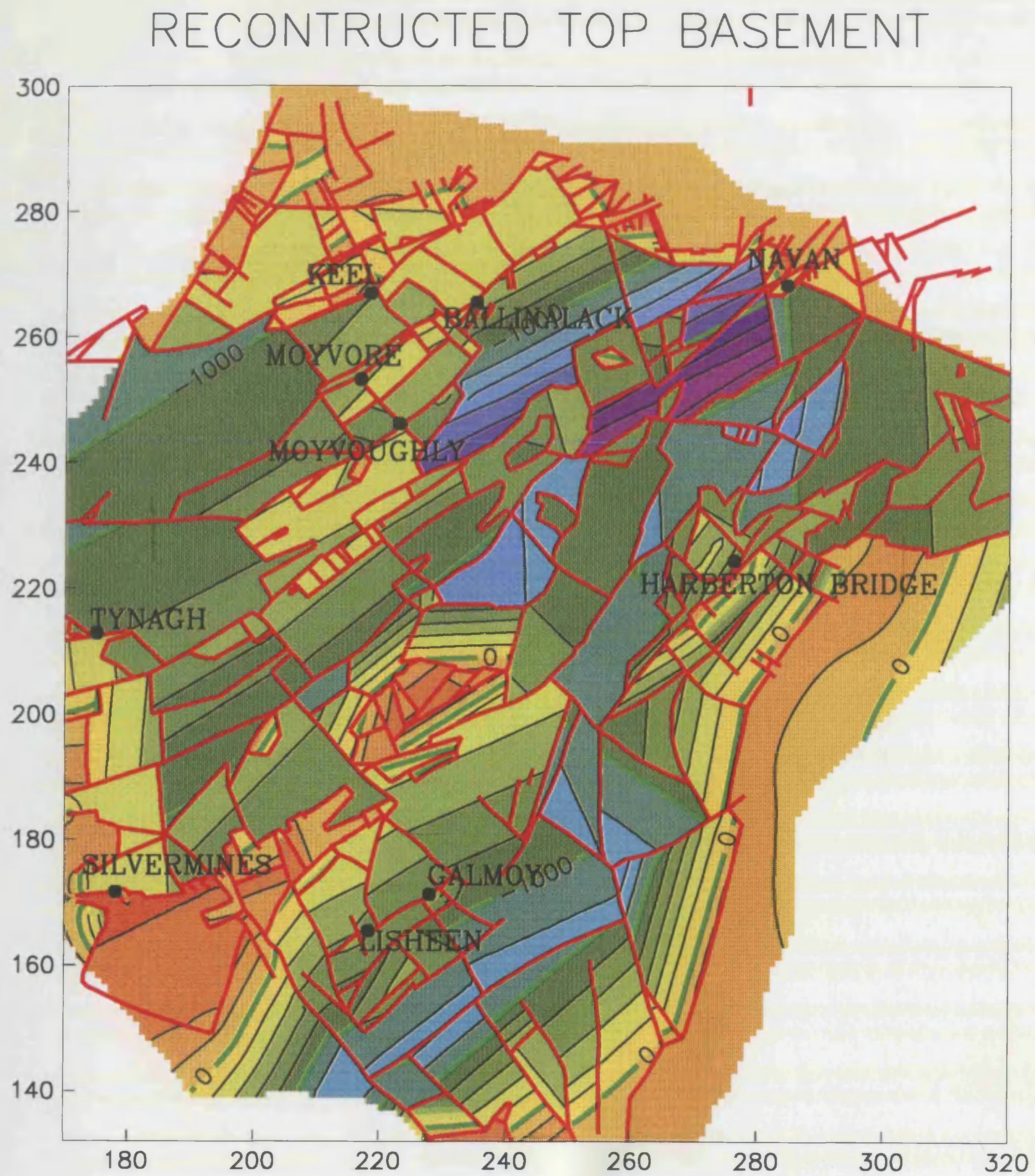
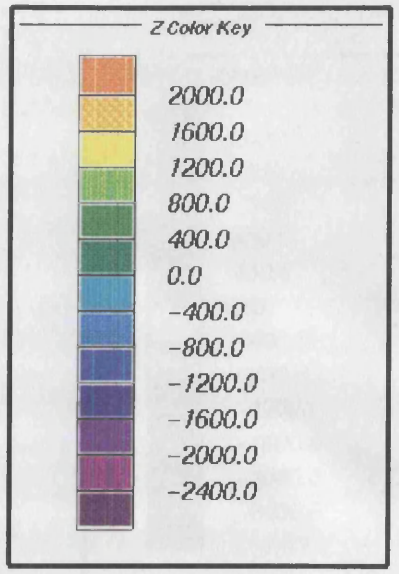


Figure 8a. Colour Structure Contour Map on Reconstructed Top-Basement With Deposit Locations. Faults in red. Depth Values Given by Colour Key of Figure 8b. Axes Use Irish using Irish National Grid (km).

Depth Colour Key – 400m Depth Increments (Positive Values Used for Thickness)



Depth Colour Key – 100m Depth Increments (Positive Values used for Thickness)

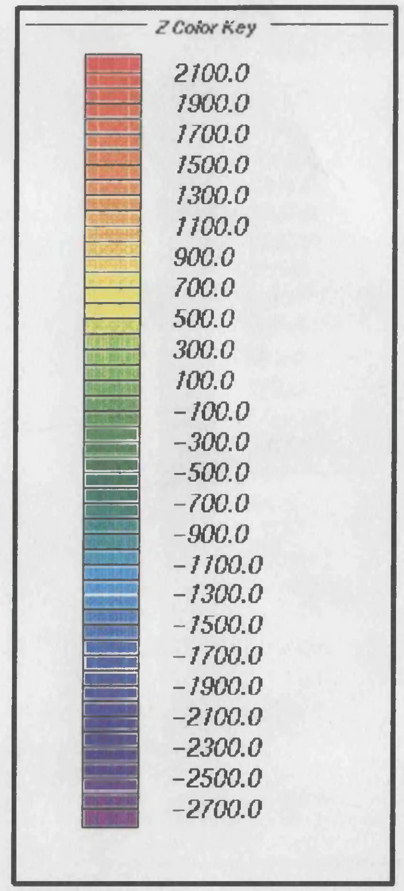


Figure 8b. Colour keys to be used with depth and thickness maps using colour to represent depth ranges. Key with 400m increments used for maps with large depth range. Key with 100m increments used for maps with smaller depth range, and for isopach maps. All depths and thicknesses are in metres. All depth maps use sea-level as zero.

so to represent the development of the basin in terms of, for example, prograding sequences, development of carbonate ramps, and the depositional effects of faulting.

3:4:2 The Isopach Maps

The first generation of isopachs is created by assembling the thickness data for each unit, and then gridding each dataset, avoiding time-consuming hand-generation of preliminary structure-contours, followed by digitisation and gridding. This short-cut is taken because the thickness data is sparse, and no suitable model for the variation in unit thickness is available.

The data used for gridding are the calculated true vertical thicknesses of each unit, (contained in Appendix D) and a file containing locations for which the unit is known to be absent (See Table 3). These data are gridded using a convergent gridding algorithm (see Appendix C) using the same one km grid interval as was used for the top-basement grid. Each resulting grid is contoured and displayed, together with its control data, superposed on a map of the faults at top-basement level Figure 9 is an isopach map for the ABL unit that was produced in this way. The isopachs of the other units show very similar results. There is a general pattern of regions of very similar isopached thickness separated by regions with large thickness changes. These regions with relatively uniform (or uniformly changing) thickness are generally bounded by thin regions with a rapid change of thickness. The thin regions generally occur across faults identified at the top-basement surface. This concurrence of a rapid change in sediment thickness and a fault strongly suggests that each fault identified fin this way was active at the time of sedimentation. This pattern emerges for all the sedimentary units, suggesting that synsedimentary faulting is active throughout the early Carboniferous, and that it strongly influences the patterns of sedimentation. This conclusion is in marked contrast to that of Andrew (1992) who identified no influence of synsedimentary faulting in the ORS and Navan units' depositional pattern for north-Central Ireland.

The next step is to generate maps of the faults active during sedimentation, and to regrid the unit thicknesses incorporating these faults. The paleo-environment-of-deposition maps (Figs 15 - 26) , which are described in Section 5, are also used to guide the choice of synsedimentary faults, as sharp changes from shallow to deep water environments could well correspond with an active fault. The active faults are selected from the top-basement faults. The choice of the synsedimentary faults made for each unit is discussed below, along with a description of the units' thickness patterns and lithofacies distribution.

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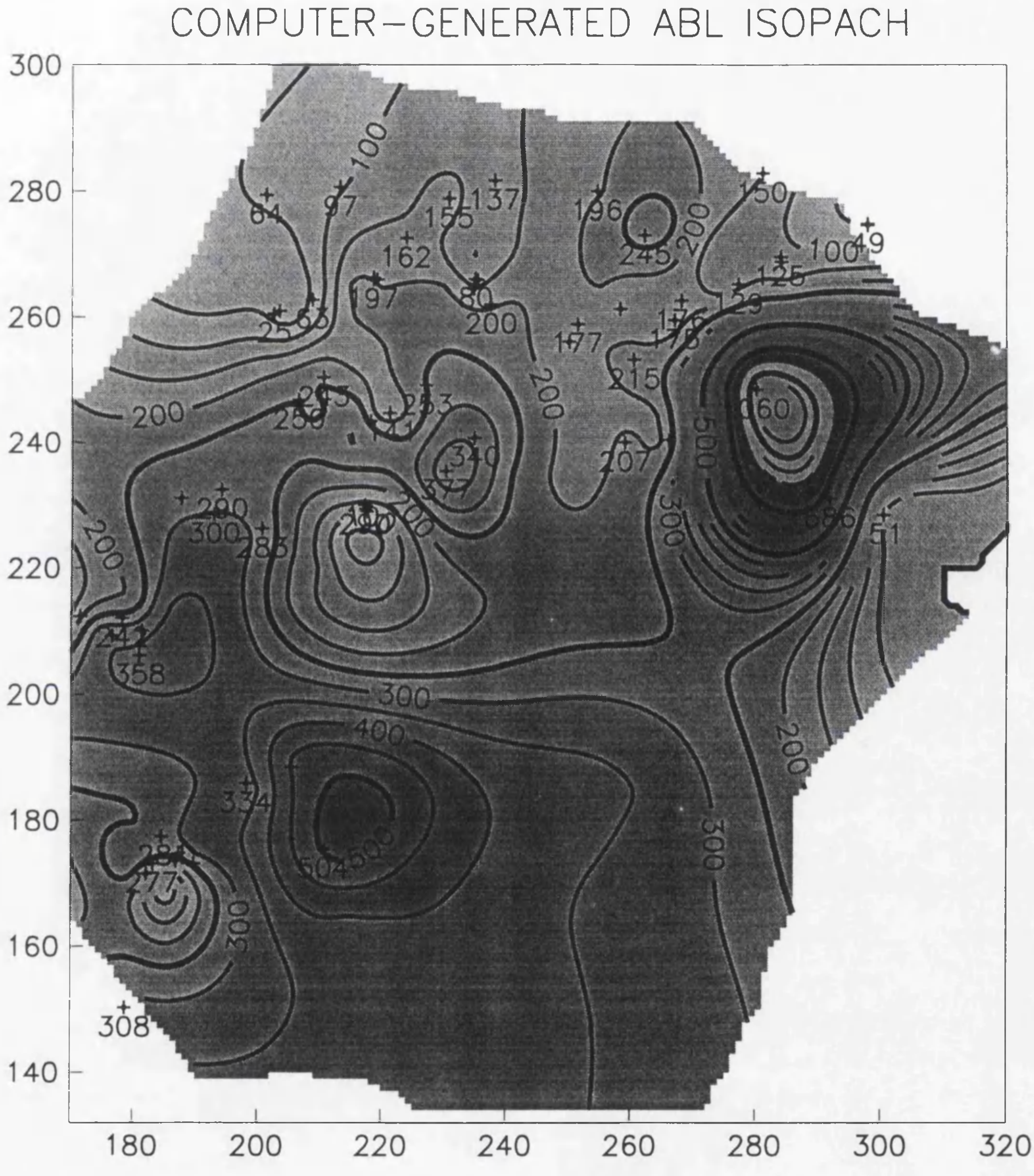


Figure 9. Computer-generated isopach of ABL with measured and estimated ABL thicknesses

3:4:2:1 Faulted Isopach Old Red Sandstone (ORS): Figure 10

The sandstones of the ORS unit are primarily partially reworked fluvial or alluvial deposits. However, there is no major change in lithofacies either vertically or laterally and there is no significant regional unconformity at the top of the ORS unit. The preserved ORS is generally 50 to 150m thick, is thinnest in the north and east, thickening to the south and southwest to a maximum thickness of about 350m. This is in keeping with the regional thickening of the ORS to the south and southwest (Phillips and Sevastopulo, 1986).

Thickness variations across potentially active faults allow a number of syn-sedimentary faults to be identified with reasonable confidence. Although a large part of the Carboniferous section is missing in the far northeast of the region, in the remainder of the area missing section is equated with local highs during part or all of ORS deposition.

The present-day northern margin of ORS deposition has been interpreted as a depositional edge. This edge may or may not have been defined by minor faulting, but is interpreted as essentially unfaulted because any faults would have had vertical displacements of only a few metres. The eastern margin of ORS deposition is more difficult to interpret. Subsurface data in the eastern side of the Midland Basin region is sparse but the ORS is missing in outcrop along most of the western margin of the Leinster Granite massif. The far eastern edge of the ORS unit is also interpreted to be depositional, but with a large synsedimetary fault separating the thin edge of depositon from the much thicker section about 20km to the west. The ORS continues to thicken across the southern boundary the region studied with no obvious fault control on its thickness.

3:4:2:2 Faulted Isopach Navan Unit: Figure 11

The faulted isopach which represents the combined LLS and Navan Group, plus some of the ABL units in the south (see Rock Succession, Section 2 of this chapter) is particularly difficult to generate. However, some synsedimentary faulting has been identified.

The LLS is composed primarily of calcareous shales and thin, dark argillaceous limestones, and Navan Group of argillaceous limestones with minor shales, oolitic units and calcareous sandstones. The ABL unit consists primarily of argillaceous calcarenites with thin calcareous shales, and with local oolitic units in the south. The change from LLS and Navan Group to ABL is transitional. The environment of deposition appears to have been shallow shelf or upper ramp (Ahr 1973, Wright and Faulkner, 1990), with an occasional shoreline position.

The Navan unit is generally a little thicker than is the ORS, but, in contrast to the ORS, it has a depositional centre (maximum thickness about 450m) at about Irish Grid reference (250,230), and the northern margin of the Navan unit extends beyond the northern limit of the region. However, the eastern (Leinster Granite) margin had the same character

FAULTED ISOPACH OF ORS UNIT

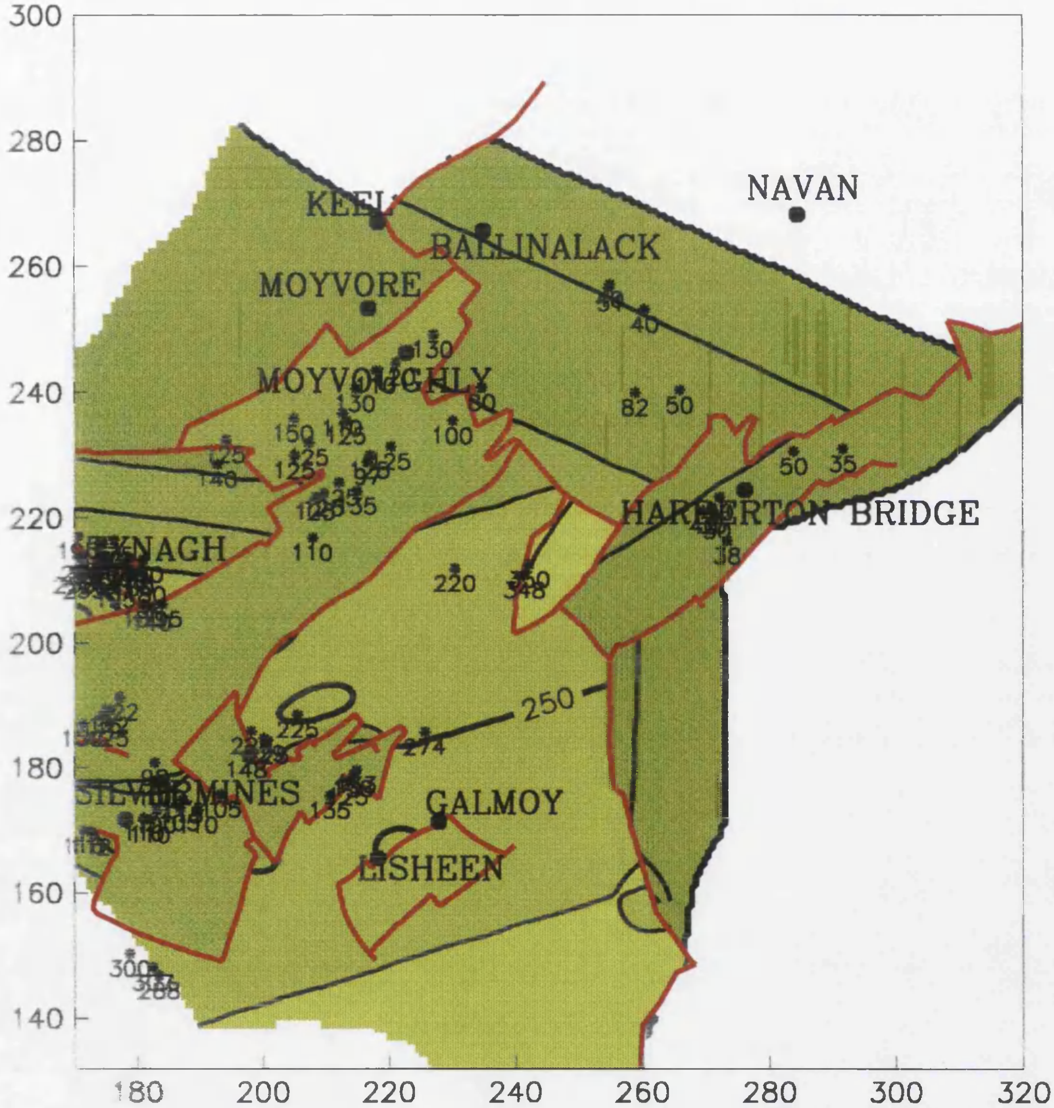


Figure 10. Faulted isopach of ORS unit with ORS time faults in red. Colours represent thickness; thickness values given in Figure 8. Deposit locations in black. Measured and estimated ORS thicknesses in black

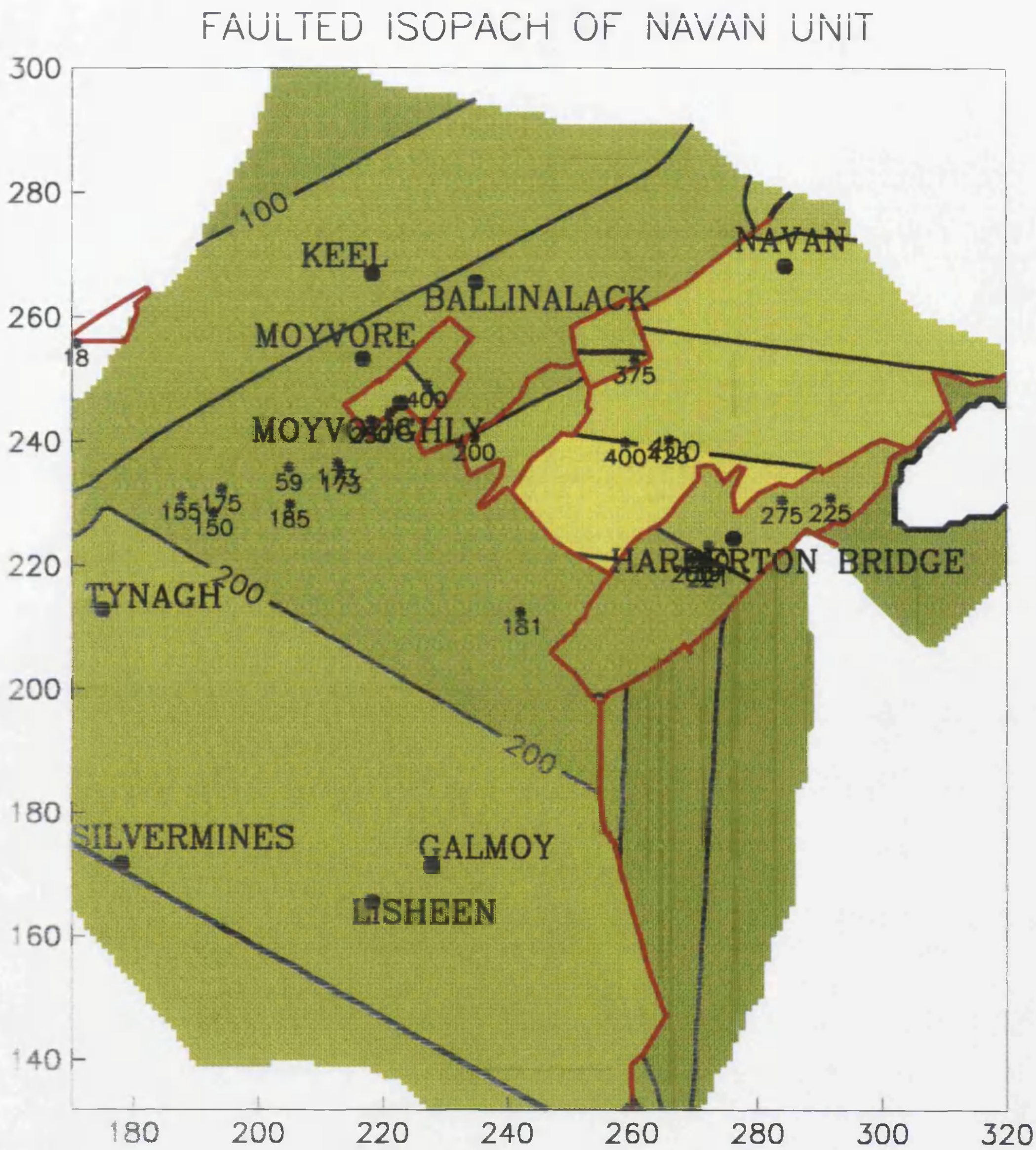


Figure 11. Faulted isopach of Navan unit with Navan time faults in red. Colours represent thickness as given in Figure 8. Deposit locations in black. Measured and estimated Navan thicknesses in black

as it had during ORS deposition and the Navan unit also continues to thicken southward, as did the ORS.

Syn-sedimentary faulting in the northern part of the region is reasonably easy to identify, but it is not possible to identify such faulting in the southern part of the region because the LLS unit is uniformly thin, and a uniformly thickening part of the ABL has been used.

3:4:2:3 Faulted Isopach Argillaceous Bioclastic Limestone (ABL); Figure 12

The ABL unit consists primarily of argillaceous calcarenites with thin calcareous shales, and with local oolitic units in the south. This leads to an interpretation for the north of a quiet shelf setting with occassional interuptions by storms in the north (see Strogen et al, 1990); similar rocks suggest a similar interpretation for the south of the region.

The ABL has more active faults and is generally somewhat thicker than is the underlying Navan unit. Like the Navan, the ABL also has a depositional centre, but the ABL centre is somewhat to the east of the Navan depositional centre (at about Irish Grid reference (270,240)). The ABL unit's maximum compacted thickness has reached at least 1100m.

Identifying syn-sedimentary faulting is relatively simple for the ABL, even though part of the lower portion has been assigned to the underlying unit. The northern depositional margin again extends outside the region, and the eastern margin again seems to be partly controlled by the relatively highstanding Leinster Granite Massif -- though ABL deposition extends somewhat further east than it did during Navan and ORS deposition. ABL deposition extends outside the southern and western boundaries of the region, though it is not clear whether the ABL is generally thickening to the south.

3:4:2:4 Faulted Isopach Waulsortian Unit (Waulsortian): Figure 13

The Waulsortian unit consists primarily of skeletal wackestones interpreted as carbonate buildups, and argillaceous wackestone with black shales interpreted as the interbank deposits. It is generally believed (Lees, 1964; Lees and Miller, 1985a; Lees et al. 1985) that the individual Waulsortian buildups are part of laterally extensive sheets generally separated by thin interbank intervals, and that the buildups initiate in relatively deep water (>250m) growing rapidly to reach the photic zone (at about 100m).

Calculated thicknesses for the Waulsortian unit have quite a high degree of local variability, reflecting the complex depositional pattern of this unit. The majority of the syndepositional faults are reasonably easy to identify -- the problem for creation of an isopach lies in assigning thicknesses to the regions bounded by the faults. In lieu of a model to control the Waulsortian unit thickness, regional thickness trends were used. The Waulsortian unit typical thickness is in the range of 150 to 250m, which is similar to the underlying ABL unit. But rather than one major depositional centre, the Waulsortian unit

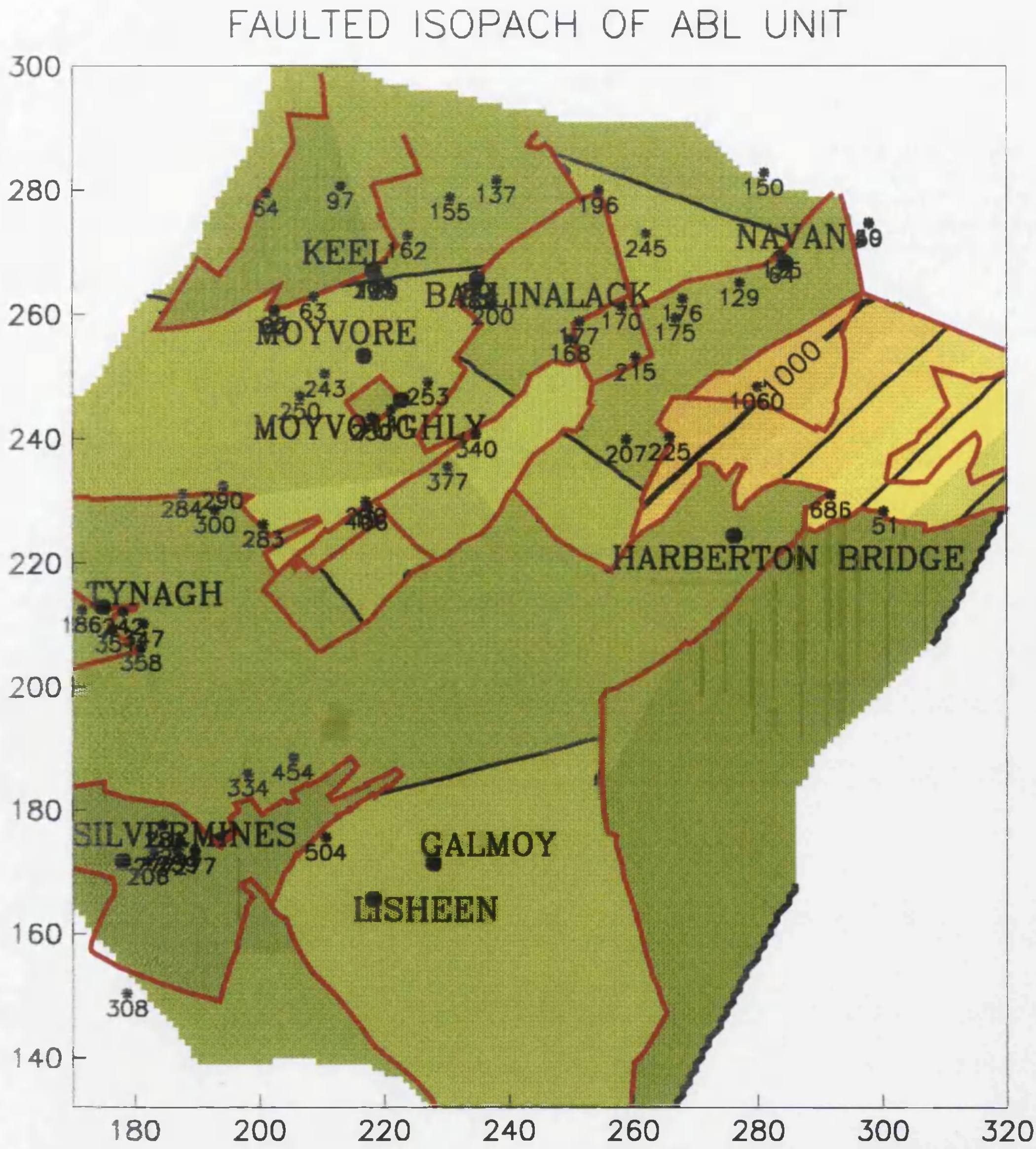


Figure 12. Faulted isopach of ABL unit with ABL time faults in red. Colours represent thickness as given in Figure 8. Deposit locations in black. Measured and estimated ABL thicknesses in black.

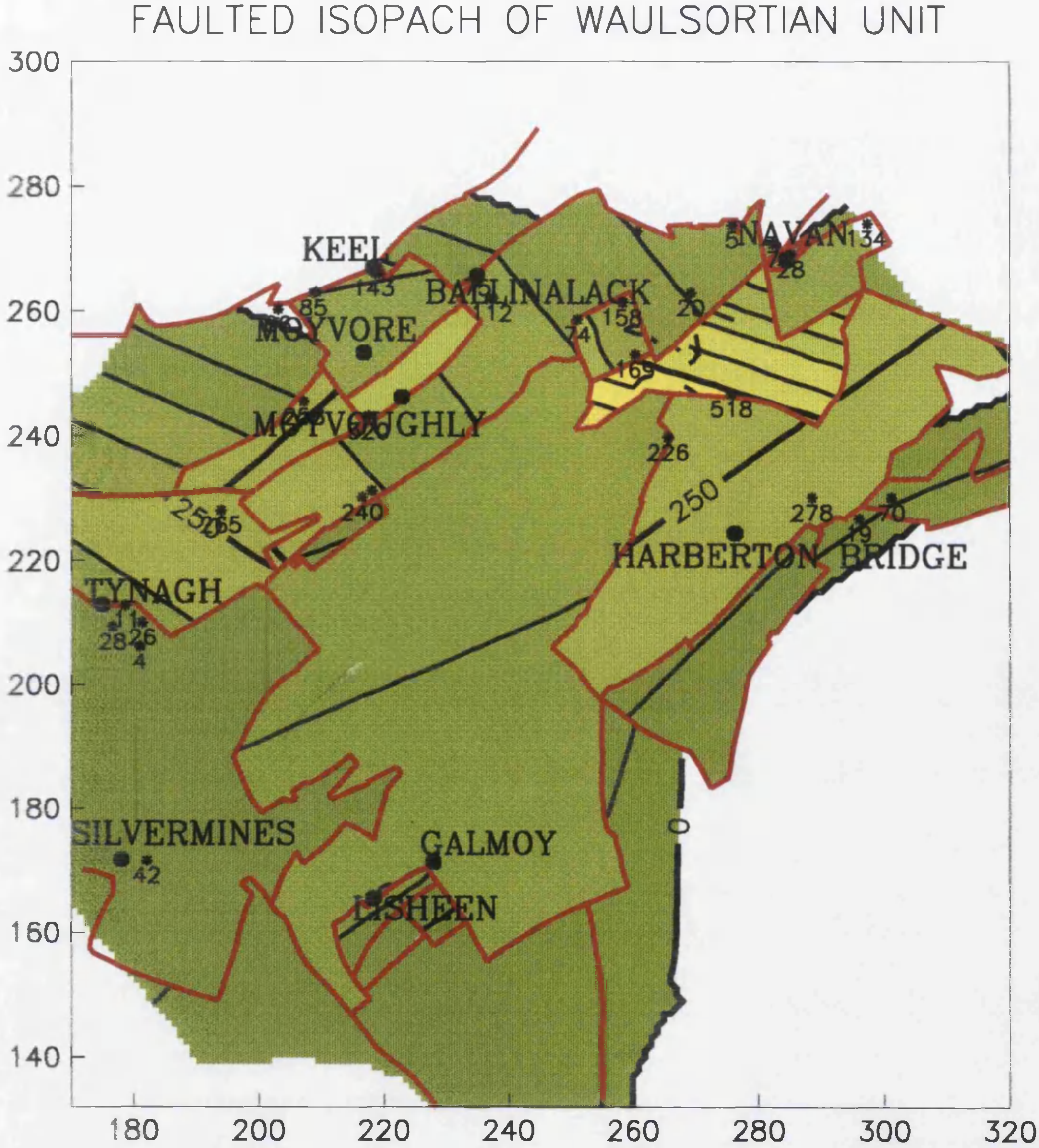


Figure 13. Faulted isopach of Waulsortian unit. Waulsortian time faults in red Colours represent thickness as given in Figure 8. Deposit locations in black Measured and estimated Waulsortian thicknesses in black

has two thicker regions (300m+) and several quite thin regions (50m or less). One of the thicker regions (Irish Grid reference 260,250), which reaches about 600m (compacted), is in a similar position to the Navan and ABL depositional centres.

There is considerably more identifiable synsedimentary faulting during Waulsortian unit deposition than during deposition of the underlying ABL unit. This increase in faulting suggests the start of the break-up of the shelf into several sub-basins; this breakup becomes more pronounced in the Chadian unit.

The northern margin of Waulsortian mudmound occurance is reported by Phillips and Sevastopulo (1986) to correspond approximately with the southern boundary of the Longford-Down massif, with deposition of limestone, shale and sandstone of Waulsortian age to the north. The subsurface and outcrop data available in this study suggest that the Waulsortian unit thins, and possibly locally disappears, towards the northern margin of the Midland Basin region. The eastern margin has a similar character to that of the underlying units, though the depositional edge in the southern part of this margin has moved westwards. Deposition again continues across the southern map boundary, though the Waulsortian unit does not show a general southward thickening.

3:4:2:5 Faulted Isopach Chadian Unit (Chadian)

The rocks contained within the Chadian unit are somewhat variable. Hitzman (1993) choses to use three subdivisions, pale grey massive limestones, oolite banks, and bioturbated black mudstones. He interprets these environments to be shallow marine, shelf margin, and lower ramp or basin, respectively (Fig. 19). Hitzman also identifies volcanic rocks of Chadian age, which are present in the centre of the study area.

There is very little regional thickness data available for the sedimentary rocks. Outcrop patterns suggest a uniformly thin unit (Hitzman, 1993), while Strogen et al. (1990) show Chadian age rocks to be about 100 m thick in the North Dublin Basin, and Pickard et al. (1992) describe rocks of this age, also in the Dublin Basin area, as a few metres to tens of metres thick. The Chadian unit has been assigned a uniform thickness of 100m in this study, and so no faulted isopach map has been generated.

Because of this lack of thickness information, synsedimentary faulting during deposition of the Chadian and overlying units is identified primarily by using changes in the environment of deposition (Figs. 19 -21 and Figs 24 -26). Never-the-less, because Hitzman (1993) divides the Chadian into shelf, shelf margin and basinal environments, it is possible to use the depth-of-deposition implications of these designations to identify potential active faults.

The Chadian is absent in large portions of the west of the area (and so is assigned a zero isopach thickness). In several cases, the overlying unit is present, so the areas of missing Chadian have been interpreted as relatively high blocks during Chadian times and their bounding faults as active during the Chadian. The faults near the transitions between the environments-of-deposition have also been interpreted as active. The volcanics are adjacent to synsedimentary faults.

The juxtaposition of Chadian oolites and dolomitised Waulsortian limestones suggests that dolomitising fluids penetrated downwards into the underlying Waulsortian. This occurrence has been taken here to imply fault conduits for the fluids, and so the appropriate faults have been interpreted as active during the Chadian.

3:4:2:6 Faulted Isopach Late Chadian through Brigantian (L+UBS): Figure 14

Separate environment-of-deposition maps are created for the LBS and UBS units, but lack of thickness information requires that they be isopached together. Hitzman (1993) has used shelf and basinal facies divisions for both the LBS and the UBS units. The shelf rocks of these units are primarily calcarenites with dark grey micrites and minor shales, and the basinal rocks are limestone turbidites and argillaceous calcsiltites with bioclastic calcarenites and calcareous shales.

Map outcrop patterns (Hitzman 1993) suggest that both units are fairly thin in the south and central parts of the region, but these units cover large areas in the north in which there is virtually no change in topography, and so the map patterns cannot help in estimating the units' thicknesses. Strogen et al. (1990) have identified a 1100m thick section of late Chadian through Brigantian age rocks from drillcore interpreted to extend across part of the Dublin Basin, assigning approximately 60% of this thickness to the late Chadian through Arundian age rocks and 40% to the Holkerian through Brigantian age rocks. The limits of the thick northern or northeastern section of the L+UBS unit have been chosen (lacking any better information) so as to make the reconstructed geometry agree with the outcrop maps. The remainder of the unit has been assigned a thickness of 200m, which is in approximate agreement with the outcrop patterns in the southern and central areas.

The environment-of-deposition maps for both units (Figs. 20,and 21, and Figs 25 and 26) have been used, together with missing section, to identify syn-sedimentary faults. The LBS unit is missing in only a few areas, the major interpreted absence being in the Tynagh Basin (approx. Irish Grid reference (175,210) to (200, 230)), where, in outcrop, the younger UBS unit rocks overlies Chadian or older rocks. While the UBS may have onlapped further than did the underlying LBS, the map pattern has tentatively been interpreted as representing missing LBS in the main part of the Tynagh Basin.

3:4:3 Isopach Grid Generation and Verification

Each synsedimentary fault set and its thickness contours are digitised and gridded, again using convergent gridding at a 1km spacing. The process of isopach generation is

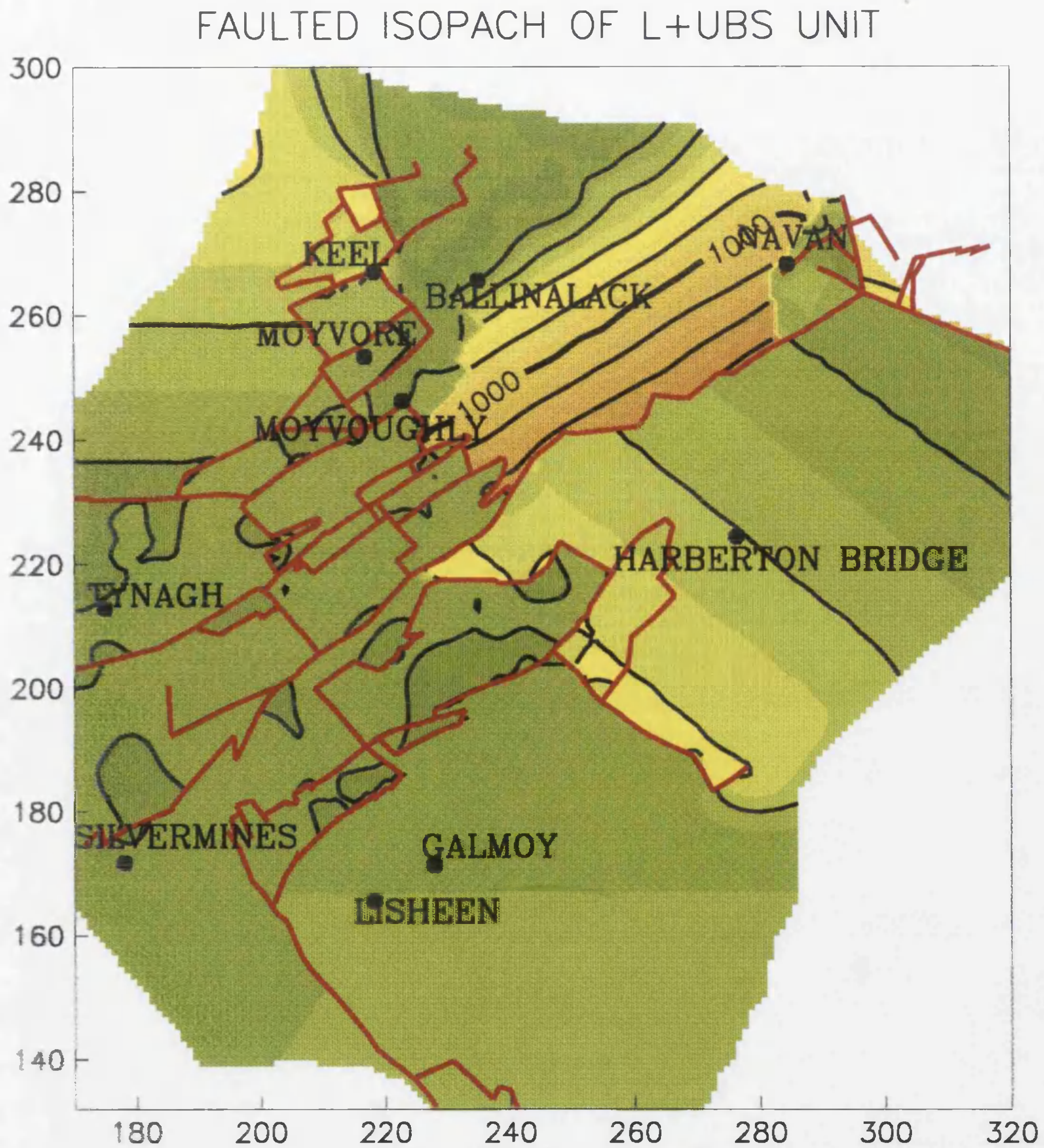


Figure 14. Faulted isopach of L+UBS unit with L+UBS faults in red. Colours represent thickness as given in Figure 8. Deposit locations in black.

done iteratively: completion of each new (younger) isopach prompting a reinvestigation of the older isopachs. In practice, each new faulted isopach is sequentially added to the lower units, starting with the top-basement, to create grids of the present-day top surface of each unit, and this top surface is tested against the available surface and subsurface data.

As an additional check, each unit is decompacted to its' thickness at deposition, and the reasonableness of the interpretation confirmed. However, the fully compacted, not the decompacted, thicknesses are used in the reconstruction. Decompaction is essential for a proper basin restoration, and so is described in Section 5 of this Chapter.

3:4:4 Reconstructed Geometry

Once a satisfactory top-basement grid and faulted isopach grids are prepared, the basin reconstruction is little more than manipulation of grids using CPS3™. The first step is to add the ORS isopach grid to the top-basement grid, such that the resulting grid represents the elevation of the top of the ORS. The younger isopachs are sequentially added to their underlying elevation grid. Each step in the reassembly of the (uneroded) present-day basin geometry is checked against subsurface and surface data. The resulting contours of these grids are shown at a scale of 1:350,000 in Appendix B (Figs B2 - B7).

3:5 SECTION 5: RESTORATION TO EARLY CARBONIFEROUS CONFIGURATIONS

This section covers the restoration of the reconstructed Midland Basin region to its geometry at several stages of development, emphasising the role that faulting plays in basin development. The restoration is done by sequentially subtracting the youngest unit, and correcting the properties (such as thickness) of the underlying units to conditions (such as depth of burial) appropriate to the time. The maps that illustrate the restorations are used extensively in Chapter 4, and the reader is referred to that chapter.

The end of deposition of Brigantian rocks is chosen as the latest time for which a restoration is performed: this is the same choice as was made for the reconstruction. The other stages used in the restorations are: end Chadian deposition; end Waulsortian deposition; end ABL deposition; end Navan deposition; and end ORS deposition. In each case the restoration is done for the basin geometry at the end of the period in question.

As explained in Section 1, the original plan was to display the sequential basin geometries using the 3-D visualisation tool SGM™, to add isochronous surfaces to the displays, and then to redisplay "hanging" the display on time lines. As this approach has proven unachievable because of hardware problems that developed during the project, the basin is restored to the "times" given above.

The restoration is performed by grid manipulation within CPS3^{TM}. It starts with the thickness isopachs for all units (generated in the reconstruction) decompacted to their end-UBS (end -Brigantian) thickness, attatching them underneath the Brigantian palaeo-surface (see below). This produces the basin geometry, faults, and top-basement depth at the end of the Brigantian. The L+UBS (late Chadian to Brigantian) rocks are then removed, and the remainder of the sequence (in the appropriate compactive state) attached beneath the end-Chadian palaeo-surface. This process is continued through to the ORS, producing a series of basin configurations (Figures 28 and 30 - 49, in Chapter 4).

In addition to requiring grids of the faulted isopachs, the restoration requires the generation of paleo-surface maps and environment-of-deposition maps for each unit. It also requires that the sedimentary rocks be decompacted to their porosity (and hence thickness) at the end of deposition of each unit. Both the decompaction and the environment-of-deposition maps have already been referred to in the basin reconstruction sections of this chapter but as their primary use is in the basin restoration, they are described below.

3:5:1 Creating the Environment-of-Deposition Maps

Environment-of-deposition maps are required to control both the development of the sedimentary rock isopachs and the generation of the palaeo-surface grids. In addition they are used in the assessment of basin shape and development, and so in the derivation of a general picture of the structural evolution of the region. Two types of maps are created: rock type distribution maps, showing simple subdivisions of rock types (Figs 15 - 21); and depth-of-deposition maps, which divide the deposits into sub-areal, approximately sealevel, shelf and basinal (Figs 22-26). Both types of map also display any areas of missing section. These maps include the traces of the appropriate active faults. The faults are included so that the possible influence of faulting on sedimentation can be evaluated.

The first step in creating a rock type distribution map of a particular sedimentary unit is to identify the areas in which that unit is present, the limits to those areas, and the type and distribution of rock types. This is not straightforward, as it is not always clear if the absence of the top of a unit in the wellbore data is a result of the unit being absent, or of the lithological change being too subtle to confidently pick a top. Also the available data does not specify facies. There are a number of other sources of lithofacies distribution information for the early Carboniferous (see Phillips and Sevastopulo 1986; Strogen et al. 1990). This material provides a good general picture, and, when combined with the level of local detail incorporated in the 1:100,000 Bedrock Geological Map of the Carboniferous of

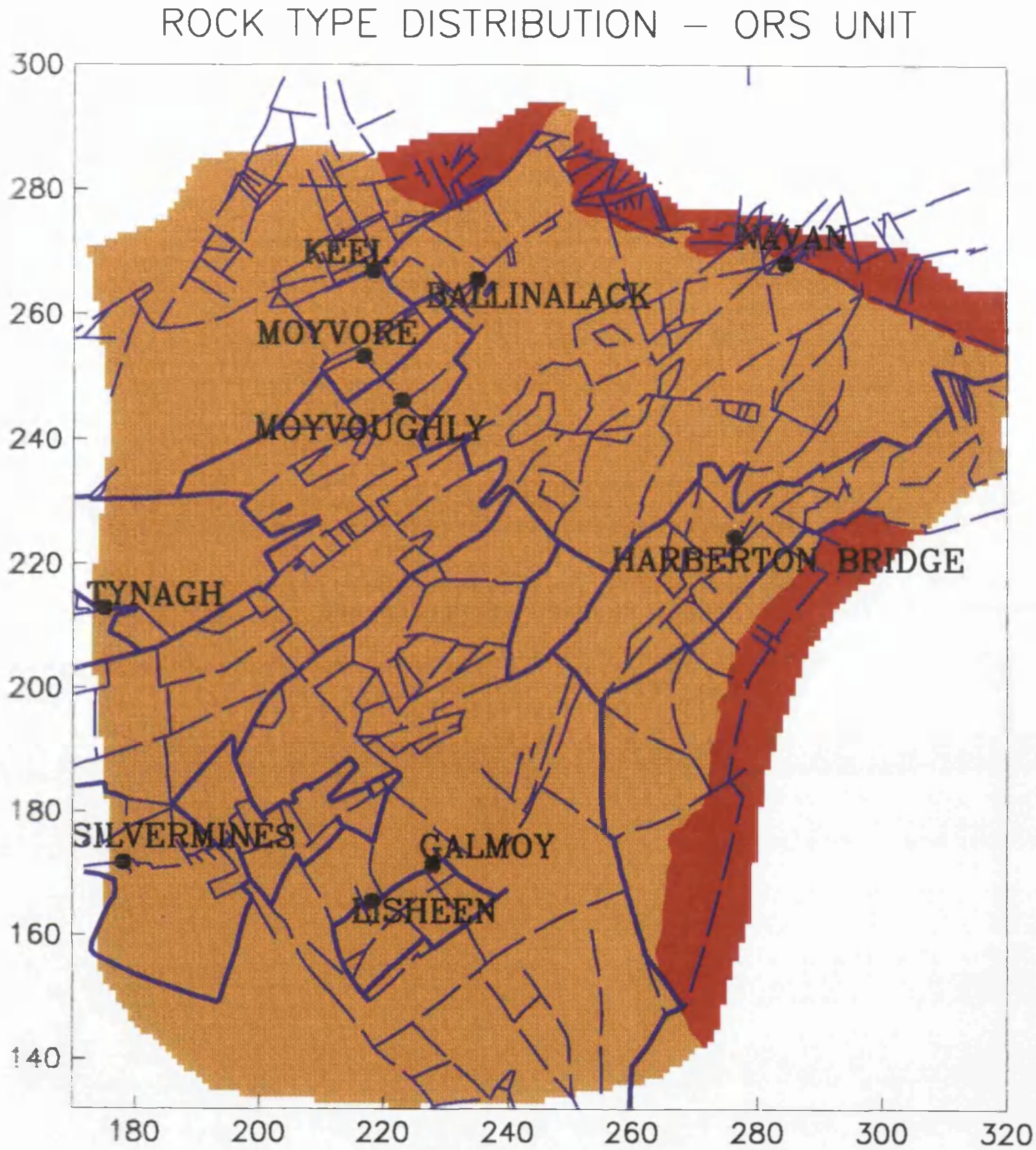


Figure 15. Rock Types for the ORS unit.
Orange = Sandstone, Red = Erosion / Non-deposition.
Heavy lines = ORS faults; Dashed lines = Reconstructed Top-Basement faults

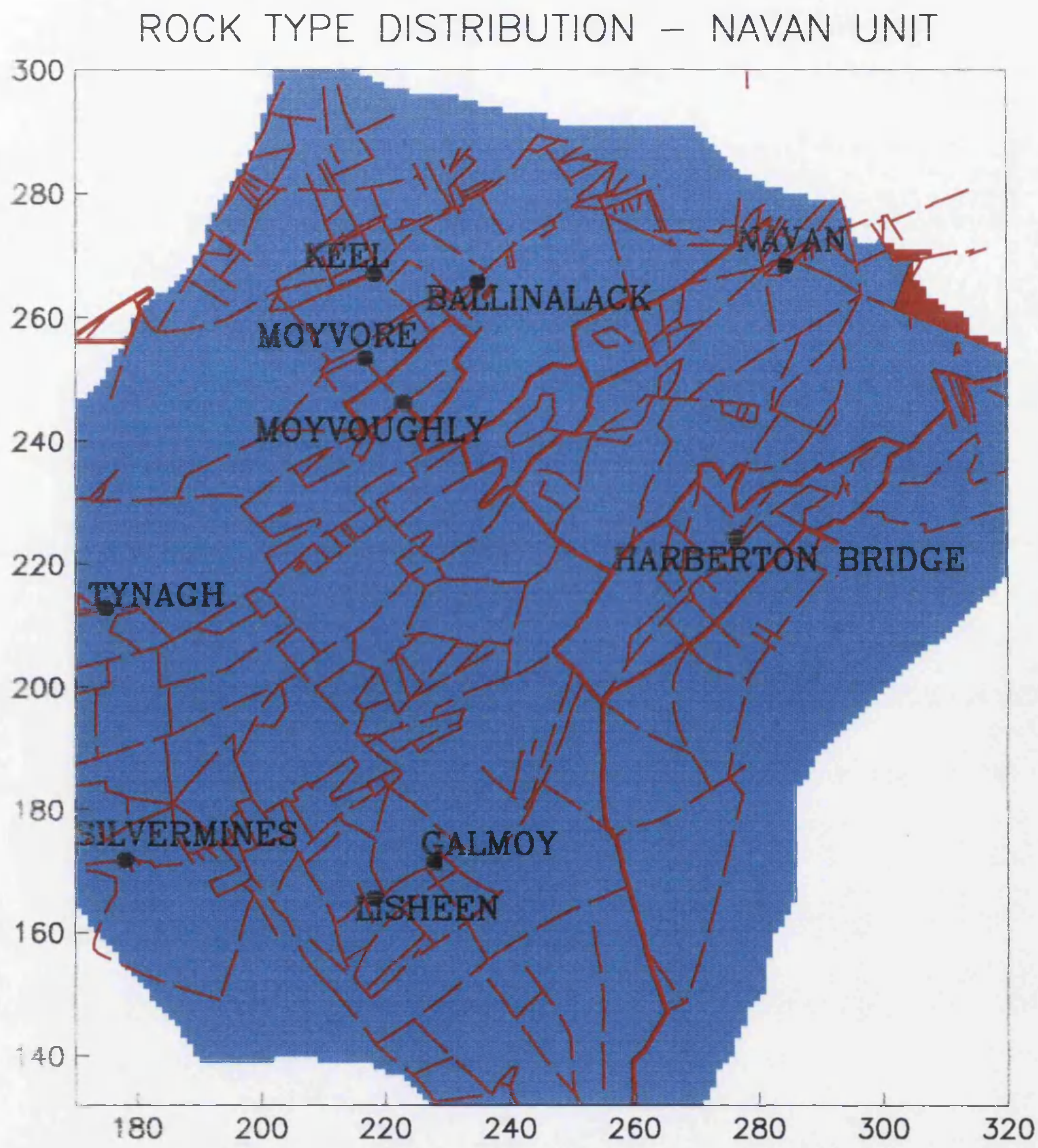


Figure 16. Rock Types for the Navan unit.
Blue = Calcareous Rocks, Red = Erosion / Non-deposition.
Heavy lines = Navan faults; Dashed lines = Reconstructed Top-Basement faults

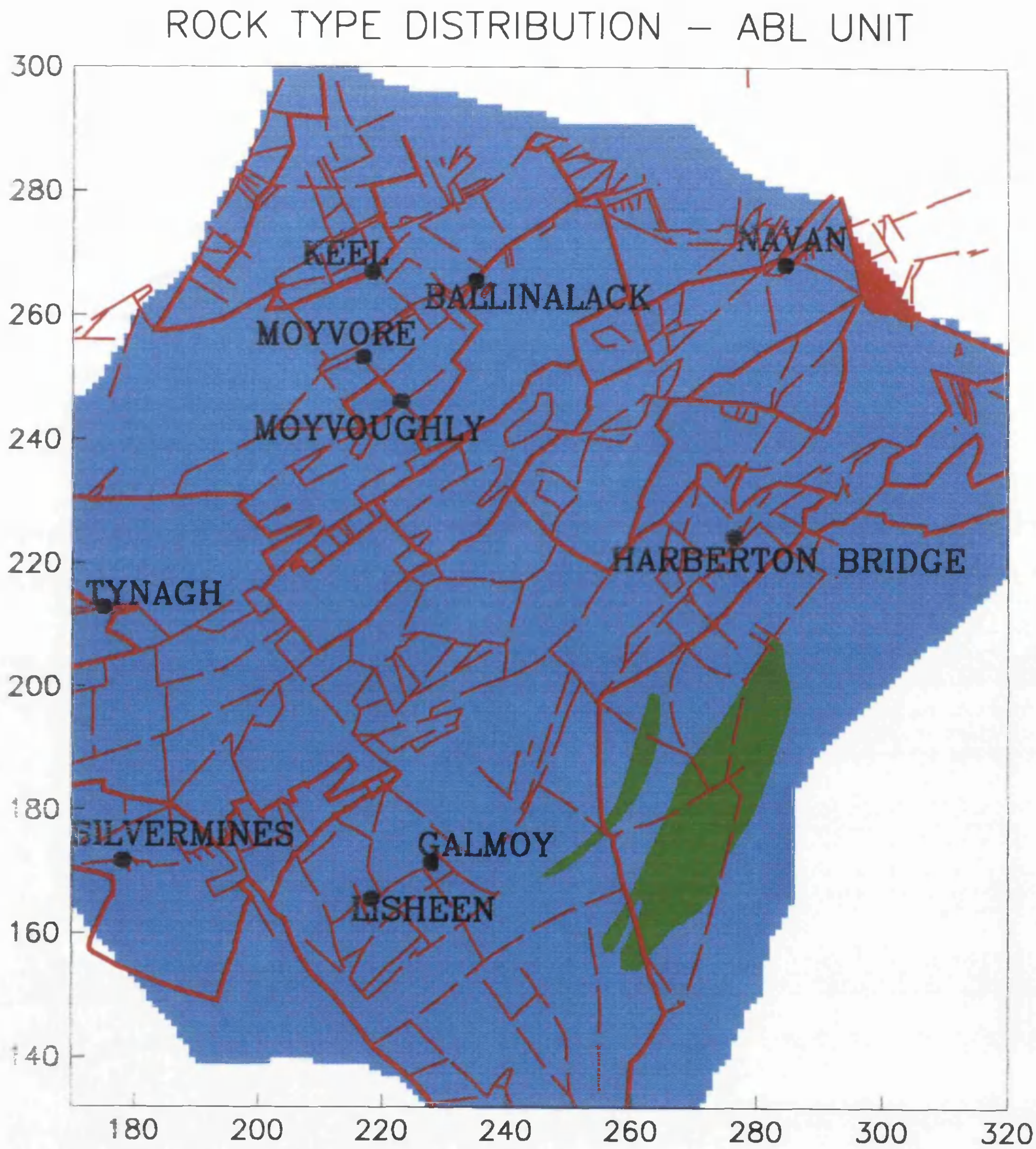


Figure 17. Rock Types for ABL unit.
Light Blue = Calcareous Rocks; Red = Erosion / Non-deposition.
Green = Dolomitised Rocks.
Heavy lines = ABL faults; Dashed lines = Reconstructed Top-Basement faults

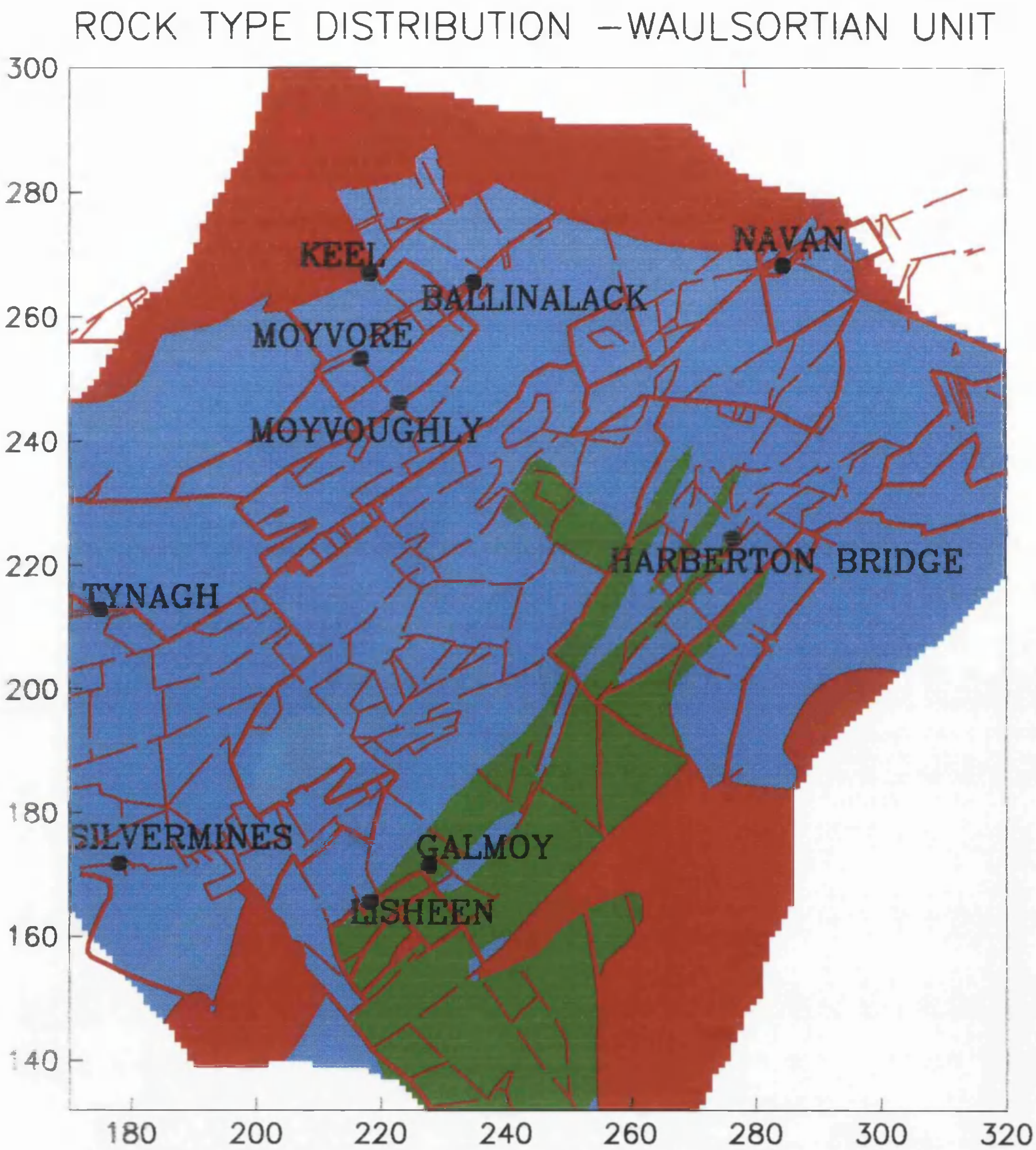


Figure 18. Rock Types for Waulsortian unit.
Light Blue = Calcareous Rocks; Green = Dolomitised Rocks.
Red = Erosion / Non-deposition.
Heavy lines = Waulsortian faults; Dashed lines = Reconstructed Top-Basement faults

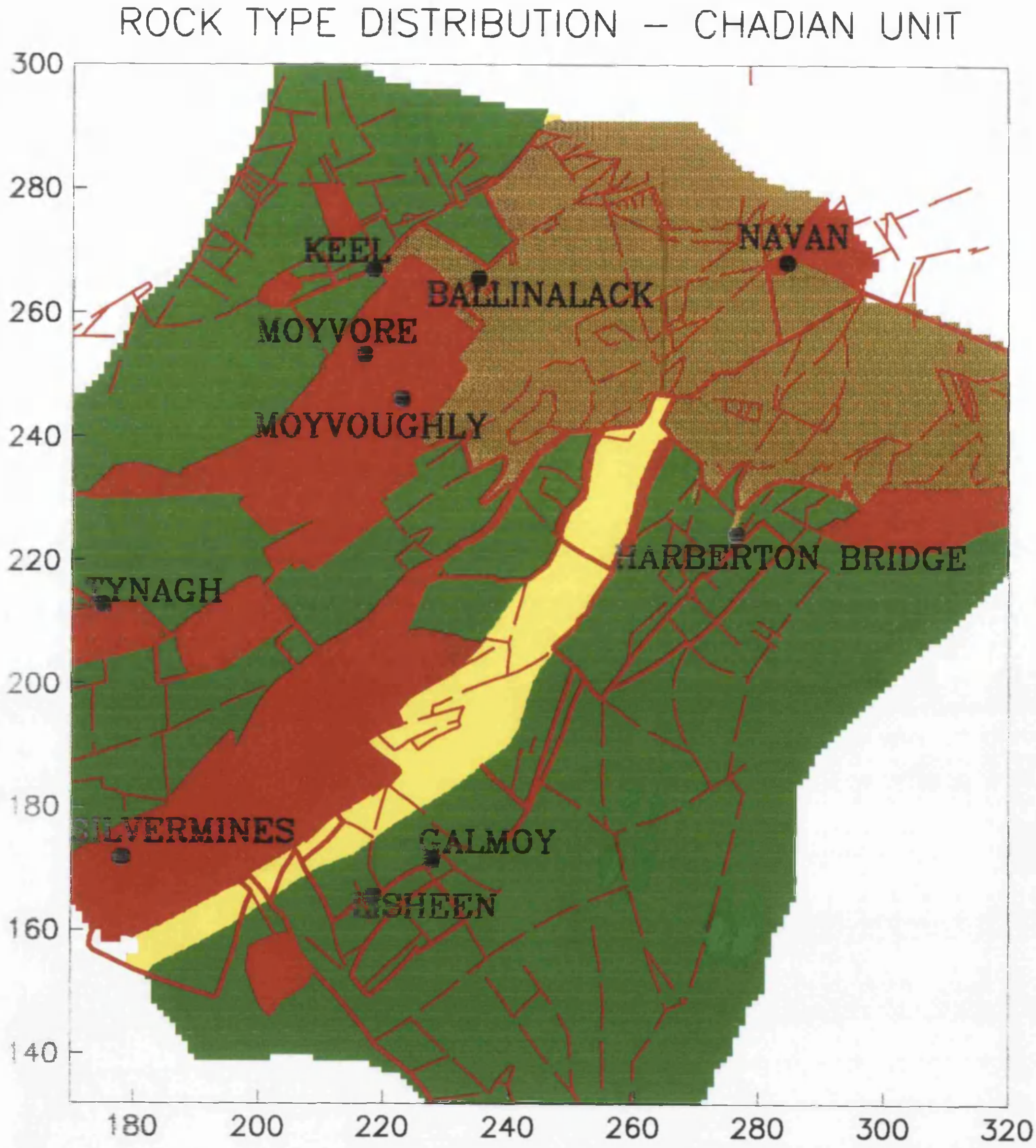


Figure 19. Rock Types for the Chadian unit.
Yellow = Oolitic Rocks; Red = Erosion / Non-deposition,
Green = Shelf Calcareous & Argillaceous Rocks
Light Brown = Basinal Calcareous & Argillaceous Rocks
Heavy lines = Chadian faults; Dashed lines = Reconstructed Top-Basement faults

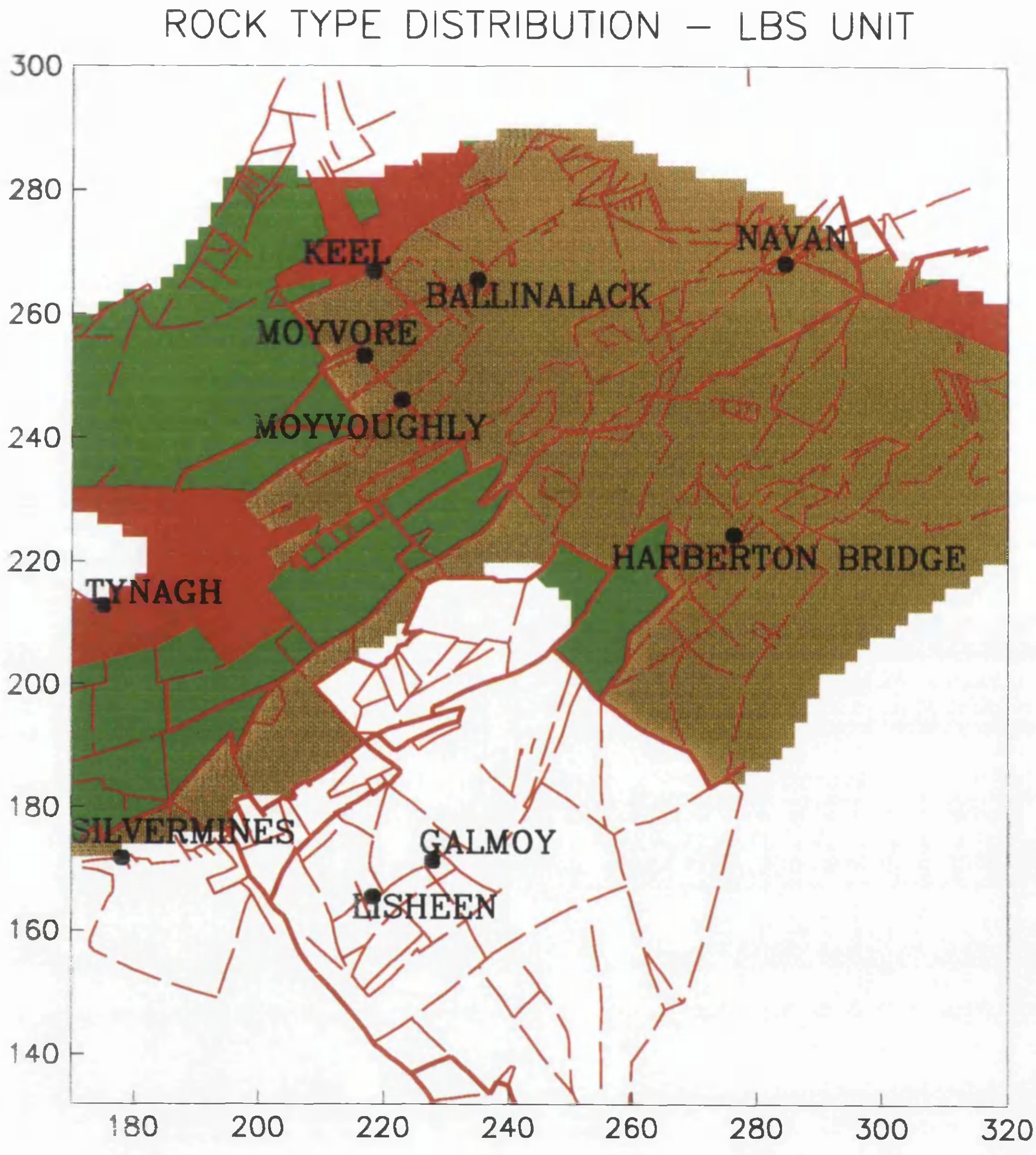


Figure 20. Rock Types for the LBS unit.
Green = Shelf Calcareous Rocks; Red = Erosion / Non-deposition.
Brown = Basinal Calcareous & Argillaceous Rocks
Heavy lines = U+LBS faults; Dashed lines = Reconstructed Top-Basement faults

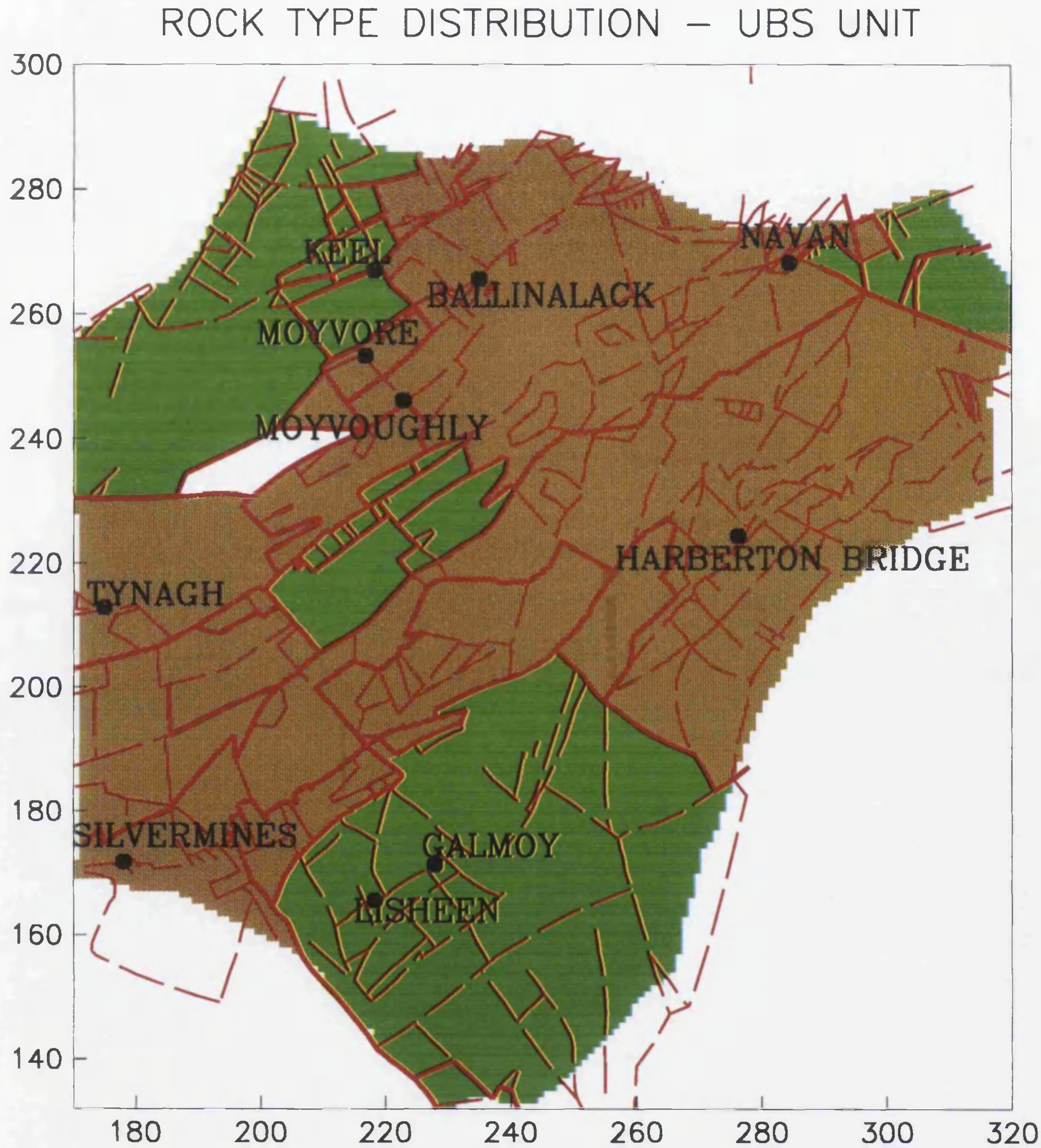


Figure 21. Rock Types for the UBS unit.
Green = Shelf Calcareous Rocks; Brown = Basinal Calcareous & Argillaceous Rocks
Heavy lines = U+LBS faults; Dashed lines = Reconstructed Top-Basement faults

Central Ireland (Hitzman, 1992a) allows generation of the rock type distribution maps (Figs 15 - 21).

The primary data used to generate the lithofacies maps for each of the units of the reconstruction and restoration is compiled using the maps of the 1:100,000 Bedrock Geological Map of the Carboniferous of Central Ireland as a base. These maps are divided into areas with the same stratigraphic units present, and a coloured stratigraphic section showing units present is generated and attatched in the appropriate place on the map (Fig. 27). Approximately 150 stratigraphic sections are used. This display is then used, together with a lithofacies interpretation from the published sources given above, to construct interpretations of the present-day map distribution of each unit, tincluding any lithofacies variations which could be discerned. The depth-of-deposition maps (Figs 22-26) are created by interpreting the facies in terms of the likely elevation or depth of the water/air to rock interface. Four depth divisions are used: above sea-level; sea-level, shelf; and basinal.

The geological significance of the environment-of-deposition maps is discussed in Chapter 4. But, very generally, the interpretation begins with a somewhat faulted, emerged, region which is subsequently submerged, becoming a shallow shelf deepening southward. This shelf setting becomes disrupted by faulting, losing its obvious southward tilt, and develops a major depositional centre in the northeast, plus several higher regions, primarily in the east-southeast, the far northwest and parts of the southwest.

3:5:2 Creating the Palaeo-Surface Maps

The paleo-surface maps are created using the depth-of-deposition maps and the appropriate fault sets for each restoration, and, lacking any more detailed information, are intended to be only very general approximations of the paleo-topography or paleo-bathymetry of the region at the end of each time period.

For the purposes of this exercise, the sub-areal regions are assigned a 10m elevation, the shelf regions are assumed to be at 10m subsea, and the basinal regions at 100m subsea. Where changes in elevation correspond with faults, the faults are designated as the boundaries to the areas. Where there are no apparent structural features, a gradual change is invoked. Grids of these palaeo-surfaces are generated by digitising a combination of points of uniform depth or elevation within each area, and contours in sloping areas. The resulting contoured palaeo-surface maps are shown in figures 22 - 26. No paleo-surface maps are created for the ORS unit as it is fully emerged, and it is treated as if it is at a uniform height of 10 m above sea level, or for the ABL unit, which is not eroded within the limits of the gridded area, and so is treated as a shelf at a uniform depth of 10 m.

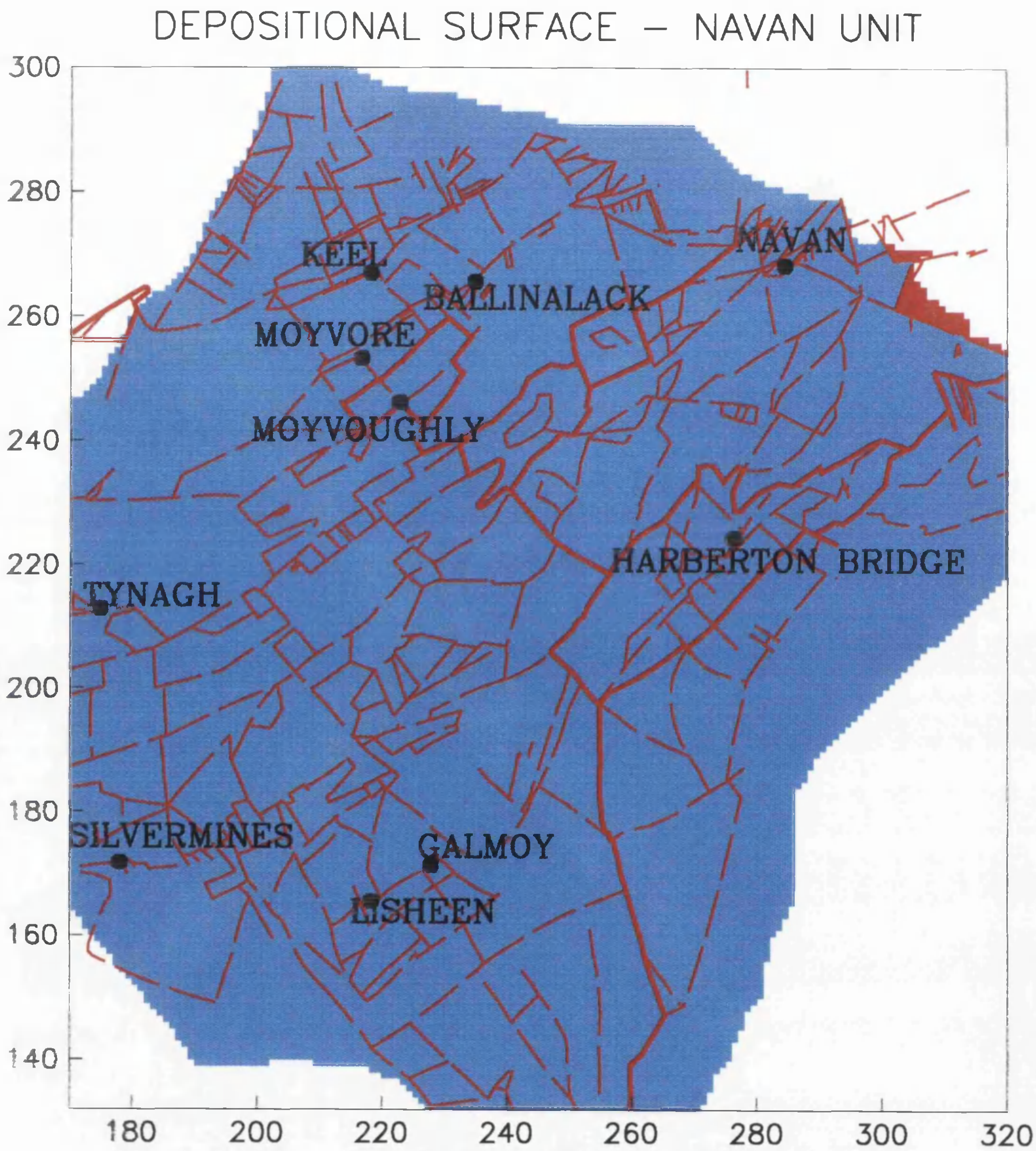


Figure 22. Depth of Depositional Surface for the Navan unit.
Light Blue = Shallow Water; Red = Above Sealevel.
Heavy lines = Navan faults; Dashed lines = Reconstructed Top-Basement faults

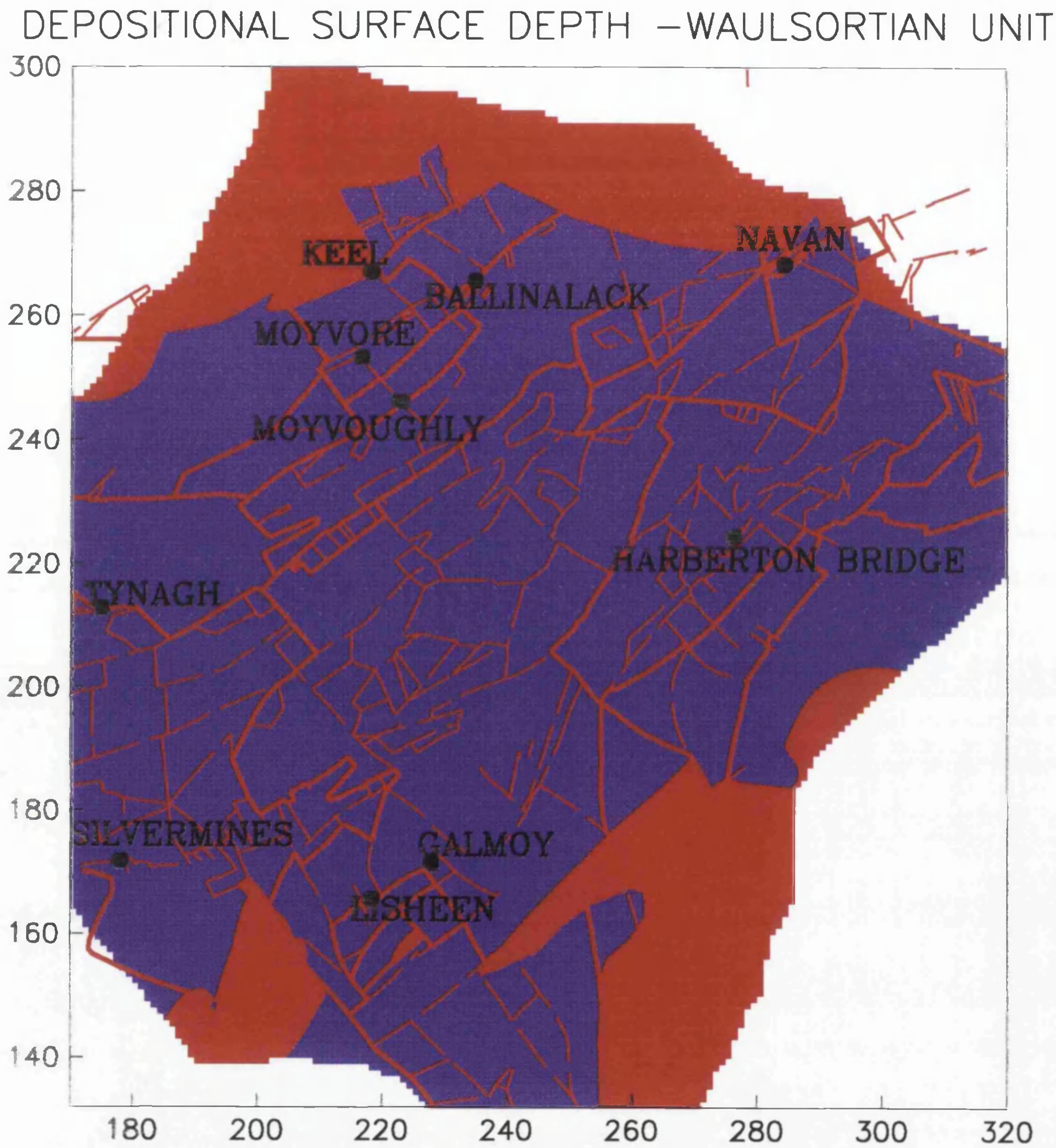


Figure 23. Depth of Depositional Surface for the Waulsortian unit.
Dark Blue = Deep Water; Red = Above Sealevel.
Heavy lines = Waulsortian faults; Dashed lines = Reconstructed Top-Basement faults

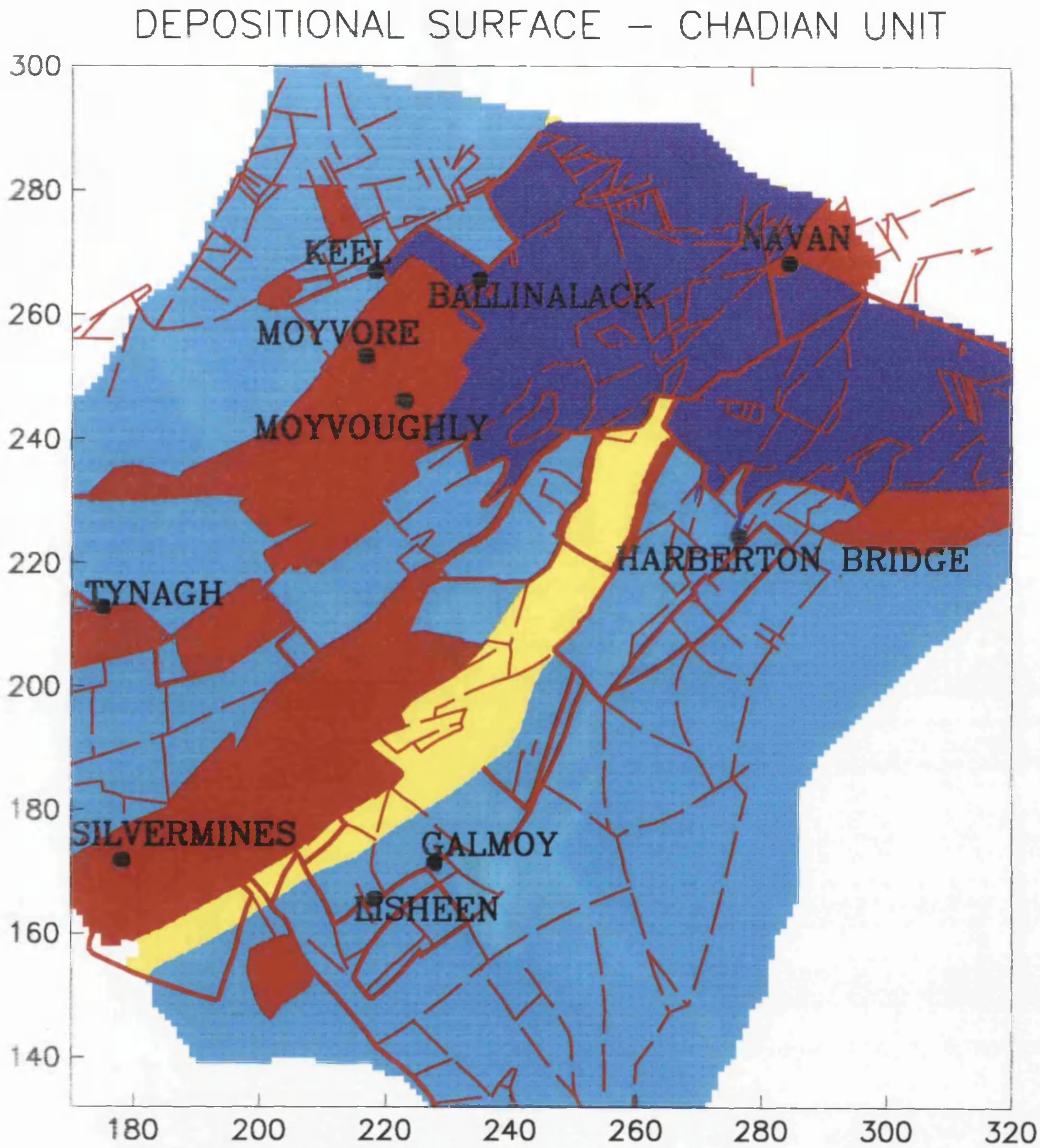


Figure 24. Depth of Depositional Surface for the Chadian unit.
Light Blue = Shallow Water; Dark Blue = Deep Water;
Yellow = At Sealevel; Red = Above Sealevel.
Heavy lines = Chadian faults; Dashed lines = Reconstructed Top-Basement faults

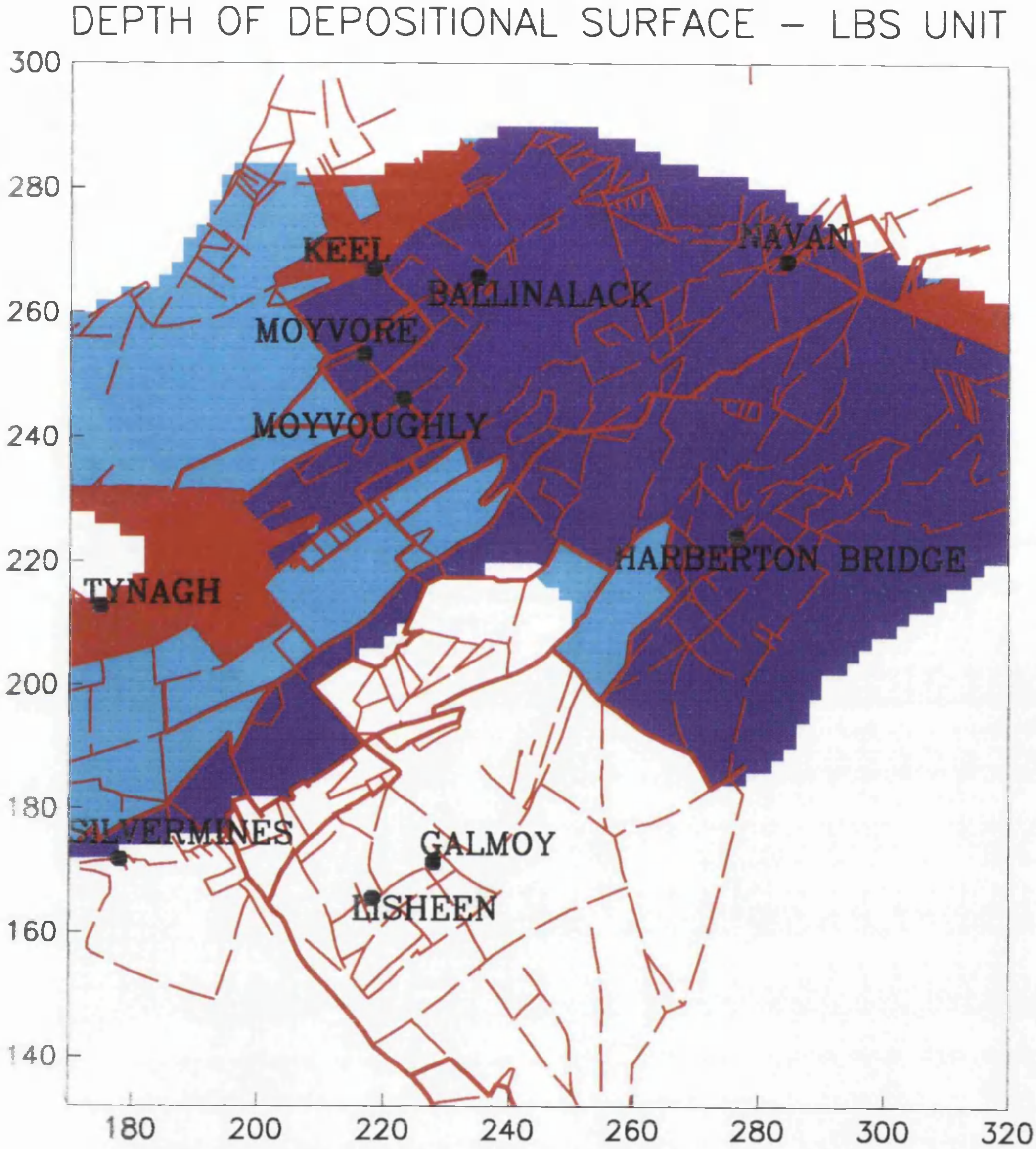


Figure 25. Depth of Depositional Surface for the LBS unit.
Light Blue = Shallow Water; Dark Blue = Deep Water
Red = Above Sealevel.
Heavy lines = U+LBS faults; Dashed lines = Reconstructed Top-Basement faults

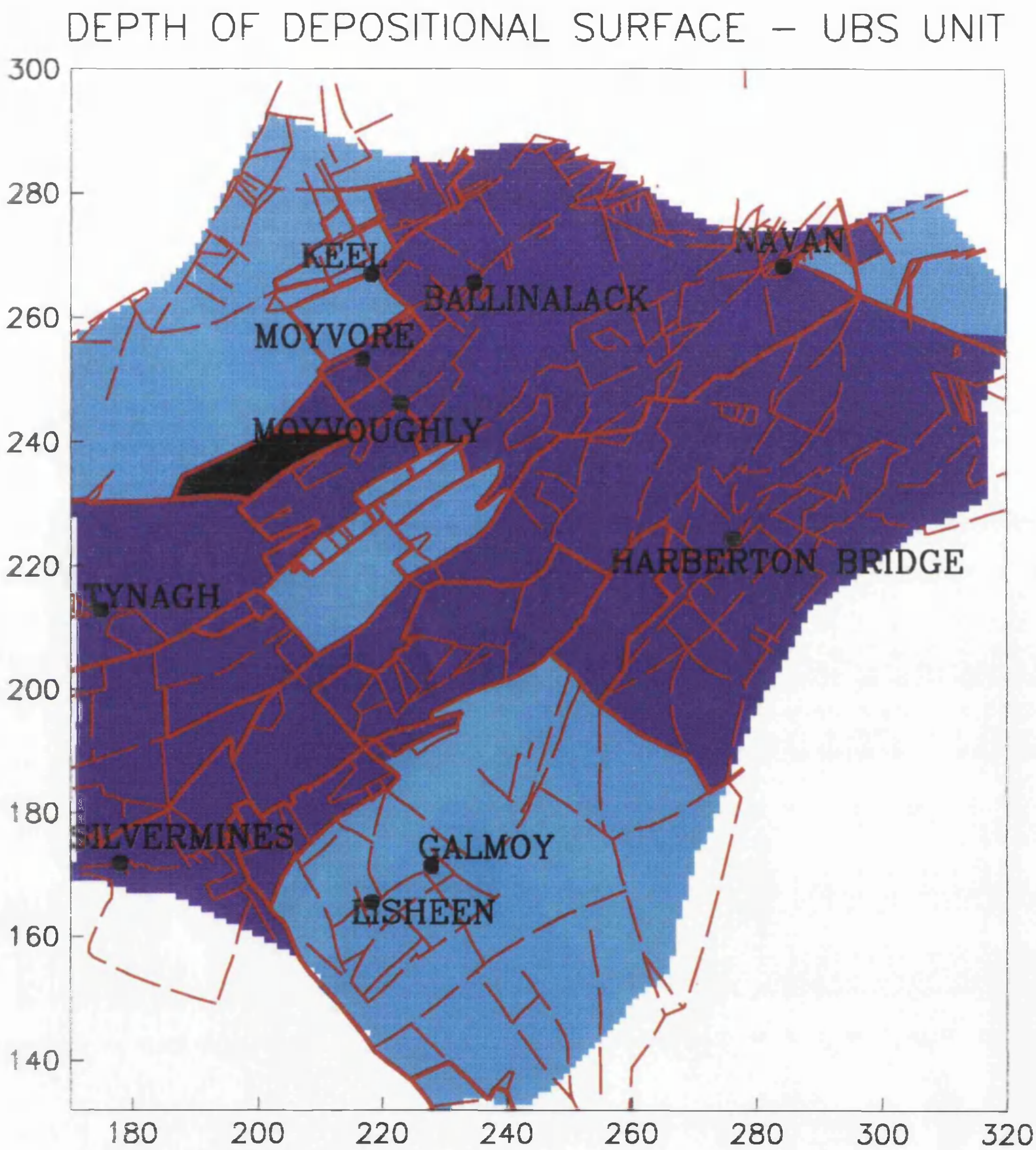


Figure 26. Depth of Depositional Surface for the UBS unit.
Light Blue = Shallow Water; Dark Blue = Deep Water
Heavy lines = U+LBS faults; Dashed lines = Reconstructed Top-Basement faults

3:5:3 Decompaction of the Basinal Units

The present-day thicknesses of the Midland Basin region's sedimentary rocks include a considerable element of compaction, but the restorations should incorporate only the degrees of compaction which correspond to each restoration. Compaction is primarily a function of depth of burial (and is generally irreversible), and so the the present-day compaction of the basinal sedimentary rocks is considereed to be a maximum. The decompactions are performed using Basinmod™(see below), calculating the state of compaction appropriate to each of the restorations. The present-day (reconstructed) isopachs are taken as a starting point for the calculations. Their state of compaction is a result of all geological depositional and erosional events, not just those to the end of the Brigantian (L+UBS unit). To account for post-Carboniferous events, a Permian through Triassic accumulation of 300m of section -- which was retained until 60 Ma -- is assumed. The lack of any significant deposition until about Cretaceous times, followed by a Cretaceous erosional event and little or no subsequent deposition, agrees with Cope et. al (1992).

The decompactions are performed using BasinMod™. BasinMod™ is a commercial one- and two-dimensional basin modelling software package developed by Platte River Associates Inc.. Both 1D and 2D packages have a common mathematical foundation, comprising a burial history and fluid flow module, a heat transfer module, and a hydrocarbon generation and expulsion module. Only the 1D burial history and fluid flow, and the heat transfer modules have been used in this study.

Both the 1D and 2D models use a coupled fluid-flow and compaction methodology, and are based on Darcy's Law (see De Marsily, 1986) and the concept of effective stress (Handin et. al., 1963). The formulation allows simulation of the way in which: porosity; permeability; fluid viscosity; density; and the fluid flux; vary with time. This formulation is identical to that of Bethke (1985) and Lerche (1990).

Basinmod™ is used to calculate, for each restoration, the state of compaction for each sedimentary unit. A stratigraphic column, including any hiatuses or depositional and erosional events and the estimated porosity at deposition for each rock type, is specified, and a burial history is calculated for each stratigraphic section. BasinMod™ calculates the amount of compaction (expressed as a change in thickness) that each unit of a stratigraphic section has undergone at times which correspond with the end of each restoration.

The thickness calculated using BasinMod™ is normalised to the isopach thickness for each unit of each restoration. Note that the thicknesses calculated using BasinMod™ are always larger than the isopach thicknesses. CPS3™ is then used to multiply the (still fully compacted) isopachs by the normalised thickness, so producing (partly) decompacted isopachs for each restoration.

However, as both the thickness of the unit and the thickness of its overburden can be quite variable across the region, the percentage thickness change due to compaction can also be vary. BasinMod^{TM} is used to investigate how this number varies across each unit.

The decompactions are performed for a number of locations throughout the region. These locations are chosen to represent the range of conditions, such that the effects of decompaction on the thickest and thinnest, and the deepest and shallowest, parts of all units are assessed. The results are used to establish the sensitivity of the percentage compaction to the variations in the units' thickness and depth of burial.

Only the Navan and ABL units have a variable degree of compaction after they are buried by younger units. For the remaining units the percentage compaction calculated for each restoration varies across the area by only 1 or 2%. This variation is insignificant and the corrections are made using a single normalisation value.

The variation in the normalisation value is mapped for the Navan and ABL units. The values are plotted at each location, and are contoured, taking into account variations in unitb thickness and depth of burial. The resulting contours are then digitised and gridded. The Navan and the ABL units are then decompacted by dividing the (fully compacted) isopach grids by the grids of the normalised value contours. The resulting (partially) decompacted unit thicknesses are then used to build the restorations.

3:5:4 Generating The Restored Geometries

Once the basinal sequences have been decompacted and the palaeo-surfaces generated, the production of the restorations is little more than a series of operations on grids using CPS3^{TM}. The decompacted thickness isopachs for each unit (through the L+UBS) are attatched underneath the UBS unit's palaeo-surface. This results in the basin geometry (including faults) faults at the end of the Brigantian. The U+LBS (late Chadian to Brigantian) rocks are then removed, and the remainder of the sequence is attached beneath the end-Chadian palaeo-surface. This process is continued until only the ORS unit and its underlying basement remain. These reconstructed geometries are displayed Chapter 4, Figures 28 and 30 - 49, where they are described, and their geological implications discussed.

This sequence of restorations is intended to provide only a general view of the evolution of the basin, and so small-scale inaccuracies are inevitable. Particularly, the basement surface does not everywhere remain planar in the restorations. This is in part due to the (unavoidable) use of very generalised palaeo-surface geometries. Also, the position of faults cannot be represented accurately by the grids: fault traces are digitised and the digitised lines can be plotted, but the grid does not contain fault planes, and it represents the change in elevation across the fault at only a one kilometer (cell size) resolution. Minor differences in fault digitisation can move the elevation change across a fault by one or two kilometers, producing anomolous areas adjacent to some faults.

3:6 SECTION 6: VALUE OF THE RECONSTRUCTION AND RESTORATION

The basin reconstruction is useful to this project in two ways: it provides an exploration tool in the form of a fault-oriented geological framework in which the position of ore deposits can be viewed; and it is required for the basin reconstruction. The basin restorations are useful both as a framework within which to view both the basin evolution and the position of deposits at their time of formation, and as input to the fluid- and heat-flow modelling. The fluid-flow modelling attempts to simulate flow systems that could have been active in the basin, and the fractured basement, of southern and central Ireland in the Carboniferous: those systems that could have delivered hot mineralised fluids to the sites of ore deposition are of particular interest. The geometry of the reconstruction and restoration, the geological story they tell, and the inferences that can be made from this story are discussed in the following chapter (Chapter 4). The fluid- and heat-flow modelling, and its results, are discussed in Chapter 5.

CHAPTER 4

THE GEOLOGICAL SIGNIFICANCE OF THE RECONSTRUCTION AND RESTORATIONS OF THE MIDLAND BASIN REGION

The previous chapter emphasises the techniques and information used in creating the reconstructed and restored geometries. This chapter focuses on the geological discoveries resulting from that process, and it considers their consequences, both in terms of the geological evolution of the region and in defining some of the conditions under which mineralisation took place.

The restoration and reconstruction are addressed in logical order (rather than in the order in which they were created) beginning with a description of the basin development as revealed by environment-of-deposition maps and by the restored basin geometries. This is followed by a description of the reconstructed (present-day) geometry and the information which it provides. The improved understanding of the general geological aspects of the region is then addressed, and this is followed by an assessment of the positions of some of the mineral deposits.

4:1 BASIN DEVELOPMENT

The evolving shape of the region is revealed quite well by the restorations. However, even though the environment-of-deposition maps are an integral part the restorations, their rock type and depth-of-deposition information is not displayed in the restorations. Therefore the depositonal-setting maps are treated first, and are followed by a description of the restorations.

4:1:1 Environment-of-Deposition Maps

Figures 15 - 21 show the distribution of rock types, and Figures 22- 26 the environments in which the sediments are deposited -- expressed in terms of the depth range within which deposition occurred. The time units defined in the previous chapter are used here, and the description begins with the oldest of these units.

The ORS map rock type distribution map (Fig.15) shows an emergent region of fluvial and and alluvial deposition that covers most of the region. The ORS unit continues across the southern and western boundaries of the region, but is bounded by non-deposition or erosion towards its northern and eastern margins. This distribution pattern is replaced in Navan times by deposition on a shallow shelf of a mixture of clastics and carbonates (Figs 16 and 22). Possible emergence and erosion or non-deposition are confined to the far northeastern corner . In the time period represented by the ABL unit there is a general increase in the carbonate component, but otherwise little fundamental change in the depositional setting (Fig.17). Deposition in ABL times again appears to have been predominantly in shallow water.

By the time represented by the Waulsortian restoration, carbonates dominate the lithofacies, and they remain dominant during the remainder of the Early Carboniferous (Figs 18 and 23). The Waulsortian mudmounds developed in water depths between the photic zone and storm wave base, at depths up to about 100m subsea (Wright and Faulkner, 1990; Lees et al, 1985; Lees and Miller, 1985), implying generally clear water conditions with very little clastic sediment supply. Waulsortian deposition continues to the north of the study region (Phillips and Sevastopulo, 1986), but locally dies out towards the northern margin of this region. It is not clear if this indicates: (1) non-deposition resulting from shallowing; (2) deepening to below the depth at which the mudmounds could develop (about 250 m); or (3) a result of pre end-Chadian erosion.

The Chadian maps (Figs19 and 24) show the first clearly "basinal" sediments (i.e. deep water muds); these occur in the northeast of the Midland Basin region, in the developing Dublin Basin (Fig 1). The maps also show areas that were close to sea-level, since they developed oolite banks: some of the oolite banks have adjacent areas of missing section which represent either non-deposition or early erosion of shallow-water deposits. Most, but not all, of the areas where the Chadian rocks are missing are overlain by latest Chadian to Arundian (LBS unit) rocks, so it is quite possible that these areas of missing section were exposed at some time before the end of LBS unit deposition.

The general pattern developed during the Chadian unit is repeated during the LBS unit deposition (Figs 20 and 25), though the basinal region has expanded to the southwest, and the potentially emergent areas are in different locations. By the time of deposition of the UBS unit, (Figs 21 and 26) the Dublin Basin (or at least the area of basinal deposition) has expanded to the southwest, leaving isolated regions of shelf deposition. There was no obvious signs of emergence during the time represented by the UBS unit.

4:1:2 Restored Basin Geometries

The restored basin geometries and palaeo-surface maps are shown in Figure 28 and Figures 29 - 49. These restored basin geometries are particularly useful in that they represent, for each restoration, both the most recent step in basin evolution and the cumulative effects of displacements on the top of each unit, including the basement. The maps also illustrate the regional subsidence, and its occasional local reversal. The original intention was to depict the configuration of each restored unit in 3-D using displays generated by SGM™. But, because of hardware problems that developed during the project, this was not possible, so maps are used to display the information in as succinct a manner as possible.

Each restoration is described below, noting any features indicating significant changes in the basin evolution. The later restorations can be complex. In these cases the bathymetry (or topography) of the palaeo-surface pertinent to that restoration and the character of the most recent depositional unit are described first. It is the shape of these two elements that are superposed on the cumulative geometry of the previous restoration.

The thicknesses referred to, and the resulting depths to various horizons, are the partially decompacted thicknesses, and will generally be larger than the values reported in the decription of the faulted isopach maps (Chapter 3:4:2).

4:1:2:1 ORS Restoration: Figures 28 and 29a

The ORS unit was deposited sub-aerially (Fig. 15), and its restoration (Figure 28) and cross-secton (Figure 29a) show, at Top-Basement, a general thickening to the south and southwest, with no cumulative sedimentation at the northern and eastern margins. A rather simple set of synsedimentary faults divide a region of fluvial and, later, alluvial deposition. The top-basement surface in this earliest restoration reaches a depth of about 400 m subsea in the south of the area. Thickness changes across faults are as much as 250 m, but are generally in the range of 50 to 100 m.

4:1:2:2 Navan Restoration: Figures 29b, 30 and 31

The Navan restoration shows the situation at the end of Navan unit deposition, by which time both the ORS and Navan units have been deposited and the sedimentation surface is below sea level (but shallow) (Fig 22). The top-basement surface has subsided (relative to a sea level; see discussion later) a further 200 to 400 m, reaching a maximum depth of about 700 m subsea in both the south and the northeast of the region. Deposition

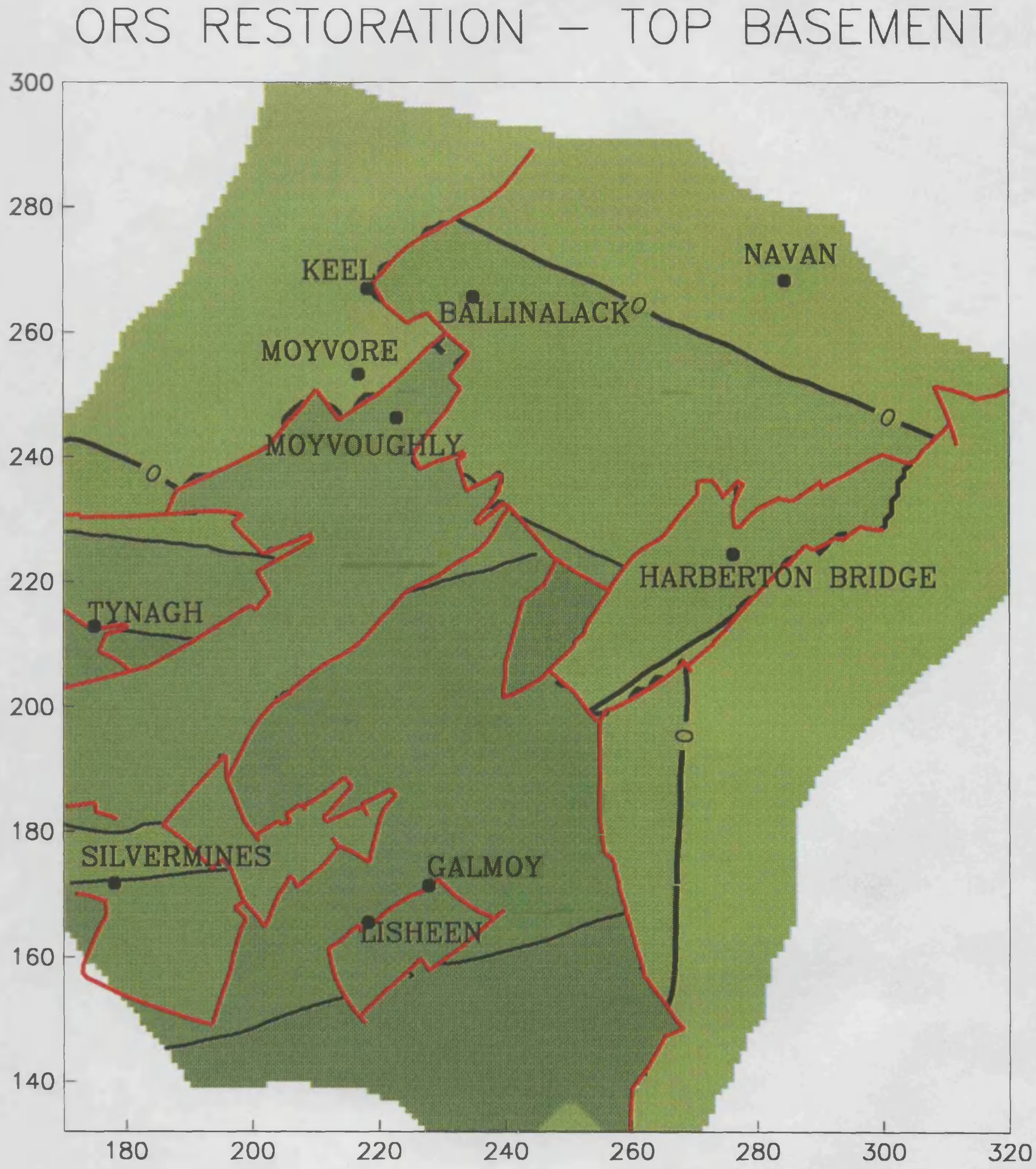
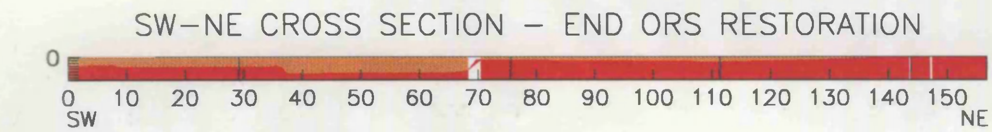
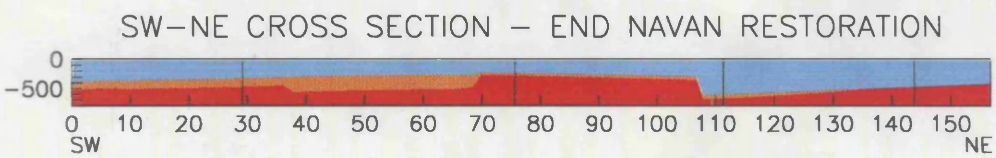


Figure 28. Top of the Basement at the end of the ORS Restoration with ORS time faults in red. Colours represent depth, with depth values given in Figure 8. Deposit locations in black.





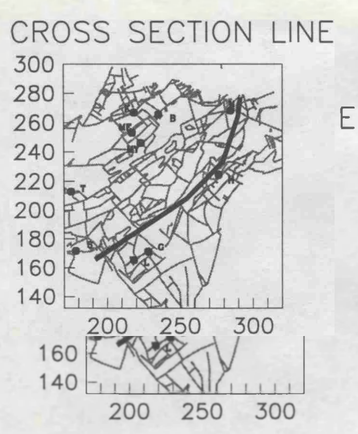
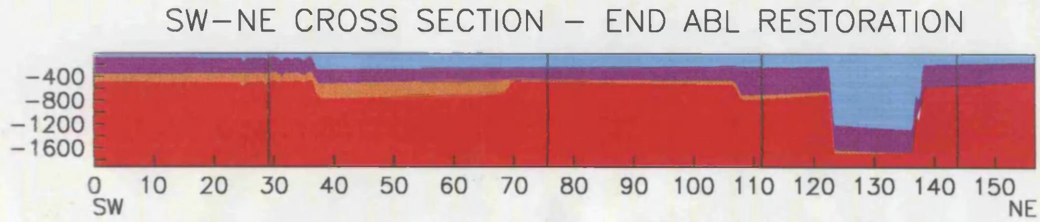
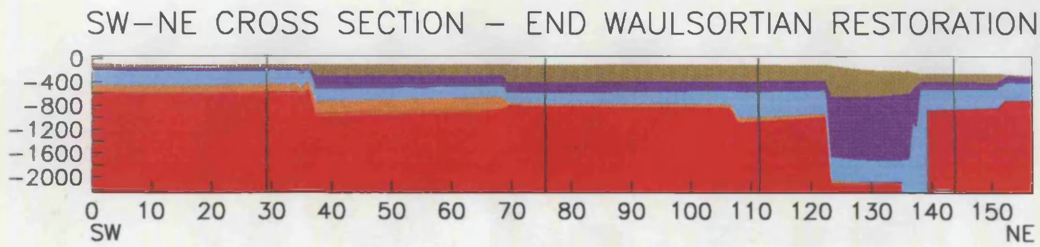
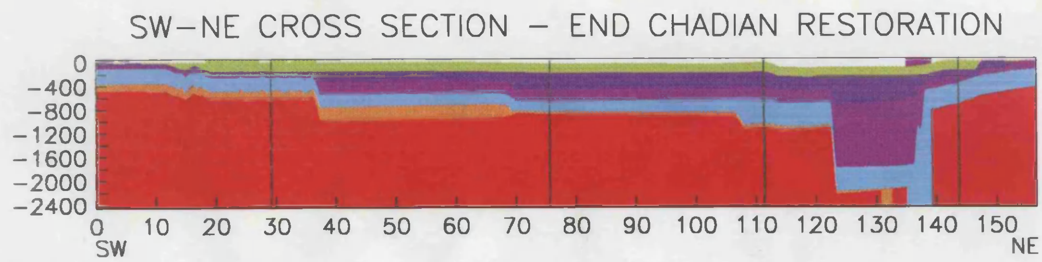
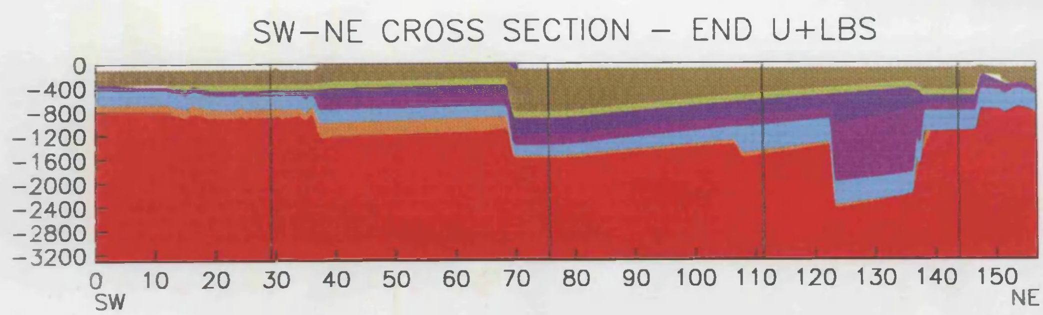


Figure 29. Composite of SW to NE cross sections from ORS restoration (1st) through U+LBS restoration (last). Map shows location of cross sections. Basement = Red; ORS = Orange; Navan = Light Blue; Waulsortian = Dark Blue; Chadian = Yellow-Green; U+LBS = Beige. Horizontal scale is 1cm = 15km. Vertical scale is 1cm = 1km. Zero is sea level.


SW–NE CROSS SECTION – END ABL RESTORATION
-400
-800
-1200
-1600
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150
SW
NE


SW–NE CROSS SECTION – END WAULSORTIAN RESTORATION
0
-400
-800
-1200
-1600
-2000
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150
SW
NE


SW–NE CROSS SECTION – END CHADIAN RESTORATION
0
-400
-800
-1200
-1600
-2000
-2400
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150
SW
NE


SW–NE CROSS SECTION – END U+LBS
0
-400
-800
-1200
-1600
-2000
-2400
-2800
-3200
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150
SW
NE

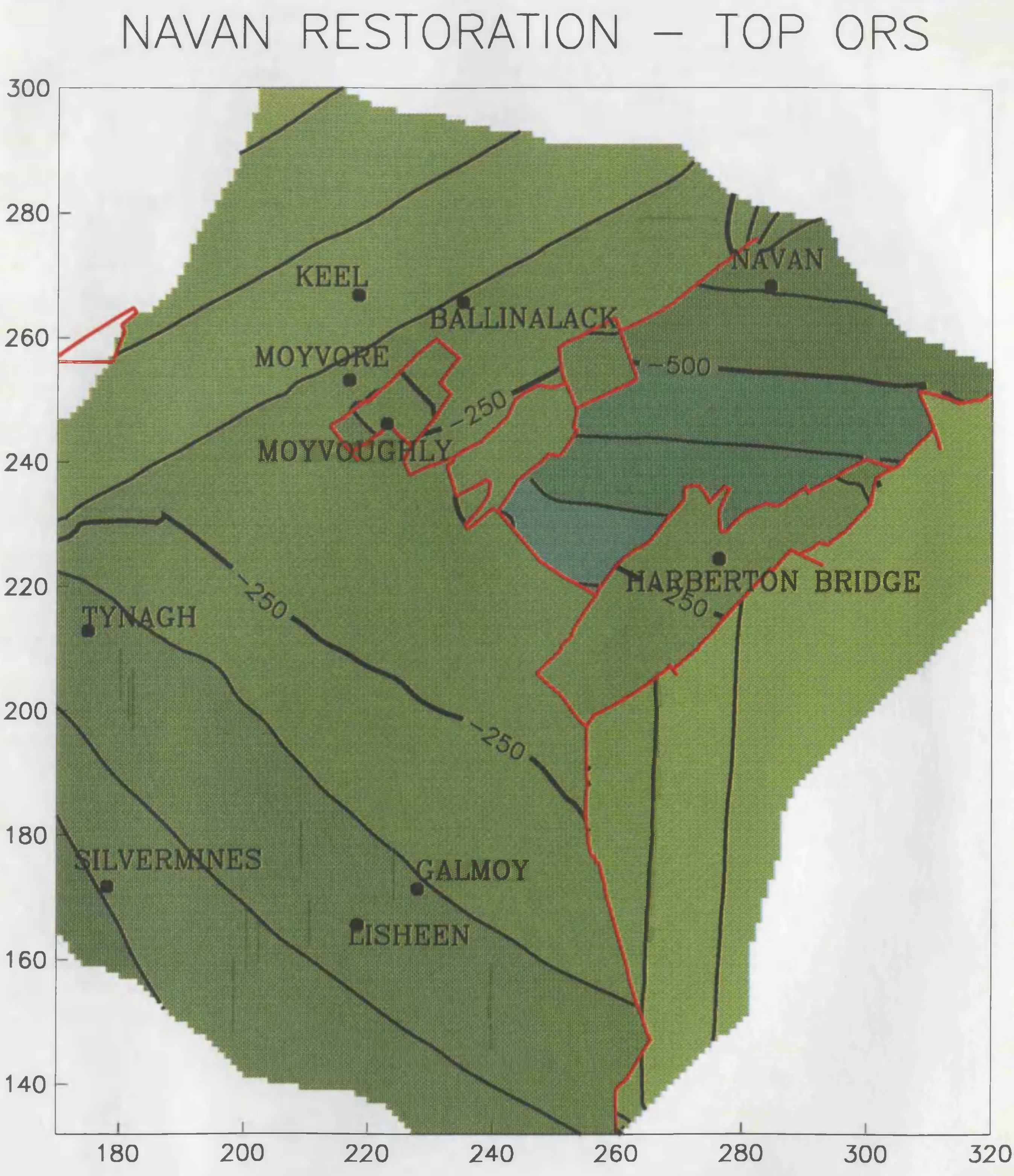


Figure 30. Top of the ORS at the end of the Navan Restoration, with Navan time faults in red. Colours represent depth, with depth values given in Figure 8. Deposit locations in black.

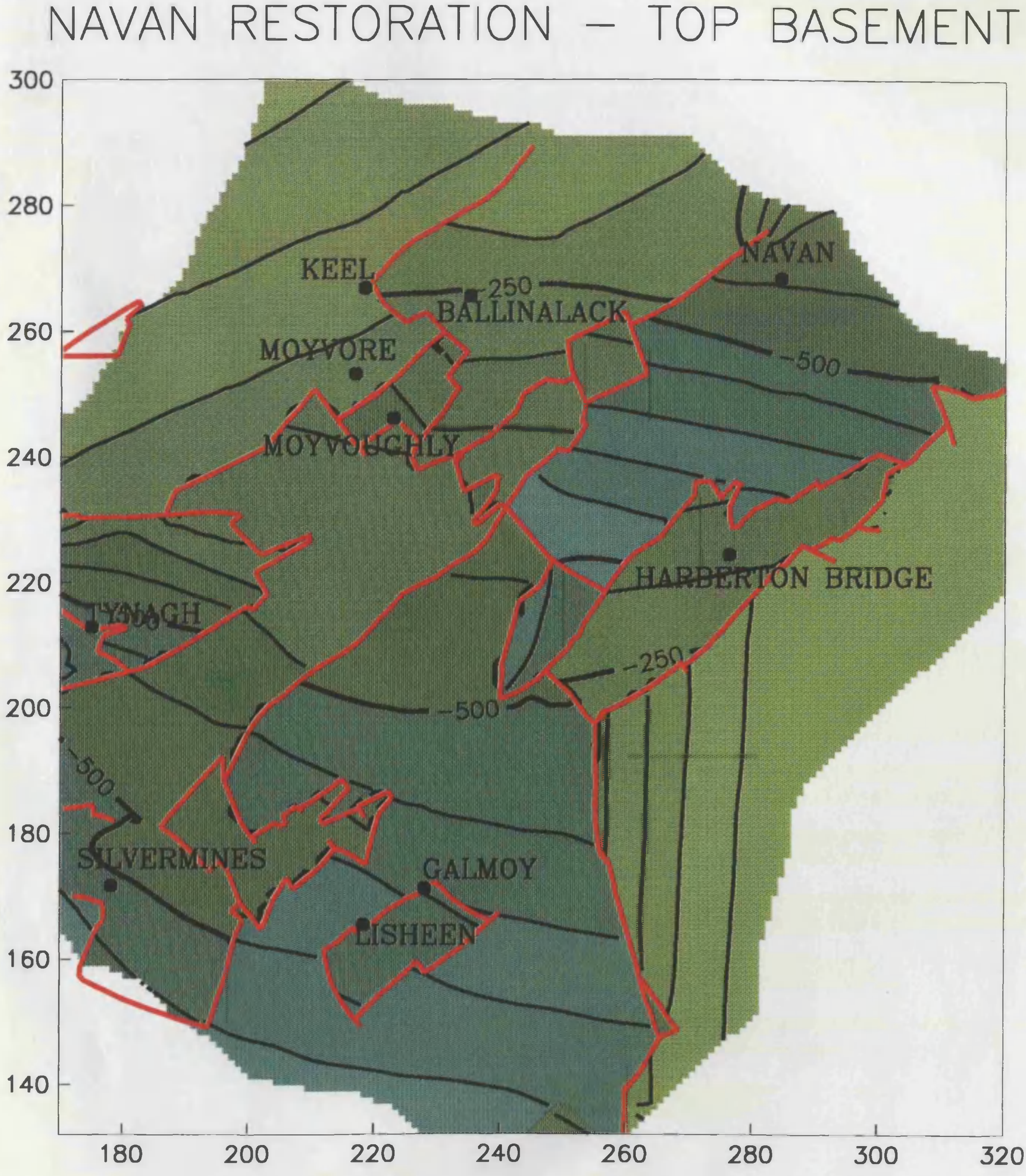


Figure 31. Top of the Basement at the end of the Navan Restoration, with Navan and ORS time faults in red. Colours represent depth, with depth values given in Figure 8. Deposit locations in black.

has extended across the region, with the possible exception of the area of Leinster Granite massif (in the east and southeast).

New fault-bounded blocks have developed in the northern part of the region, one of these faulting forms the western boundary to the Navan unit depositional centre. No synsedimentary faults are identified in the southern part of the area in this Navan restoration because there is insufficient data to allow such faulting to be distinguished (but see below). The pattern of southward thickening (of the ORS unit) dominant in the ORS restoration is replaced by a local depositional centre in the northeast, in which has accumulated more than 600 m of Navan unit rocks. The development of this depositional centre (at the expense of southward thickening) is very clear in the Navan unit (Fig 31), but the change of depositional pattern is rather more difficult to discern from only the top-basement map (Fig. 30).

4:1:2:3 ABL Restoration: Figures 29c, and 32 - 34

The sea remains shallow during the time represented by the ABL restoration, as it was during the Navan restoration. The central portion of the area has become more faulted. Faults that were active in the ORS restoration are also active in the ABL restoration. In light of the lack of available information for the Navan restoration in this area, these faults may well have remained active through Navan times.

The ABL restoration depositional centre (Fig. 32) is contained within the limit of the Navan restoration depositional centre (Fig. 30) . This ABL restoration depositional centre has accumulated in excess of 1200 m of ABL unit rocks -- twice the thickness of the Navan unit that accumulated in the Navan restoration depositional centre. The basement in this restoration is everywhere below its position at the end of the Navan (and earlier) restoration (compare figures 29b and 29c), reaching a maximum depth of about 1700 m subsea in the northeast below the ABL depositional centre (Fig.34 Irish Grid 280, 250 approx.),. But the rate of subsidence has become quite variable: below the ABL restoration depositional centre average rate of descent is quite rapid, but in parts the northwest and southwest, the top-basement has only moved down 50 to 100 m (see Figs 31 and 34) during the ABL restoration. The Leinster Granite massif in the southeastern corner is probably still partly emergent.

4:1:2:4 Waulsortian Restoration: Figures 29d and 35 - 38

By the time represented by the end of the Waulsortian restoration, the water-sediment interface is generally at a depth of 100 m to perhaps as much as 250 m.. The depth decreases towards the Leinster Granite massif, which still appears to have been partly emergent. The water-sediment interface has been interpreted as deepening locally to the north, where sedimentation continues but in conditions unsuitable for Waulsortian mudmound development (see Waulsortian Faulted Isopach, Chapter 3:4:2:4), though

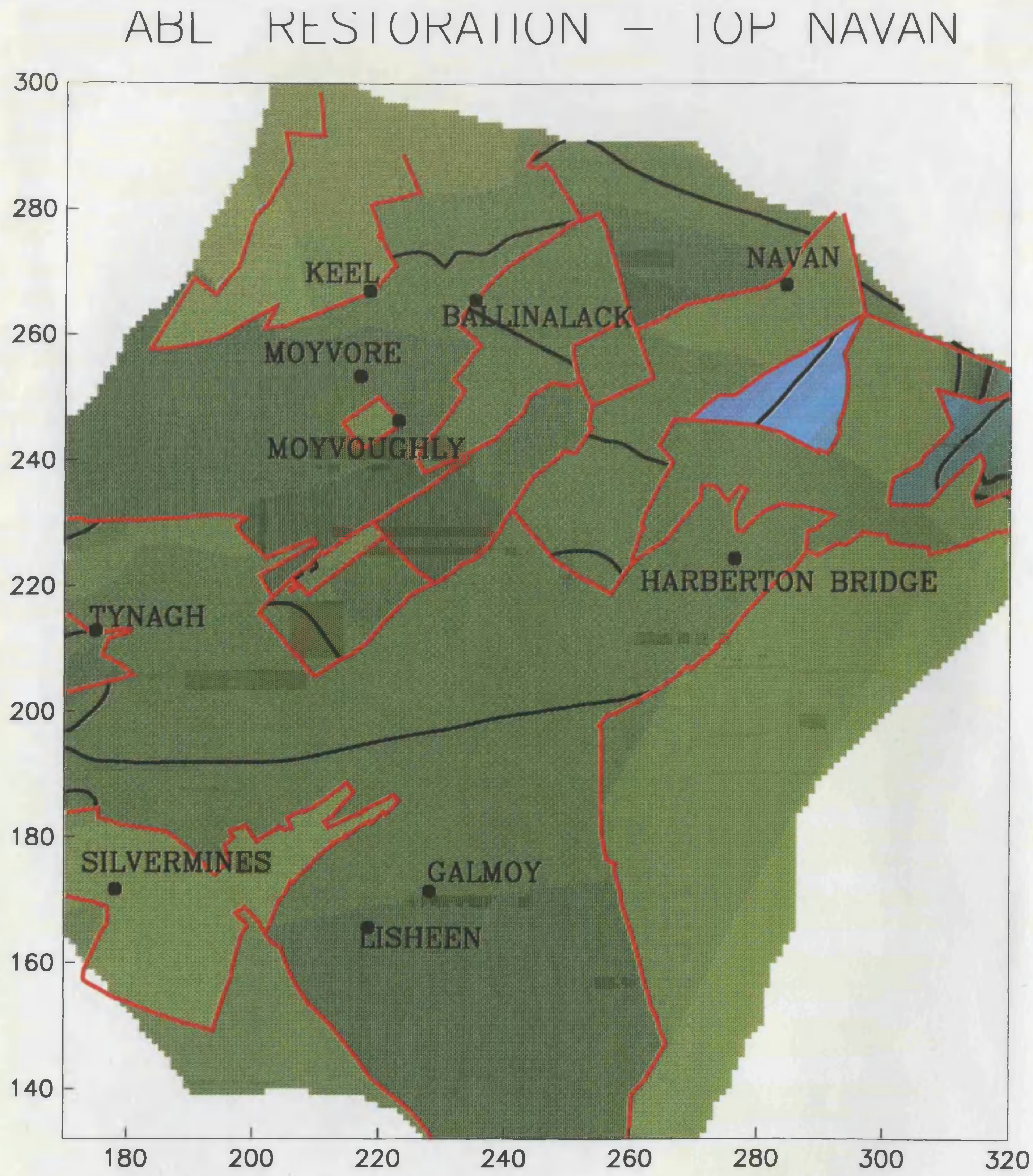


Figure 32. Top of the Navan unit at the end of the ABL Restoration, with ABL time faults in red. Colours represent depth, with depth values given in Figure 8. Deposit locations in black.

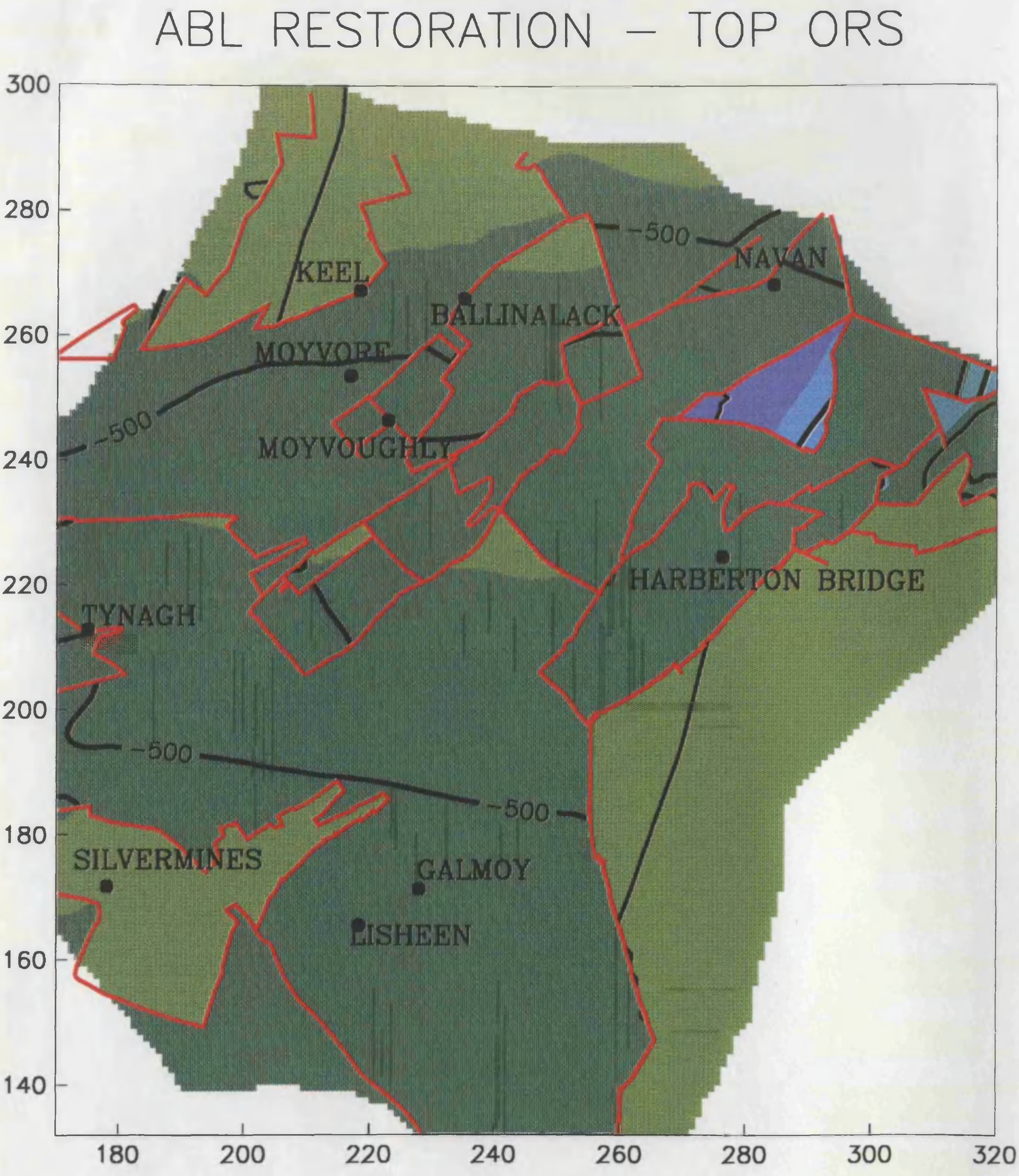


Figure 33. Top of the ORS unit at the end of the ABL Restoration, with ABL time faults in red. Colours represent depth, with depth values given in Figure 8. Deposit locations in black.

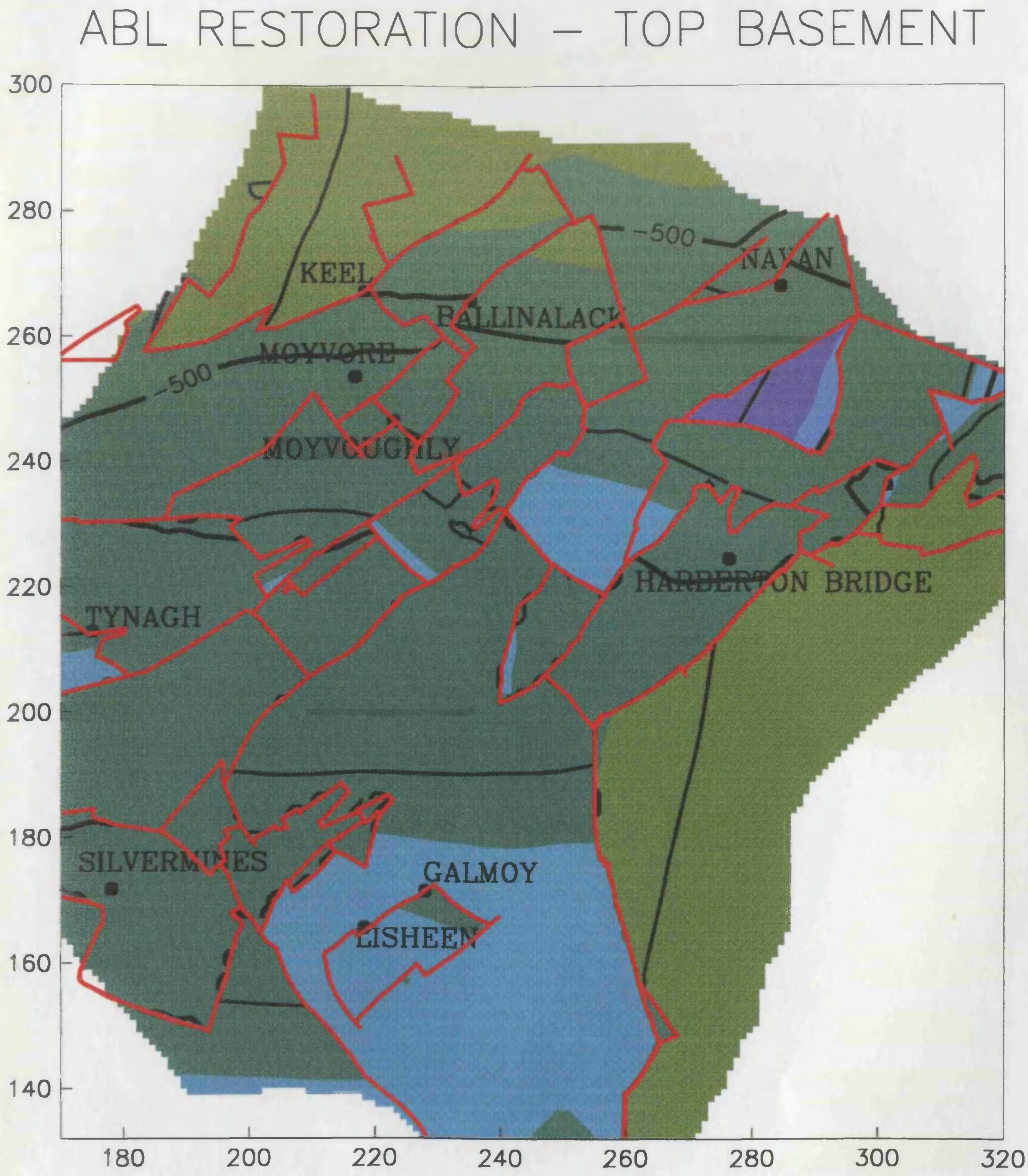


Figure 34. Top of the Basement at the end of the ABL Restoration, with ABL, Navan and ORS time faults in red. Colours represent depth, with depth values given in Figure 8. Deposit locations in black.

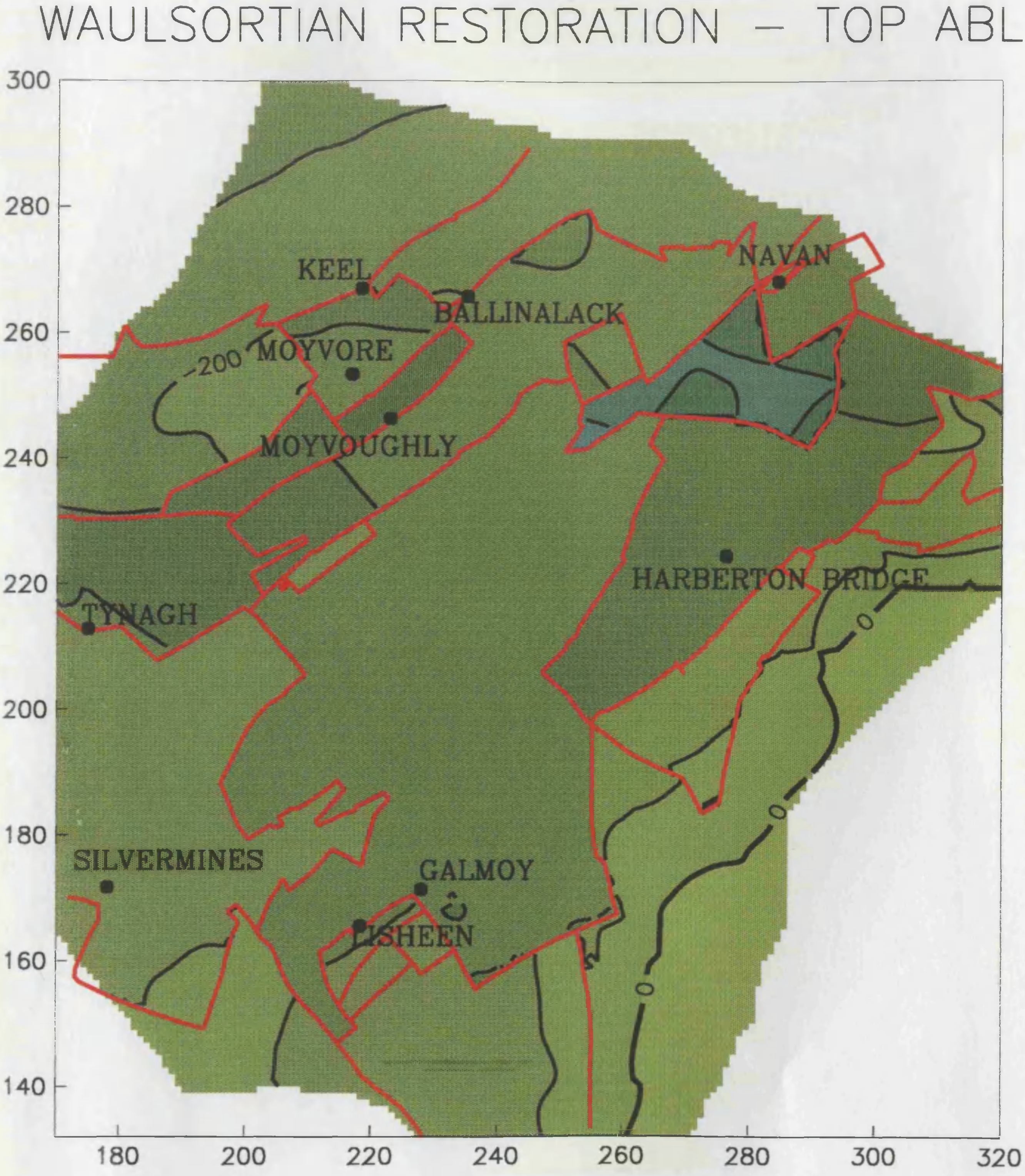


Figure 35. Top of the ABL unit at the end of the Waulsortian Restoration, with Waulsortian time faults in red. Colours represent depth, with depth values given in Figure 8. Deposit locations in black.

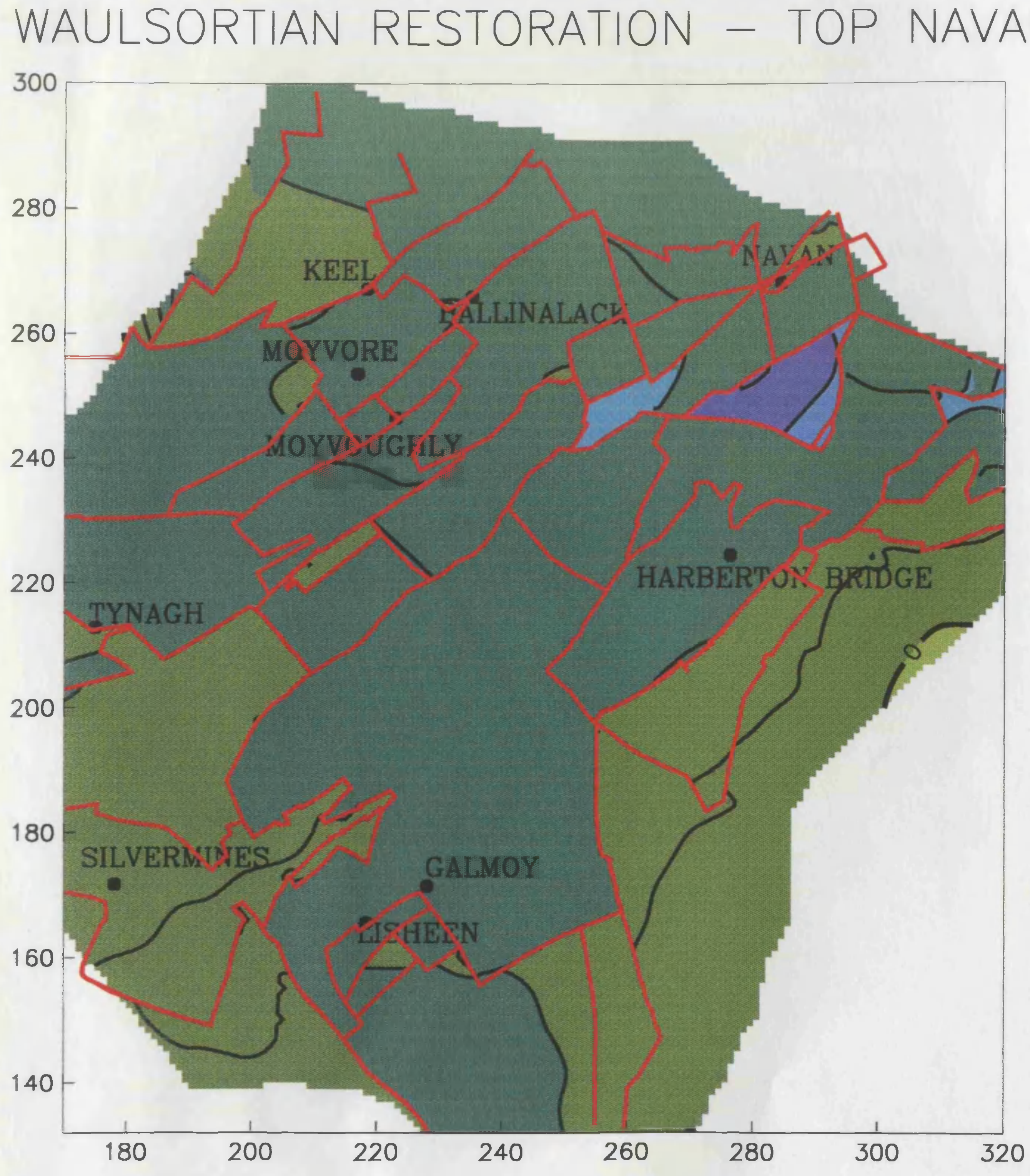


Figure 36. Top of the Navan unit at the end of the Waulsortian Restoration, with Waulsortian and ABL time faults in red. Colours represent depth, with depth values given in Figure 8. Deposit locations in black.

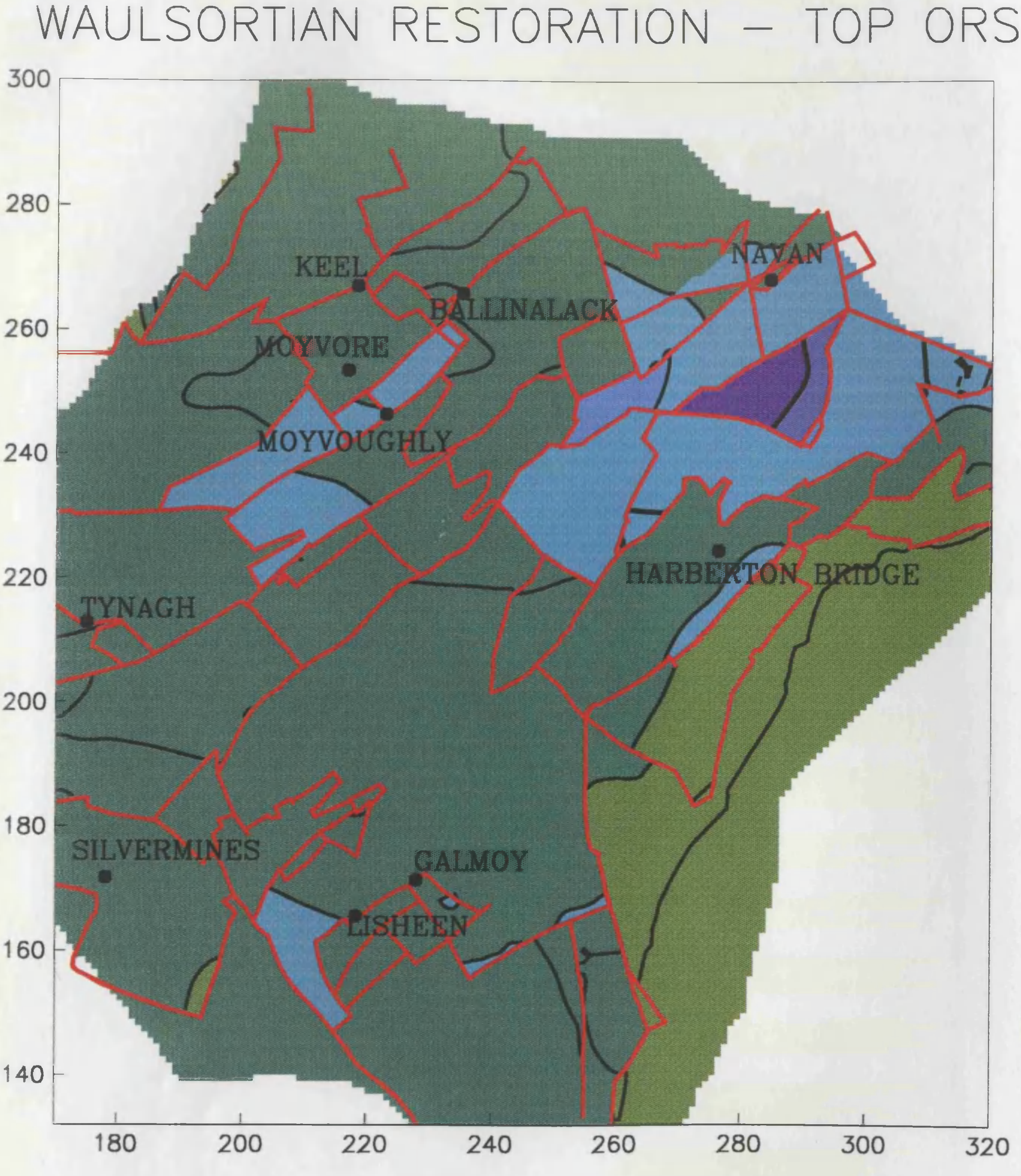


Figure 37. Top of the ORS unit at the end of the Waulsortian Restoration, with Waulsortian, ABL and Navan time faults in red. Colours represent depth, with depth values given in Figure 8. Deposit locations in black.

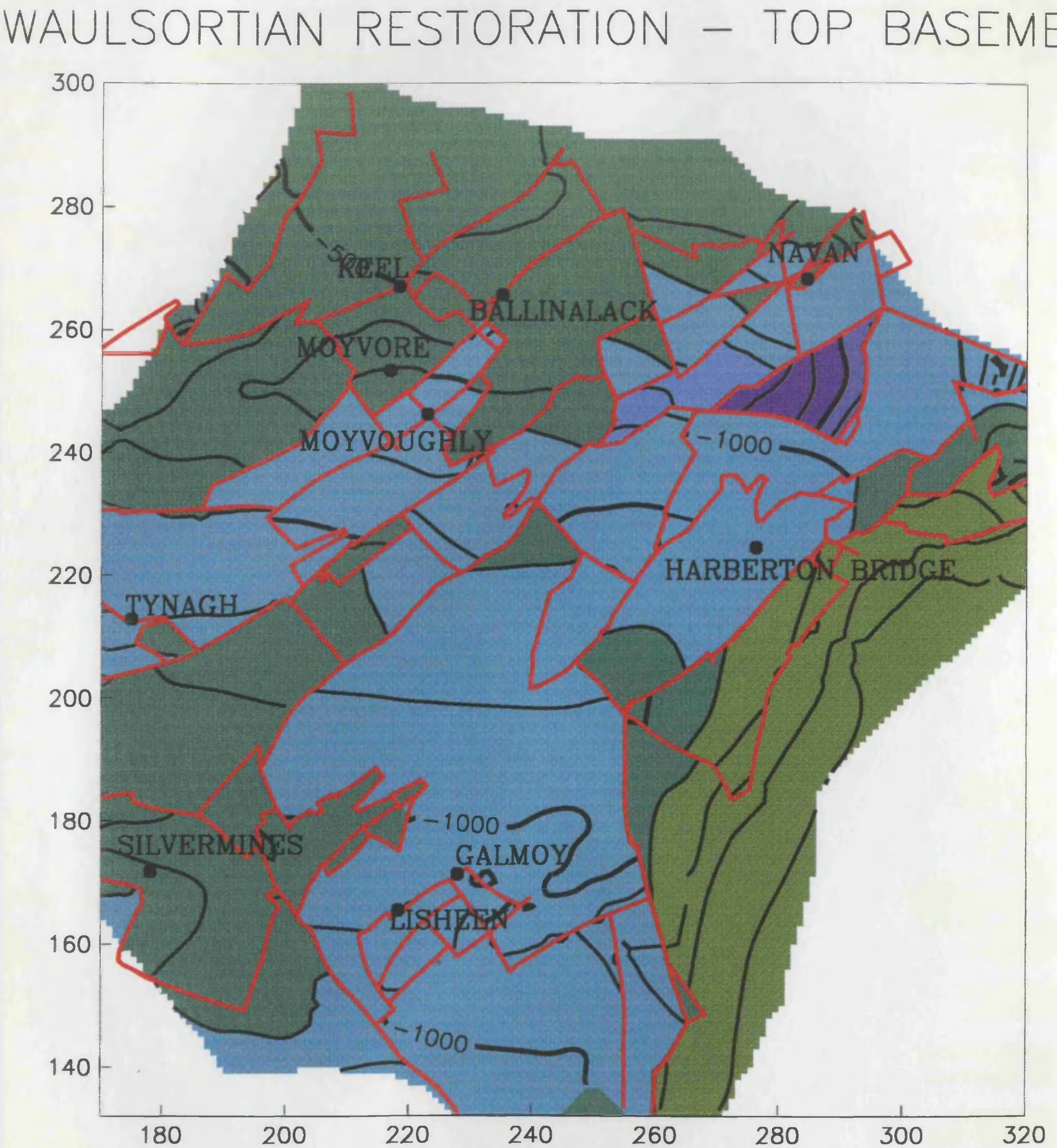


Figure 38. Top of the Basement at the end of the Waulsortian Restoration, with Waulsortian, ABL, Navan and ORS time faults in red. Colours represent depth, with depth values given in Figure 8. Deposit locations in black.

shallowing is also possible. The number of fault-bounded blocks in the region continues to increase during the time represented by the Waulsortian restoration.

The Waulsortian restoration's main centre of deposition (in which Waulsortian unit thicknesses exceed 600 m) overlaps that of the ABL restoration, but it also extends furtherwestwards (Fig. 35). The Waulsortian unit is also generally thicker in the northern part of the region than the southern part. The Leinster Granite massif is still shallow to emergent.

The result is a discernable pattern of basin development during the Waulsortian when looking at the Waulsortian unit (Fig. 35). But below the Waulsortian unit, the cumulative depositional pattern is dominated by the ABL unit -- and so by the pattern of basinal development during the time represented by the ABL restoration. The basement has continued to descend during the time represented by the Waulsortian restoration, reaching a maximum depth of about 2200 m below sea level under the ABL depositional centre (Fig. 38 Irish Grid 280, 250 approx.). Basement at the end of the Waulsortian restoration is shallowest in parts the the south and southwest, in which only a few metres to tens of metres of sediment accumulated during the ABL and Waulsortian restorations.

There is very little thickness data available for the remaining two restorations. They have been constructed using surface map information and a very small amount of subsurface information, and should be considered as only approximations.

4:1:2:5 Chadian Restoration: Figures 29e and39 - 43

The Chadian palaeo-surface is more complex than the previous palaeo-surface maps in that it incorporates emergent regions, shelf regions, and basinal settings (Fig. 19). New synsedimentary faults have been interpreted, but the lack of thickness information restricts fault identification considerably, and there are probably quite a few more faults that could be identified with thickness information (see Chadian Faulted Isopach, Chapter 3:4:2:5). The existance of Chadian-age volcanics in the Midland Basin (see, for example, Hitzman, 1993) lends support to the general impression of an increase in tectonic activity in the Chadian.

Because of this lack of thickness information, the Chadian unit is modelled to be of uniform thickness except where published surface maps (Hitzman, 1993) show it to be eroded. This use of a uniform thickness for the Chadian unit results in the map on the top of the Waulsortian unit (which shows the subsidence due to the deposition of the Chadian sediments, plus any change in water depth) being artificially simple (Fig. 39). It primarily reflects the end-Chadian palaeo-surface. Consequently, the lower units have a very similar appearance in this restoration to that in the Waulsortian restoration (but see below).

Basement in the Chadian restoration has reached a maximum depth of nearly 2400 m subsea (Fig. 43 Irish Grid 280, 250 approx.) but this restoration is the first to show any upward movement, however small, of the top-basement surface (compare Figure 29e with

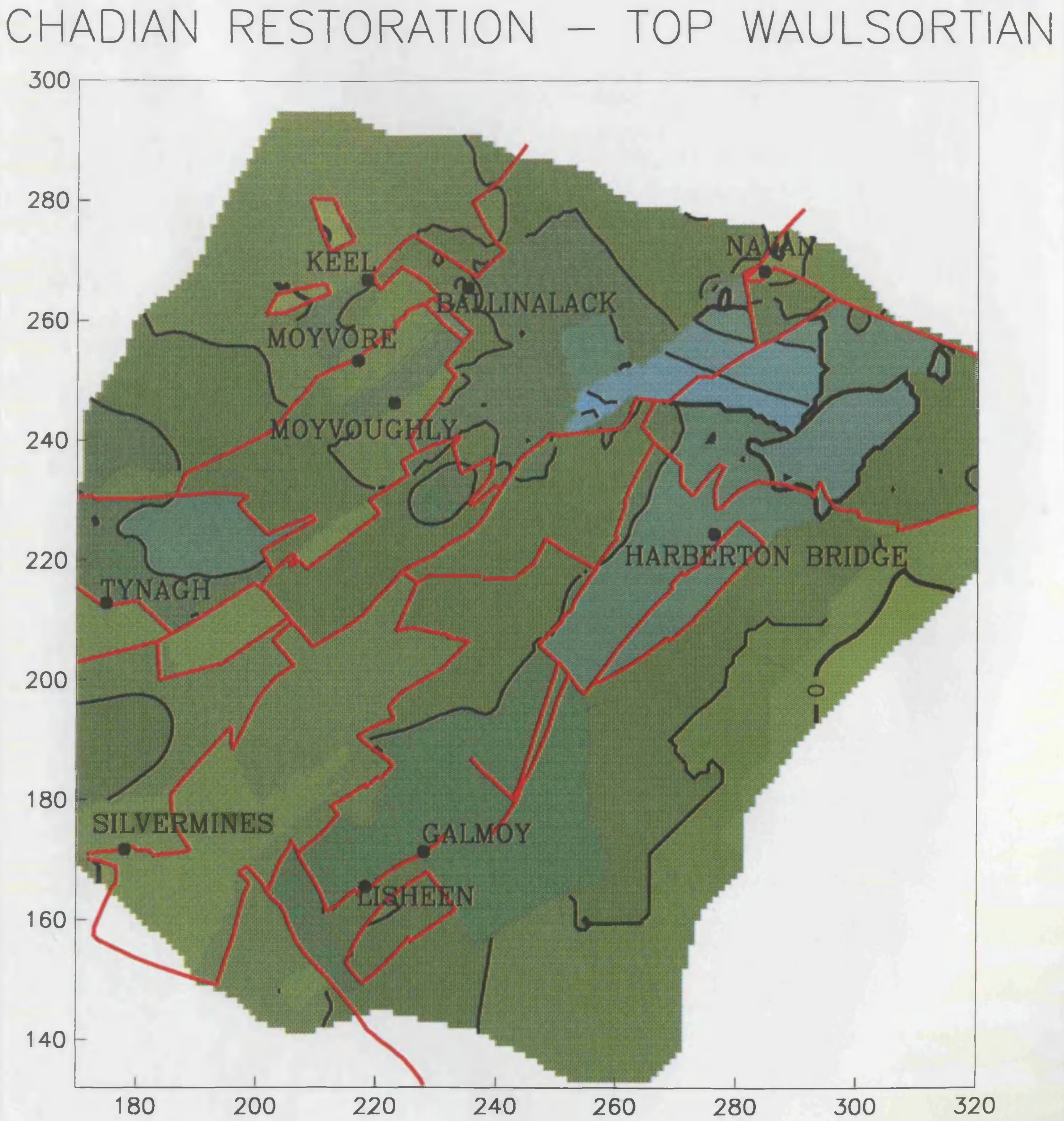


Figure 39. Top of the Waulsortian unit at the end of the Chadian Restoration, with Chadian faults in red. Colours represent depth, with depth values given in Figure 8. Deposit locations in black.

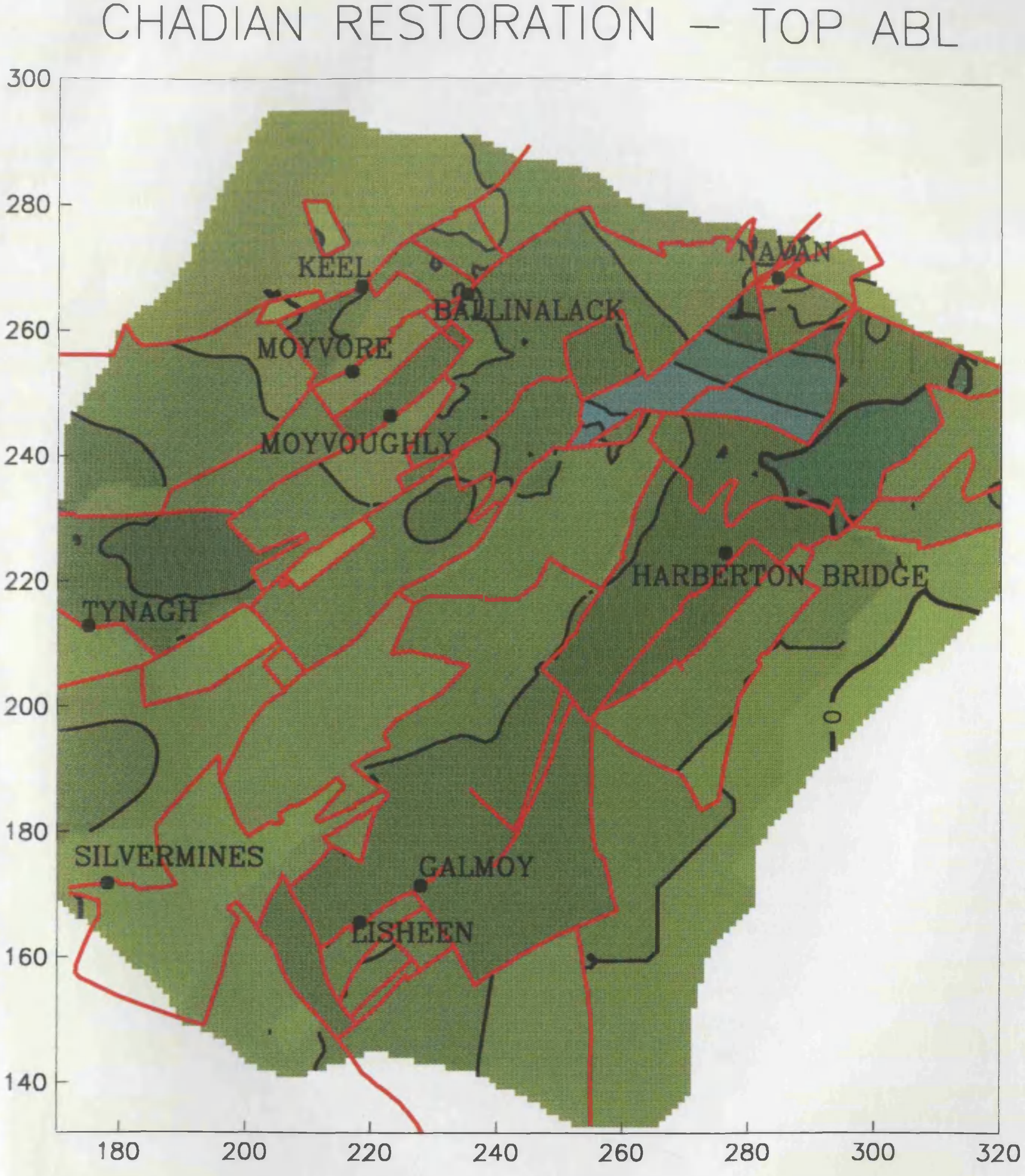


Figure 40. Top of the ABL unit at the end of the Chadian Restoration, with Chadian and Waulsortian time faults in red. Colours represent depth, with depth values given in Figure 8. Deposit locations in black.

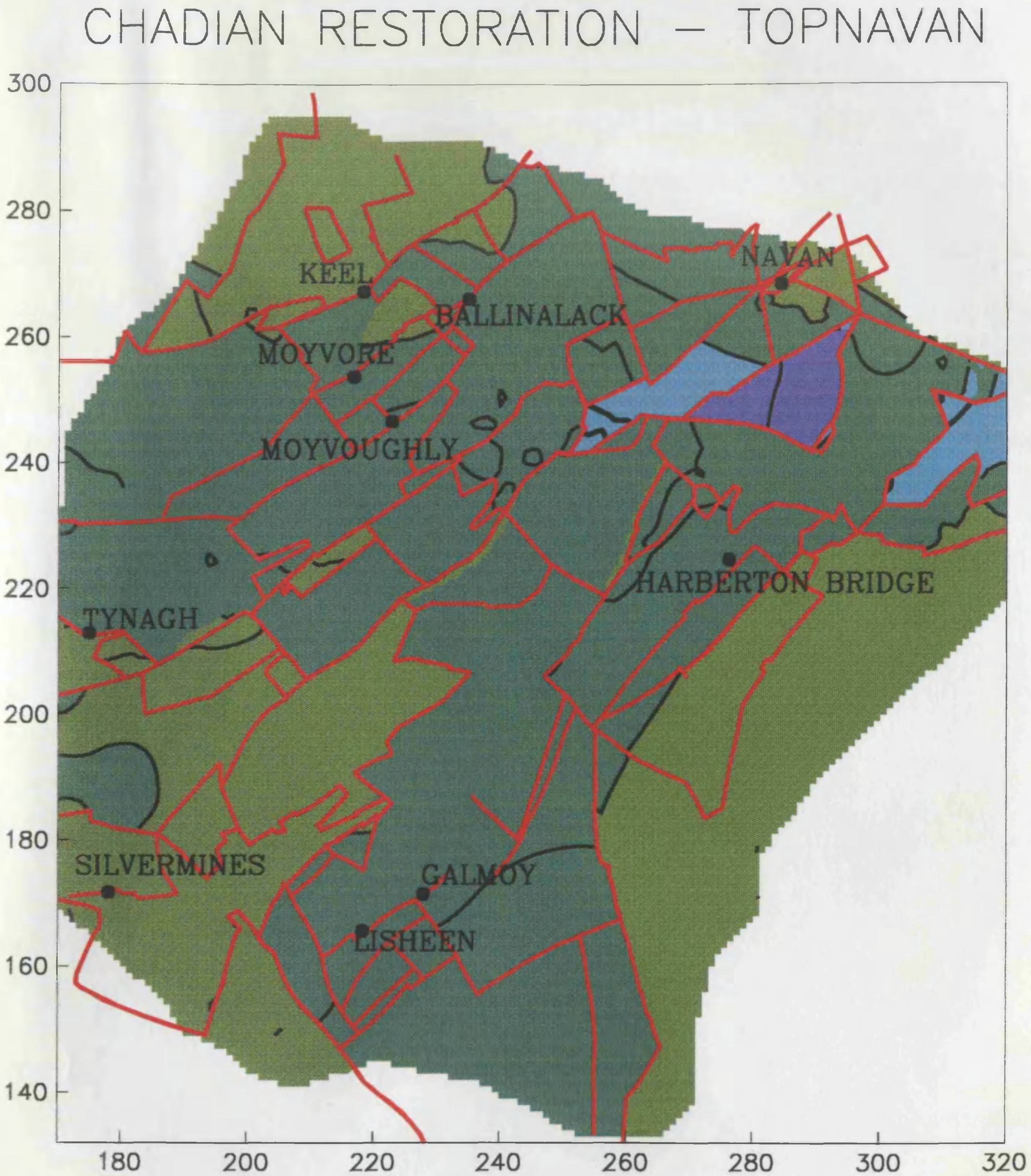


Figure 41. Top of the Navan unit at the end of the Chadian Restoration, with Chadian, Waulsortian and ABL time faults in red. Colours represent depth, with depth values given in Figure 8. Deposit locations in black.

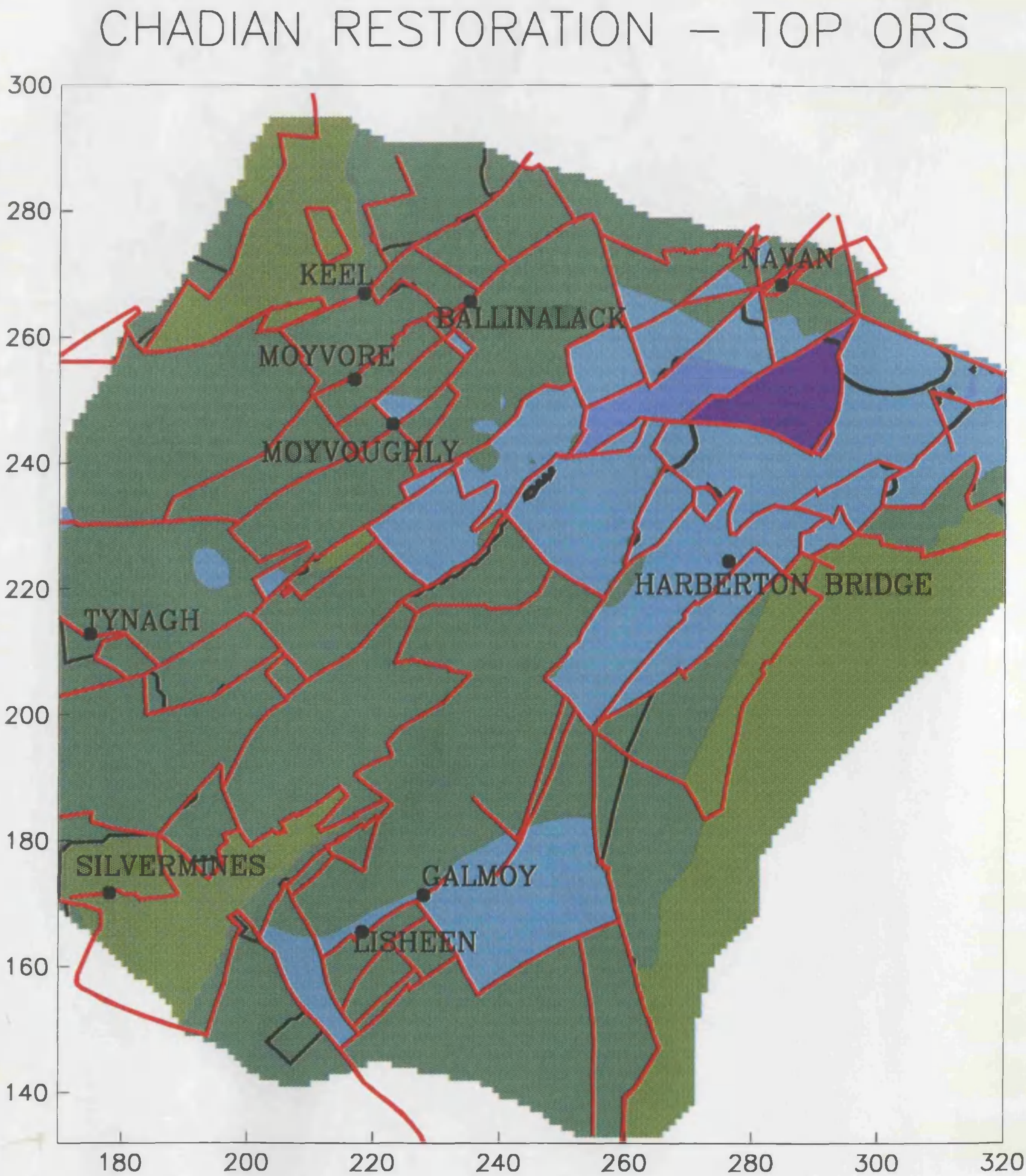


Figure 42. Top of the ORS unit at the end of the Chadian Restoration, with Chadian, Waulsortian, ABL and Navan time faults in red. Colours represent depth, with depth values given in Figure 8. Deposit locations in black.

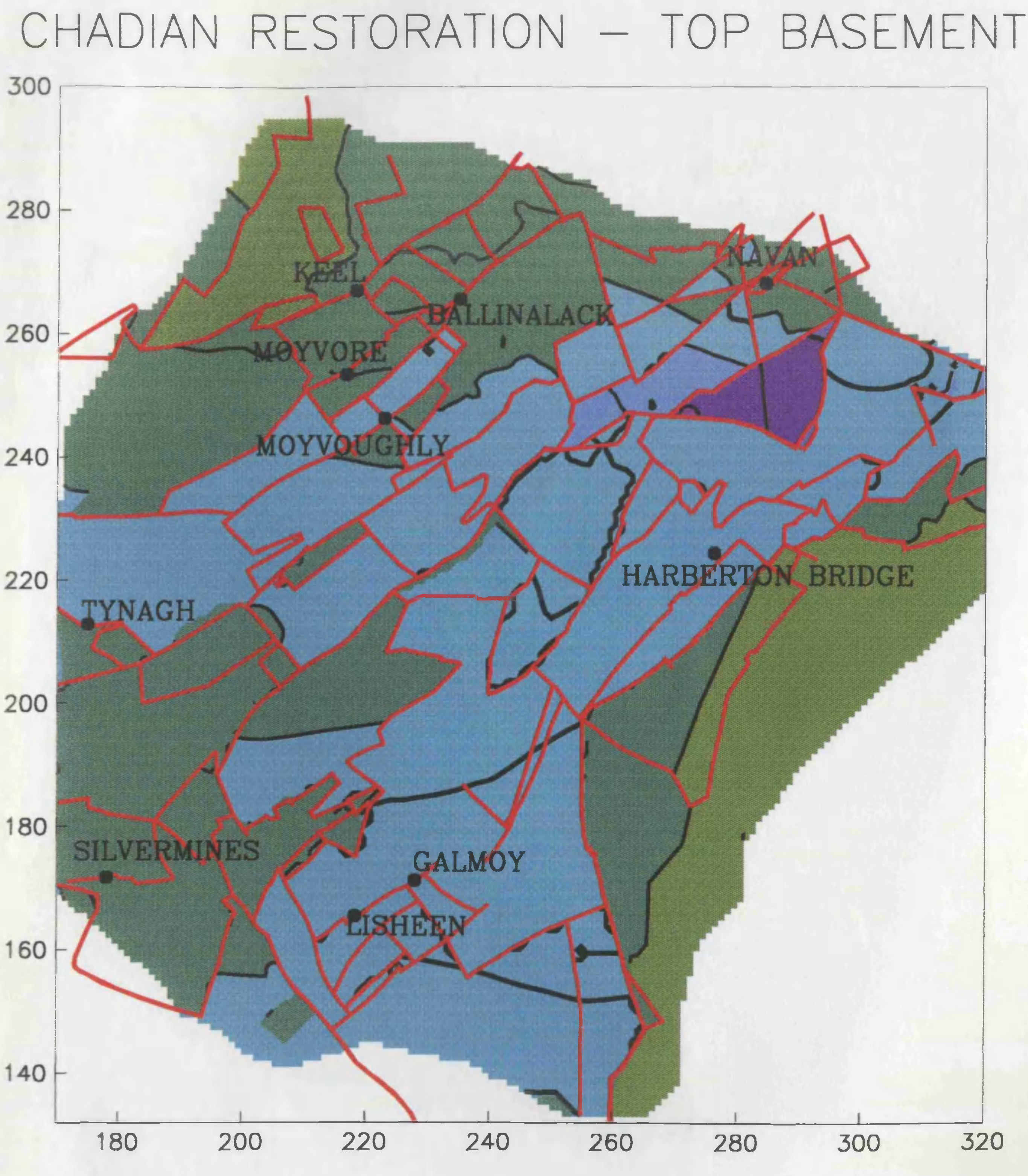


Figure 43. Top of the Basement at the end of the Chadian Restoration, with Chadian, Waulsortian, ABL, Navan and ORS time faults in red. Colours represent depth, with depth values given in Figure 8. Deposit locations in black.

Figure 29d) This upward movement occurs in the western part of the area, and, being of too small a magnitude to show on the structure-contour maps of the restored basement surfaces, is determined from the differences between the surface grid values.

4:1:2:6 L+UBS Restoration:Figures 29f and 44 - 49

The Arundian through Brigantian rocks are restored as a single unit because there is insufficient thickness information to treat them separately. Nevertheless, the LBS and UBS units have somewhat different distributions of shelf and basinal areas. Both distributions have been taken into account in identifying potential synsedimentary faults, but the top-UBS palaeo-surface has been used as the top (palaeo-bathymetric) surface in the the restoration. The L+UBS unit's depositional pattern is dominated by the much thicker section interpreted in the northeast (see L+UBS Faulted Isopach, Chapter 3:4:2:6). The limits of this much thicker section are quite speculative, though they have been made to agree with outcrop information.

This restoration also has a depositional centre in the northeast (Fig. 44). The depositional centre, in which has accumulated nearly 2000 m of U+LBS sediments, roughly corresponds to the main depositional centres developed from the Navan restoration onwards. At the end of the time represented by the L+UBS restoration, the top basement surface has developed a structural relief of more than 4000 m, with the lowest point below 4000 m subsea (Irish Grid reference 270, 250 approx.) and the highest point above 300 m asl). More than half of the region's basement is between 1000 and 2000 m below sea level. (Fig. 49), with the highest areas in the far east, in the far northwest, and in parts of the southwest -- where they have been through most of the early Carboniferous.

4:1:3 Post-Carboniferous Development

The are only a few areas of outcropping sedimentary rock of Late Carboniferous age in the Midland Basin region (Hitzman, 1993). The Late Carboniferous age rocks were deposited in shallow water and do not appear to have undergone any significant deformation. Their present (partly eroded) thickness reaches 300 m. The existence of Upper Carboniferous rocks in the study area suggests that at least part of the region continued to subside after the end of the Early Carboniferous. There is no record of any substantial sedimentation in this region or its surrounds after the Triassic, and most of the overburden was probably retained until approximately Cretaceous times (Cope et al, 1992).

The lowest point of the restored top-basement had reached a depth of about 4 km subsea at the end of the Early Carboniferous; this same location is now at about 3 km subsea -- and the whole of the Midland Basin region is several hundred metres, to a kilometre, higher today than it was at the end of the Early Carboniferous. However the uplift was not

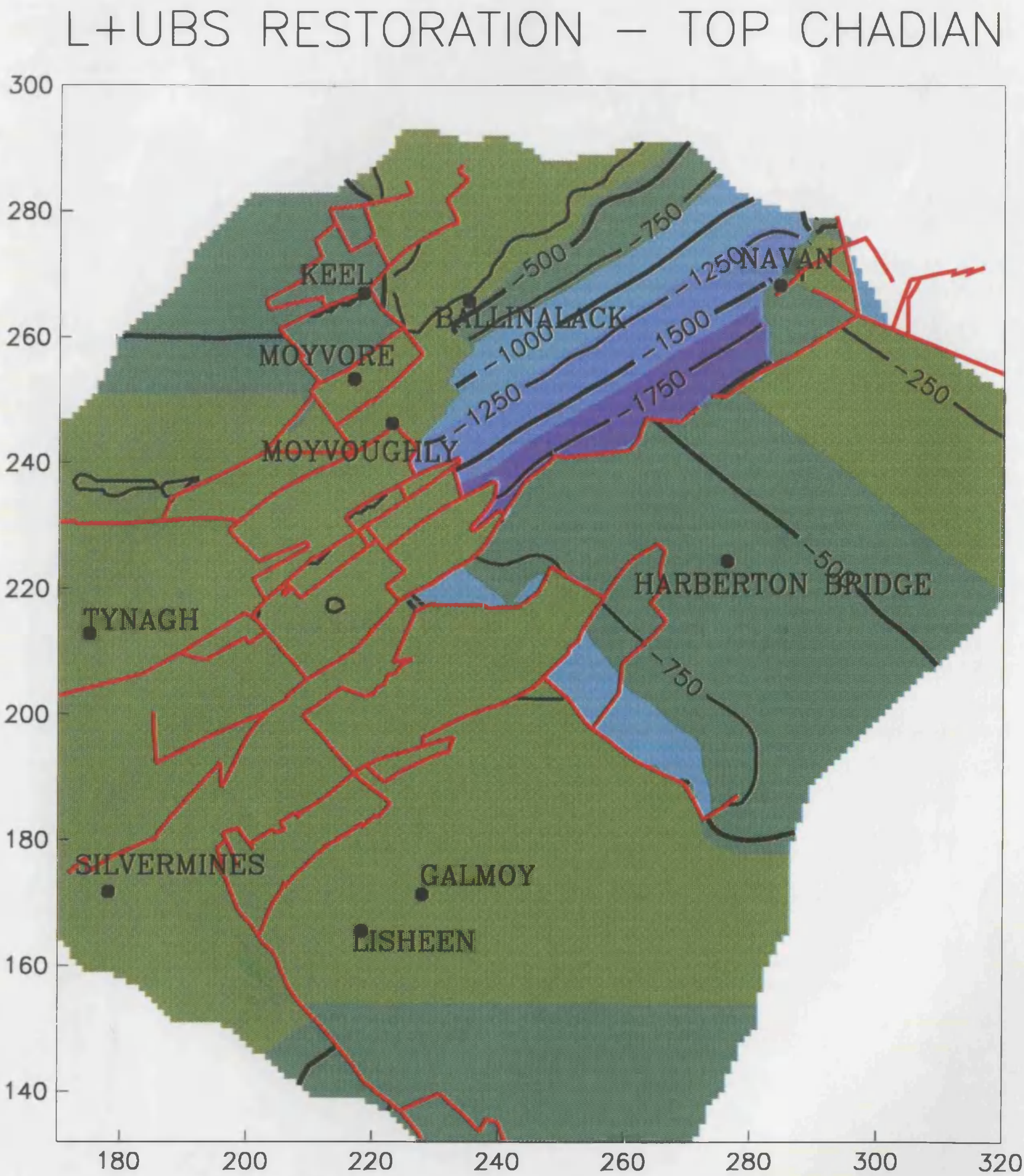


Figure 44. Top of the Chadian at the end of the L+UBS Restoration, with L+UBS time faults in red. Colours represent depth, with depth values given in Figure 8. Deposit locations in black.

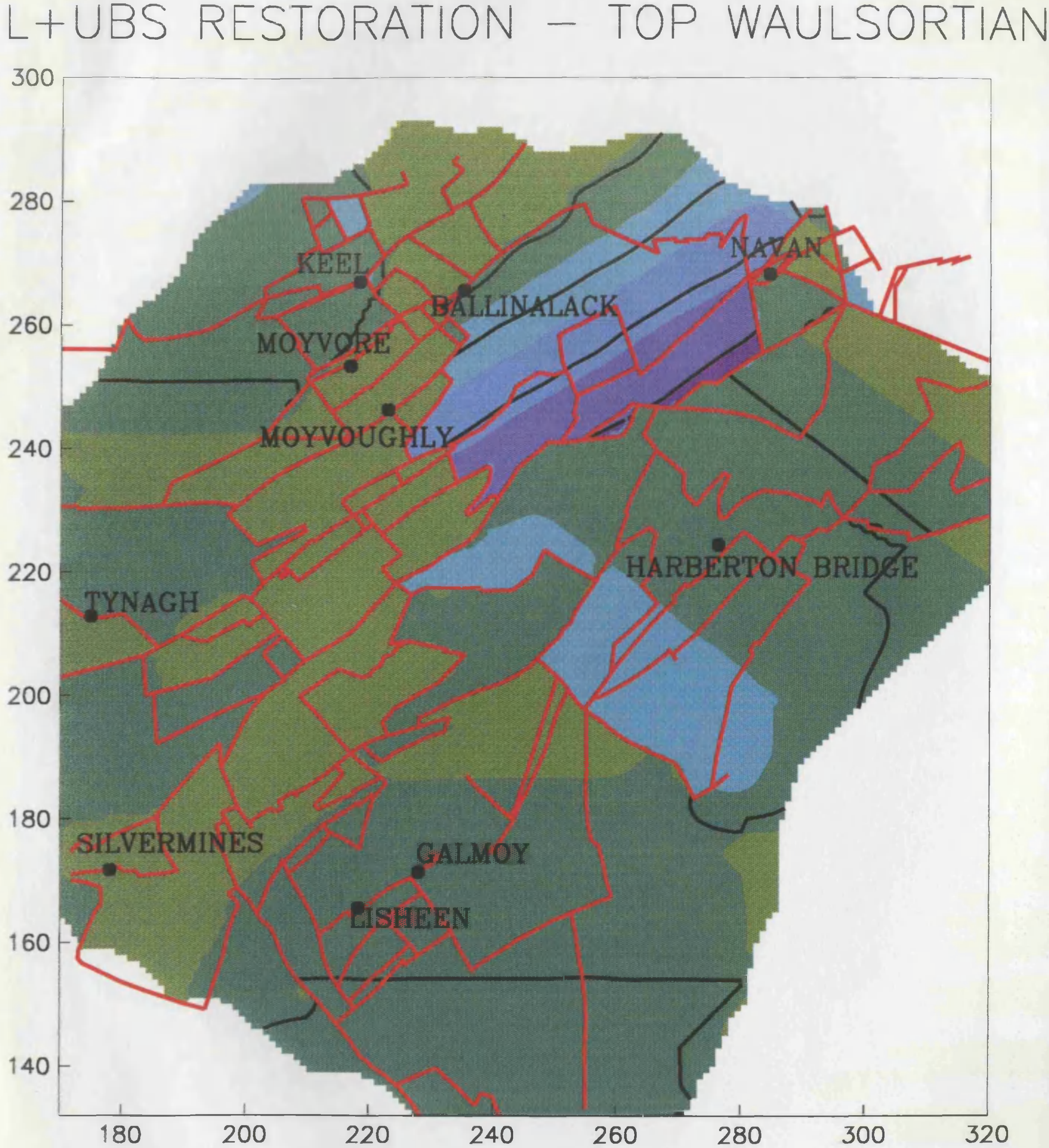


Figure 45. Top of the Waulsortian unit at the end of the L+UBS Restoration, with L+UBS and Chadian faults in red. Colours represent depth, with depth values given in Figure 8. Deposit locations in black.

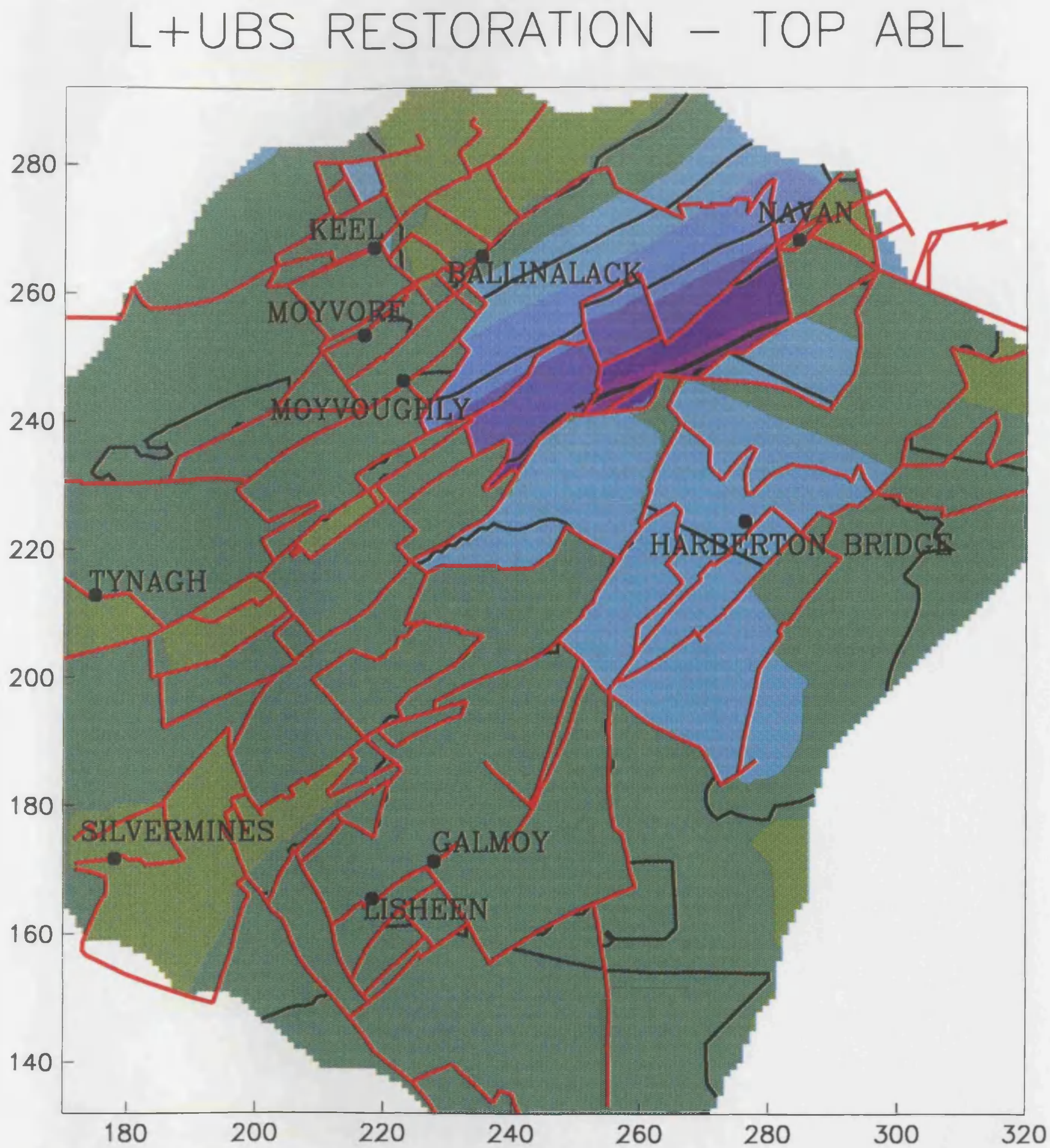


Figure 46. Top of the ABL unit at the end of the L+UBS Restoration, with L+UBS, Chadian and Waulsortian time faults in red. Colours represent depth, with depth values given in Figure 8. Deposit locations in black.

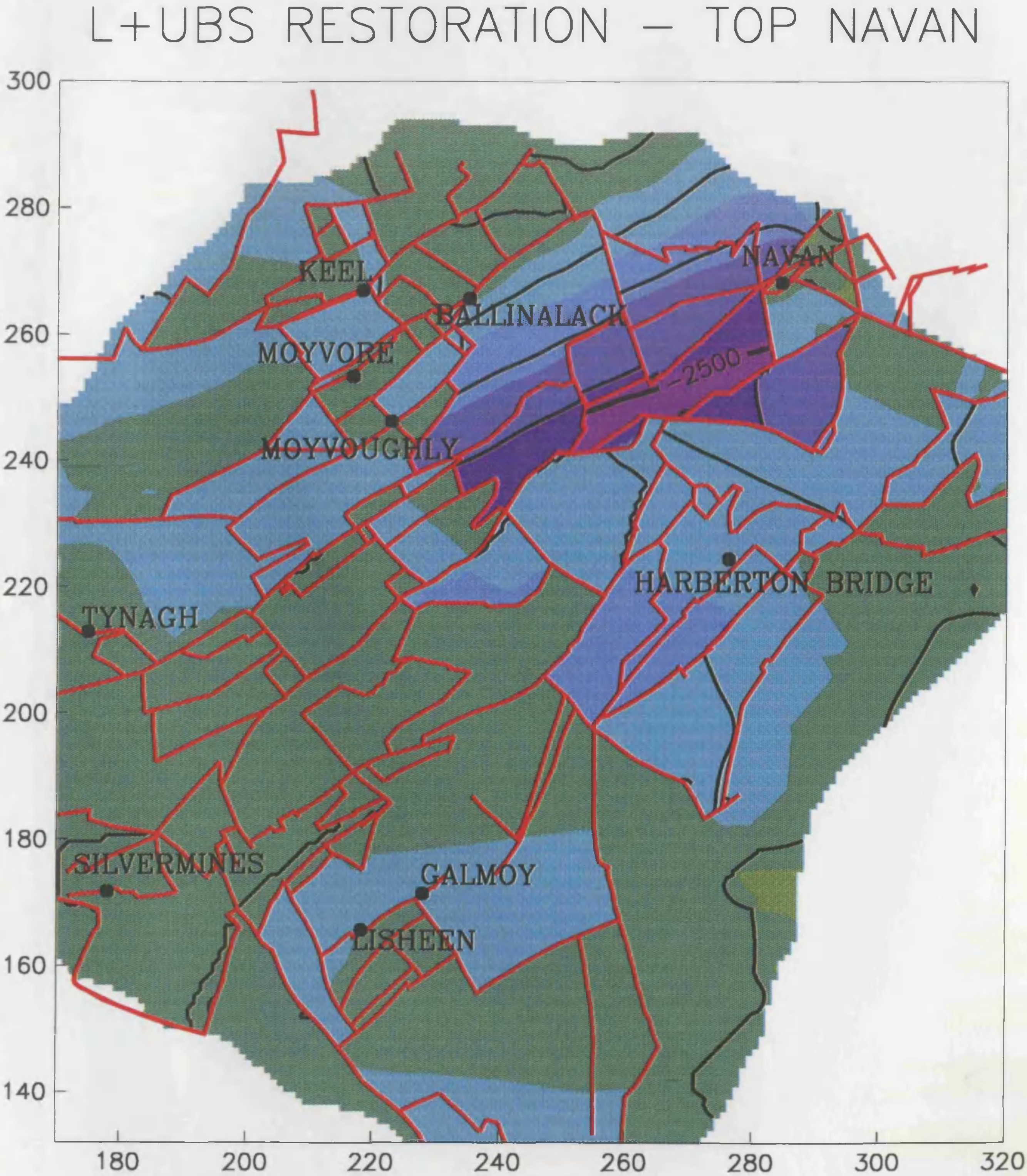


Figure 47. Top of the Navan unit at the end of the L+UBS Restoration, with L+UBS, Chadian, Waulsortian and ABL time faults in red. Colours represent depth, with depth values given in Figure 8. Deposit locations in black.

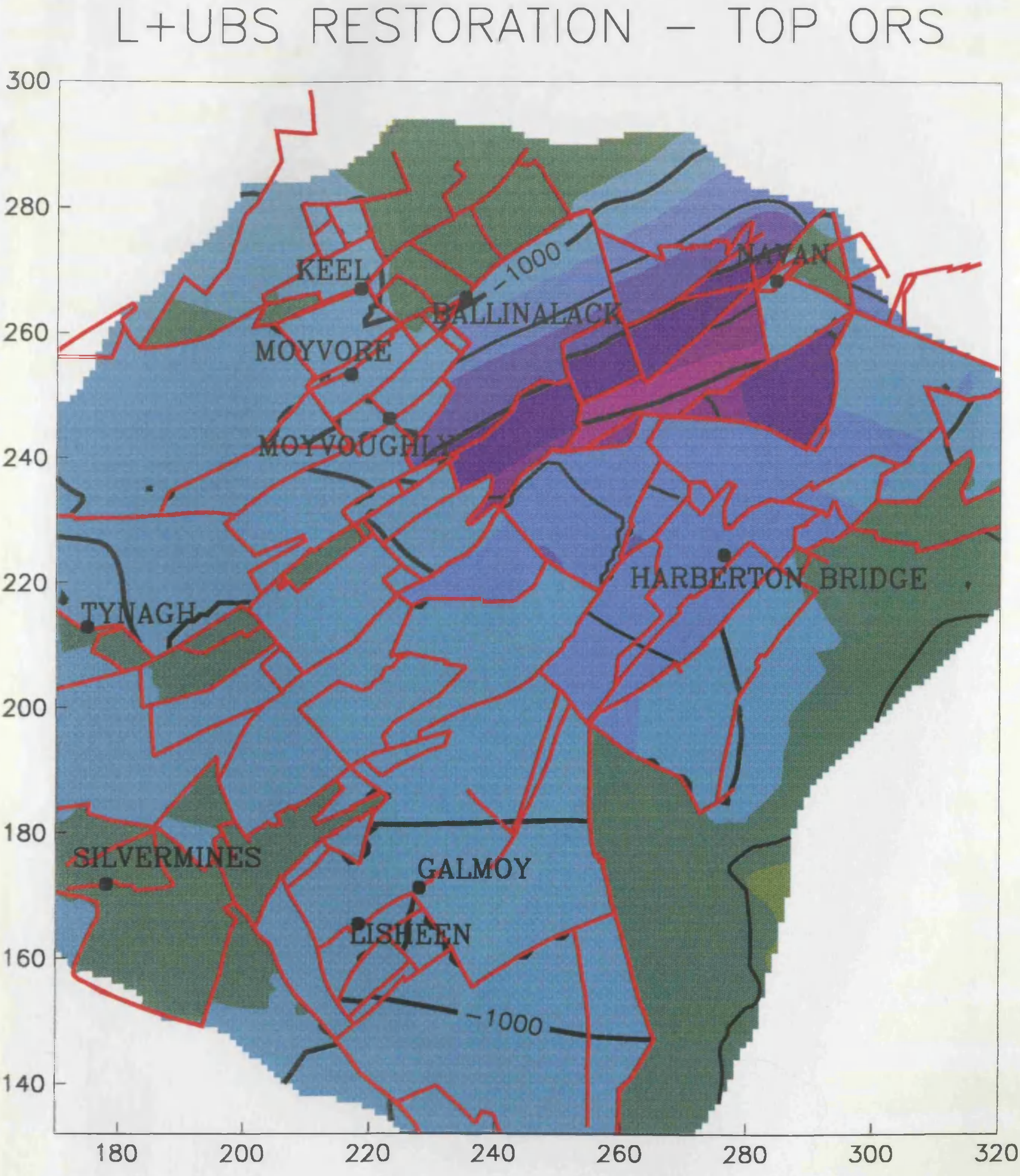


Figure 48. Top of the ORS unit at the end of the L+UBS Restoration, with L+UBS, Chadian, Waulsortian, ABL and Navan time faults in red. Colours represent depth, with depth values given in Figure 8. Deposit locations in black.

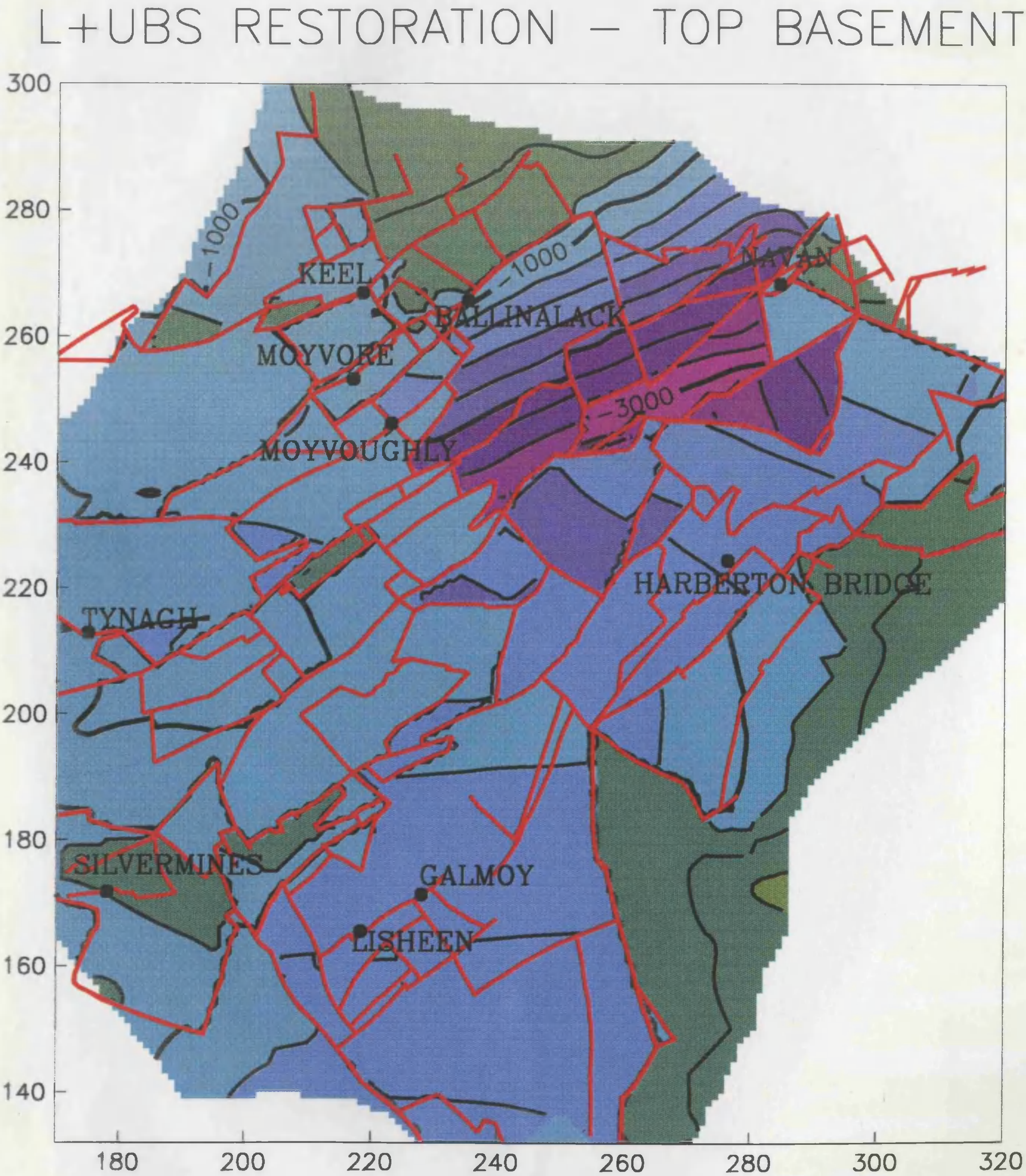


Figure 49. Top of the Basement at the end of the L+UBS Restoration, with L+UBS, Chadian, Waulsortian, ABL, Navan and ORS time faults in red. Colours represent depth, with depth values given in Figure 8. Deposit locations in black.

uniform everywhere. This study does not address the nature or timing of this uplift (but see Murray, 1992), but Figure 50 shows those present-day top-basement faults that initiated after the end of the Early Carboniferous.

4:2 PRESENT-DAY GEOMETRIES

The methods used to reconstruct both the top-basement surface and the tops of the sedimentary units, have been described in detail in the previous chapter, together with the information available and the assumptions made in the reconstruction. This section focuses on those features of the reconstructed geometries which help in the interpretation of the structural evolution of the region. All maps have been reconstructed above the present erosion surface and are shown as structure contour maps at a scale of 1:350,000 in Appendix B.

4:2:2 Top-Basement

Figure B1 is a 1:350,000 map showing both the faults cutting the top-basement surface and contours of the top-basement surface grid. As explained in Section 2, Chapter 3, the top-basement structure-contour map uses a tilted fault-block structural style, and it is reconstructed above the present-day erosion surface.

This map shows a large sub-sea region, with marginal elevated areas representing the Longford-Down massif to the north, and the Leinster Granite massif to the east. The elevated area in the southwest corner represents the Slieve Aughty and Slieve Felim Mountains. The Slievenamon upland partly bounds the southern margin of the region. This bowl-shaped depression is transected by several uplands, some reaching a (reconstructed) top-basement elevation of several hundred metres above sea-level. The map also depicts a series of sub-basins with a dominant SW - NE trend, and several more equilateral sub-basins -- or local depressions. The deepest of these sub-basins, the Dublin Basin in the NE of the area, reaches a depth in excess of 2800m.

The top-basement map shows about 150 faults. Most of the faults exposed in Central Ireland are high angle normal faults, but all faults are treated as vertical in the reconstruction. This is because, at the scales used in this study their lateral component of movement is too small to be distinguishable. Because of the way the map is constructed, many of these faults must represent the accumulated displacement occuring on a number of smaller faults. Never the less, the faults both adequately represent the fault displacement pattern and the fault distribution for a <u>regional</u> interpretation. This approach is not sufficiently detailed for use in local studies.

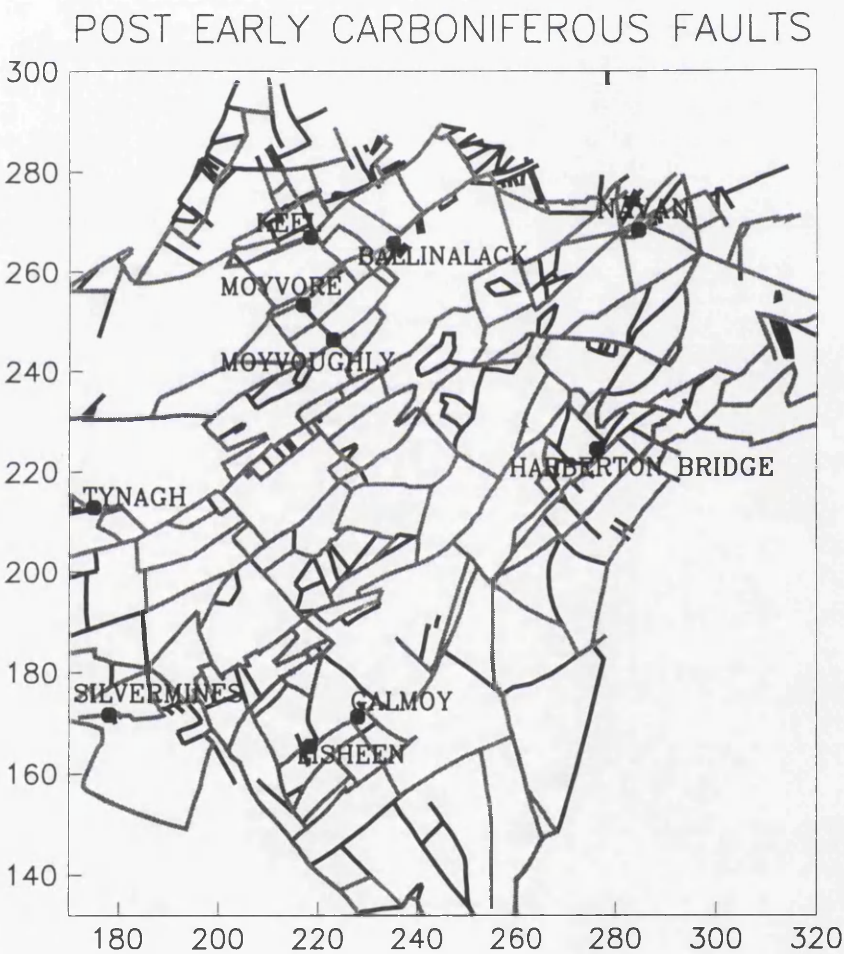


Figure 50 Map showing Post Early Carboniferous Faults in Black and Early Carboniferous Faults in Grey.

The larger portion of the faults, and most of the longer faults, trend southwest-northeast, as has been observed by many workers (see, for example, Williams and Brown, 1986). This orientation parallels the structural trend imposed by the Caledonian Orogeny on the basement rocks -- a fact which has also been noted by many workers. However, there is not necessarily a causal relationship, and Figure B1 reveals a number of other trends, including one approximately normal to the southwest-northeast trend. These southeast-northwest faults are typically shorter, except in the less well constrained southern portion, where they dominate. The orientations at and near the Longford-Down Lower Palaeozoic inlier margins do not follow the pattern developed in the rest of the region, which casts some doubt on the importance of Caledonian structures in controlling fault orientation.

The present-day configuration of the basement created in this project is in general agreement with previous work (Phillips and Sevastopulo, 1986: Williams and Brown, 1986; Andrew, 1992)), though there is general uncertainty as to the depth of the Tynagh Basin (Fig 1) and of the Dublin Basin (Jones et. al,. 1988; Strogen et. al., 1990). The interpretation presented here also differs from some earlier work in that it has not identified any obvious transcurrent motions (see, for example, Coller et. al. 1986). In addition, this reconstruction includes faults along most, but not all, of the trace of the interpreted Iapetus Suture Zone. Those faults that do lie along the trace of the Iapetus Suture are not fully connected, and they do not correspond with any notable structural features.

4:2:3 Sedimentary Units

The reconstructed structure contour maps on the top of all the sedimentary units are contained in Appendix B, and do not require detailed description. The general shape of the lower units do not diverge significantly from the shape of the top-basement surface. The shape of the top-ORS structure contour map (Fig. B2) is virtually indistinguishable from the top-basement map (Fig. B1). The top-Navan unit surface (Fig. B3) is again very similar in shape to, the top-ORS unit map, except in the northeast, where several fault blocks (which bound the Navan depositional centre) are notably higher.

The top-ABL structure contour map (Fig. B4) still retains the general shape of the top-basment map, but the relative elevations of the faults blocks in the northeastern part of the region have changed considerably from the top-basement to the top-ABL surface, the top-ABL surface being some 1500 m above the top-basement surface in the vicinity of the ABL depositional centre, while most of the remainder of this surface is about 500 m above top-basement. However, in the far northwest, at the margin of the Leinster Granite massif, and, to a lesser extent, in the southwest of the region, the top-ABL surface is only 100 to 200 m above the top-basement surface. This pattern of thicker units in the northeast (in the developing Dublin Basin) and thinner units in the far northwest and the eastern margin continues to reduce the structural relief of the developing "basin" though the remaining units.

The top-Waulsortian surface is also relatively higher in the parts of northeast, reaching sea level in an area where the basement is 2 kilometres subsea, though in adjacent fault-blocks, the top-Waulsortian surface is still about 1 kilometre below sea level. The general shape of the "bowl" of the top-basement surtace still remains in the top-Waulsortian surface, but the structural relief is much subdued, and the northestern region is no longer obviously the deepest part of the :"basin".

The top-Chadian surface has a very similar form to that of the top-Waulsortian surface, but the top L+UBS surface differs, again by being relatively much higher in the northeast. Virtually all of the top L+UBS reconstructed surface is above sea-level: the exceptions are a very few areas (where there are Namurian-age rocks) including parts of the south- southeast (where there is no subsurface control -- see below) where the top L+UBS surface is at several hundred metres below sea-level. While it is possible that the reconstruction is accurate in this south-southeastern area (of no subsurface information) it is probable that at least the upper reconstructed surfaces are too low here.

4:2:4 Quality of the Reconstructed Surfaces

The reconstructed surfaces match all available surface and subsurface information, but such information is very unevenly distributed (Fig. 6). The top-basement through Waulsortian surfaces are quite well constrained (by data) in all but the southeastern parts of the region. Data constraints for the remaining units is poor almost everywhere.

But the quality if the reconstruction must be judged more generally. Is it geologically sensible, and how free of numerically-generated errors are the grids? The style of the reconstruction -- tilted fault-bounded blocks at the top-basement level -- has been shown to be viable (see Chapter 3:3), and has been incorporated in the restoration so that the sedimentary units are also faulted. Dip information from the late-1800s to early-1900s Institute of Geological Sciences one inch to the mile maps (see for example, James, 1857). suggests that some of the sedimentary units (particularly the lower ones) respond to continued faulting by a combination of faulting and folding. The folding has not been incorporated in the reconstructed surfaces. However, the folded regions are probably only a few hundred metres wide -- less than the size of a single grid block.

The top of the sedimentary units were generated using faulted isopachs of the each unit (see Chapter 3:4). This process involves digitising synsedimentary faults for each unit and using these faults in the generation of the faulted isopachs. It is not possible to copy a fault trace exactly via digitising, and it is not practical to identify and extract fault segments from the top-basement fault file which contains several tens of thousands of fault segments.

The result is thickness data which "finds itself on the wrong side of a fault" -- and produces anomolously high or low areas adjacent to some faults when the surfaces are added to the top-basement surface in the reconstruction (see Reconstructed Geometry, Chapter 3:4).

The result of this slight mismatch of fault positions is anomolous contours on the top-sedimentary unit maps. These contours are visually disturbing, but their origin is known, and they do not affect the interpretation. The only practical (but very time-consuming) approach is to individually edit the erroneous points. This has been done for only the lower units, as errors in a lower unit are carried to all higher units (see Reconstructed Geometry, Chapter 3:4).

4:3:1 GEOLOGICAL SIGNIFICANCE

4:3:1 Subsidence

During the Lower Carboniferous the region experiences a change from sub-aerial deposition to that of shelf and basinal environments. There is also a change from clastic deposition, through almost exclusively carbonate deposition, to carbonate-dominated deposition. The number of active faults increases, and the area affected by faulting expands. Deposition appears to have been controlled quite strongly by both synsedimentary faulting and by variations in relative subsidence. How were these changes achieved and why did they occur?

Much of the change of depositional setting in the Early Carboniferous of Central Ireland has been attributed to transgression, which is often regarded as being primarily the result of a global sea-level rise. MacCarthy and Gardinier (1987) have identified six transgressive-regressive cycles in the marine Dinantian of the Munster Basin (Southwest Ireland). This study has not attempted to extend their work to the equivalent rocks in Midland Basin region. However, a change in local sea-level, due only to changes in the global sea-level, does not explain the concurrent development of newly-emergent regions and centres of deposition. This pattern has to be the result of local relative changes in surface elevation -- or of tectonics.

This study has shown that synsedimentary faulting (probably combined with changes in sea level, and/or the rate of sediment supply) not only controls the sediment accumulation near faults, but that changes in elevation due to (synsedimentary) faulting appear to occur across whole fault-bounded blocks. That is, rather than changes in elevation being produced by some minor deformation around faults and a regional "sag" (Andrew, 1992) -- possibly as a response to the accumulation of overburden -- it is accomplished by a combination of bulk vertical motion and tilting of fault-bounded blocks. There may also be some minor lateral motion or rotation (about a vertical axis) of the fault-bounded blocks. It is therefore concluded that local changes in surface elevation are the result of block faulting.

To what extent was the change in elevation of the whole of central and southern Ireland in the Lower Carboniferous achieved by block faulting, and what drove this change in shape? This study does not specifically address the tectonics or geodynmics of these changes, though other indicators of the tectonic environment of central and southern Ireland in the Carboniferous are addressed later in this chapter, and in the Discussion Chapter.

Although the general picture of the Lower Carboniferous Midland Basin is one of a shelf and basinal setting developing via downward motion of fault blocks at top basement level, there are local anomalies which may well prove significant to the location of ore deposits. These are areas in which the most and least rapid deposition (and so the relative movement of fault-bounded blocks) do not remain in the same place through the region's evolution. Perhaps more significantly, some fault blocks which were low relative to their neighbours early in the region's evolution are relatively high later, and vice versa. At least at the sedimentation surface, fault blocks are moving up and down, both relative to each other, and absolutely. Later in the basin evolution, some fault blocks are moving absolutely up at top-basement level. This contrasts with the commonly held view (of basin formation) that all tectonic movement was absolutely down.

4:4 CONTROL ON MINERALISATION

The distribution of the mineral deposits in the Midland Basin region is described and discussed. This is followed by an investigation of the more local structural setting of several of these deposits which uses the restored geometries extensively.

4:4:1 How are the Deposits Distributed?

The Pb-Zn deposits tend to occur as widely spaced individuals or clusters. Russell (1968) pointed out that deposits, or clusters of deposits, were separated by distances of 20 km or more. He proposed that this was a result of the development of hydrothermal convective cells of about 20km diameter, which focused the hot mineralised fluids into an updraft at the deposit sites. Though this distribution still dominates, the discovery of the Lisheen and Galmoy deposits, which are separated by only about 8 km (Fig. 1), ensures that Russell's explanation of deposit separation is not the whole story.

Russell (1968), Haszeldine (1988) and Russell and Haszeldine (1992) have also suggested that mineral deposits develop on, or near, long-lived crustal scale "geofractures". The geofractures are oriented (present-day) north-south, are spaced about 50km apart, and these authors propose that mineral deposits can occur where they intersect Caledonian structures. The reconstruction and restorations neither support nor refute this hypothesis. The maps do not show many north-south faults, and certainly no through-going north-south faults in the positions proposed by Russell (1968), Haszeldine (1988), and Russell and Haszeldine (1992) for geofractures. However these authors state that they do not require a fault offset as a demonstration of the existence of a geofracture. They propose that geofractures have more of the characteristics of a joint than a fault, and so have no requirement for displacement, though, as planes of weakness, they might be expected to be the loci of appropriate fault displacement.

Hitzman (1993) provides a partial explanation for the distribution of some deposits in the south-central part of the area around the Lisheen and Galmoy deposits (Fig. 1). He describes the Rathdowney Trend as an approximately 40km long belt containing a number of prospects and mineral occurrences (including Lisheen and Galmoy) within the "Lower Carboniferous limestones". He suggests that a "dolomite front", which approximately parallels the Rathdowney Trend is both sub-parallel to a major northeast-trending Carboniferous-age fault, and to a shelf-basin facies transition in the Chadian- through Brigantian-age rocks. He further proposes that mineralisation occurs preferentially along feeder faults, or in structural traps (anticlines) at the base of the dolomitised "Waulsortian Limestone" near the structurally-controlled edge of the "dolomite front".

The restorations created as part of this study place the Rathdowney Trend near sea-level during the Chadian, and some 20km south of a shelf to basin transition in the L+UBS restorations (though information available to locate this transition is sparse). But the restorations agree with Hitzman's interpretation on the location of Lower Carboniferous synsedimenatary faults.

As was the case for the geofractures, the reconstruction and restorations are not the appropriate tools to investigate the <u>causes</u> of orebody distribution. Potential causes are assessed in the next chapter (Chapter 5) which addresses the fluid flow systems that could have developed in Ireland in the Carboniferous, and possible energy sources, driving mechanisms, and flow paths.

4:4:2 Relationship to Faulting

A number of previous workers have commented that the known orebodies and prospects occur at basin or sub-basin margins (see, for example, Large, 1980; Hitzman and Large, 1986). The reconstructed geometry supports this assertion for Navan, Silvermines, Tynagh, and possibly Lisheen, with less convincing positioning for Galmoy and Harberton Bridge (Fig B1). The prospects fall into both camps about evenly.

It is conjectured here that deposits tend to occur not just near basin or sub-basin bounding faults, but instead at fault-block corners, which are of two types: outside corners, where the upthrown block takes on the geometry of the corner of a table, and inside corners where the geometry is the inverse (Fig. 51). This conjecture is investigated using the restorations, which provide a clearer picture of the structural setting as the basin developed than does the reconstruction. The proximity of several deposits or prospects to fault-block corners is assessed, and the potential significance of corner development to interpretation of timing, and to type of mineralisation, is investigated.

As the host rocks of the known orebodies and prospects vary, and, therefore, so do the earliest time at which mineralisation can have occurred, each deposit is discussed separately, and its structural setting assessed, starting with those hosted in the oldest sedimentary rocks.

4:4:2:1 Keel

Slowey (1986) states that the Keel mineralisation is hosted primarily in the basal clastics (see below) and is closely associated with the Keel faults system and its deformation. No other deposits are interpreted as being contained primarily in basal clastics. It is not entirely clear if the basal clastics should be contained within the ORS or Navan units, so all restorations (from the ORS on) are considered as periods in which (synsedimentary or replacive) mineralisation could have occurred. During the ORS restoration Keel is adjacent to the intersection of two identified synsedimentary faults which form an inside corner (Fig. 28). Keel is on an active fault, and near, but not on, a corner during the ABL restoration (Figs 32 - 34), and is at a corner again during the Waulsortian (Figs 35 - 38) and later (Figs 39 - 49) restorations. If a corner is required for mineralisation, there appear to have been opportunities for either synsedimetary or replacement mineralisation to have developed during the ORS restoration, and replacement mineralisation from the Wausortian restoration onwards.

4:4:2:2 Harberton Bridge

The Harberton Bridge Zn-Pb-Fe deposits occur in lowermost Navan-equivalent through Arundian host rocks, primarily as breccias and fracture fills (Emo 1986). The deposit is again taken to be closely associated with local faulting. Emo interprets Harberton Bridge's inferred position near a basin margin to suggest that the movement of mineralising fluids was controlled by basin-marginal faults.

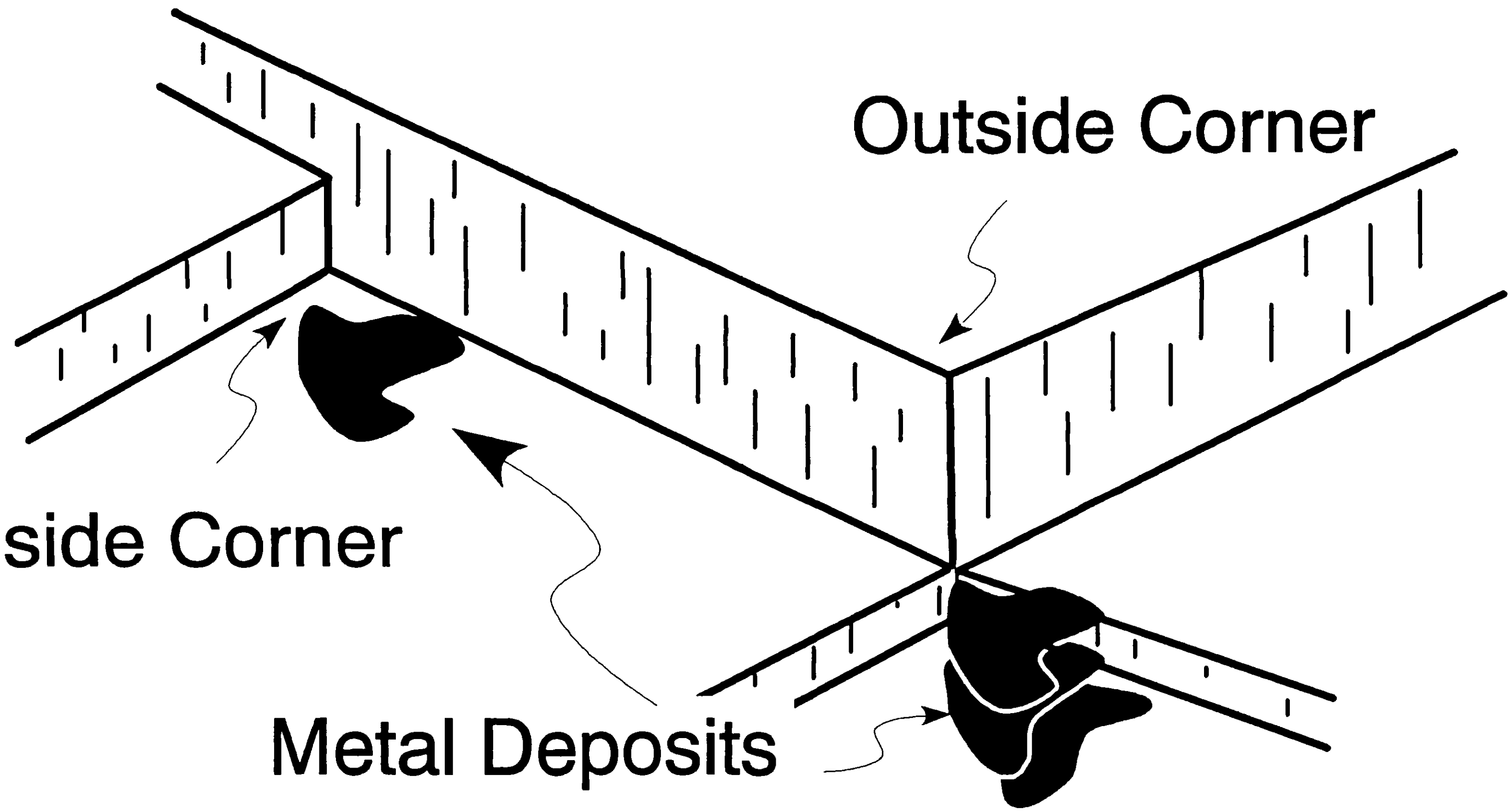


Figure 51. Sketch of Fault-Block Corners Showing Hypothetical Ore Deposits.

Harberton Bridge was near (within about 5 km, but not on) an inside corner from the ORS through the ABL restorations (Figs 28 and 30 - 34). It was not on an active fault during the Waulsortian restoration (Figs 35 - 38), and was on an inside corner during the Chadian restoration (Figs 39 - 43). Harberton Bridge was not near any interpreted active faults in the L+UBS restoration. There appear to be two opportunities for corner-associated mineralisation: potential synsedimentary and/or replacement mineralisation in the ORS through ABL restorations, and again in the Chadian restoration.

4:4:2:3 Navan

The Navan ore deposit is not only the largest Pb-Zn accumulation in Ireland, but it is also the deposit at which mineralisation is shown to have occured over the longest time interval (Ashton et al, 1992). The Pale Beds (contained in the Navan unit as used in this study) are the oldest host rocks, and the youngest mineralisation extends possibly into the Arundian, but most probably into the Chadian (Ashton et al, 1986).

The Navan site is near a synsedimentary fault during the Navan restoration (Figs 30 and 31). But, because of a lack of data near the edge of the area of study, and because of Navan's proximity to the Lower Palaeozoic Longford-Down inlier, there is not sufficient information on the configuration of the sedimentary units to tell whether the Navan is also at a corner at this time. It is at an outside corner in the ABL (Figs 32 - 34), the Waulsortian (Figs 35 - 38), and the Chadian (Figs 39 43) restorations. It is on an active fault in L+UBS restoration (Figs 44 - 49), in a complexly faulted area, but is not on a corner.

The multiple lenses at Navan (Ashton et al., 1986) strongly suggest several mineralisation events, be they synsedimentary, replacement, or both. Navan's proximity to a corner during much of the Courceyan permits mineralisation (associated with a corner) of both a synsedimentary and a replacive nature to have occured over much of the early Carboniferous.

4:4:2:4 Moyvoughly

Poustier and Kucha (1986) describe the Moyvoughly prospect as being contained in host rocks which are lithostratigraphically equivalent to the rocks hosting the Navan orebody, and of having both cross-cutting and stratiform features. In the Navan (Figs 30 and 31) and ABL (Figs 32 - 34) restorations Moyvoughly is near, but not on, an inside and an outside corner. Only a nearby inside corner remains in the Waulsortian restoration (Figs 35 - 38), while the Chadian and L+UBS restorations show no nearby active faults. This interpretation suggests that, if corners are required for mineralisation, both synsedimentary and replacive mineralisation during the Navan restoration, and ABL and/or Waulsortian replacement mineralisation during the ABL and Waulsortian restorations, are possible.

4:4:2:5 Ballinalack

The Ballinalack prospect is described by Jones and Brand (1986) as occurring primarily in Waulsortian host rocks, and secondarily in Navan-equivalent host rocks, and is suggested by these authors to be early diagenetic. But it is also described as being of late Chadian age by de Brit (1989). Ballinalack first appears on an active fault in the ABL restoration fairly near a corner (Figs 32 - 34), but is not located on an (inside) corner until the Waulsortian restoration (Figs 35 - 38). It is no longer on an active fault for the remaining two restorations. If corners are required for mineralisation, this interpretation permits Waulsortian-hosted mineralisation to be either synsedimentary or replacement, but requires replacement mineralisation of the Navan-age sedimentary rocks.

4:4:2:6 Silvermines

The Silvermines deposit, as described by Andrew (1986b), consists of several somewhat different orebodies, including epigenetic mineralisation in the basement rocks and basal clastics. The remainder (and largest part of the reserves) occur between the Lower Dolomite of Andrew (1986b) and the base of his Waulsortian Reef Limestone. Therefore the structural position of Silvermines from the ABL restoration onwards is assessed. Silvermines is at the edge of the region studied, so assessment is rather difficult for the same reasons as it was at Navan. However Silvermines does appear to have been near (within about 5 km) a corner in the ABL restoration (Figs 32 - 34), and probably in the Waulsortian restoration (Figs 35 - 38). It is on an active fault in the Chadian, and near an active fault in the U+LBS. If a corner is required for mineralisation, synsedimentary mineralisation just at the start of the Waulsortian restoration, accompanied by minor replacement mineralisation of the underlying units, is possible, as is one or more replacive mineralistions that occurred at some time during the remainder of the early Carboniferous

4:4:2:7 Tynagh

The Tynagh deposit is variously described as primarily syngenetic (Boyce et al, 1983; Banks and Russell, 1992) or primarily epigenetic (Clifford et al, 1986). Most of the ore is hosted in the Waulsortian Limestone facies (Clifford et al, 1986). Tynagh is positioned on a broad corner from the ABL through the Chadian restorations (Figs 32 - 43). However this corner changes character through this period. In the ABL restoration (which pre-dates the Waulsortian-hosted mineralisation) it is an outside corner with the south side down (Figs 32 - 34), while it is an outside corner with the north side down is the Waulsortian and Chadian restorations (Figs 35 - 43). The known mineralisation is on the north side of the Tynagh fault (Morrissey, 1970). It is not on an active fault in either the ORS or the L+UBS restorations.

If corners are required for mineralisation, the Tynagh deposit was formed by synsedimentary mineralisation during the Waulsortian restoration, and/or replacement mineralisation during the Waulsortian or Chadian restorations .

4:4:2:8 Lisheen

Hitzman et al. (1992) describe the Lisheen ores as occurring primarily in dolomitised Waulsortian Limestones, and as being replacive or void filling. They interpret the mineralisation to have occured during the Chadian or the Arundian. The Lisheen deposit is on an active fault, but not a corner, in the ORS (Fig. 28), Waulsortian (Figs 35 - 38) and Chadian (Figs 39 - 43) restorations. It is otherwise not interpreted to be on active faults. As the host rocks are contained in the Waulsortian unit, the mineralisation did not occur during the ORS restoration. If corners are required, then synsedimentary or replacement mineralisation in the Waulsortian restoration, or replacement mineralisation in the Chadian restoration are permissible.

4:4:2:9 Galmoy

The Galmoy deposit is described by Doyle et al (1992) as occurring in completely dolomitised Waulsortian Limestones. It is also described by them as primarily stratabound replacement mineralisation, mainly hosted in breccia, with secondary fracture-fill Cu-Ag mineralisation. Galmoy is on a well-defined corner in the ORS, (Fig. 28) Waulsortian (Figs 35 -38) and Chadian (Figs 39 - 43) restorations. The same arguments as to timing and type of mineralisation apply: to Galmoy as they did to Lisheen. That is Waulsortian restoration synsedimentary or replacement mineralisation or Chadian restoration replacement mineralisation are allowable if corners are required for mineralisation.

There is a good, but certainly not perfect, correlation between deposits and corners revealed by the restorations. This is encouraging both for understanding the genesis of deposits, and from an exploration viewpoint. But identification of a potential spatial relationship between deposits and corners is only a starting point. This issue is expanded in the Discussion, where the neccessity of corners is considered, together with other elements which may be necessary for mineralisation. The degree of development of corners and possible mechanical explanations for the occurrence of deposits at corners are also addressed there.

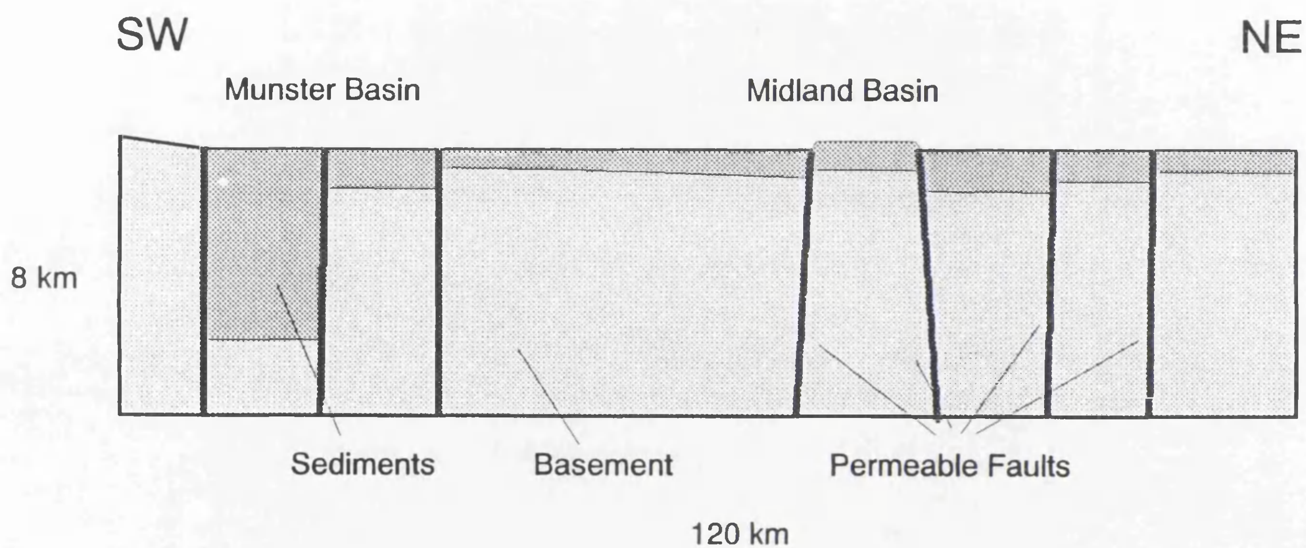
CHAPTER 5

NUMERICAL MODELLING OF FLUID- AND HEAT-FLOW SYSTEMS IN THE MIDLAND AND MUNSTER BASINS

The Mass Balance chapter (Chapter 2) has identified some of the controls on the size and character of the fluid system(s) that could have brought hot, mineralised fluids to the sites of ore deposition. Chapters 3 and 4 have defined the shape of the Midland Basin region at several stages of the basin evolution. The geological analysis reveals that synsedimentary faulting is important, and it indicates that the ore deposits have a strong tendency to be located at fault-block corners. The purpose of this chapter is to: (1) assess the fluid- and heat-flow systems that could have developed in the Midland Basin region, and its surrounds, during the early Carboniferous; (2) to determine if faulting exerts a control on the flow systems; and (3) to assess whether any of the surviving hypothesised flow systems could have provided hot fluids to the near-surface deposit sites. This investigation is performed using a 2-D heat and fluid-flow simulator which is applied to a cross-section extending from a point south of the Munster Basin to a point in the Longford-Down Lower Palaeozoics inlier (Fig. 52; NB. the Longford Down inlier was covered by basin sediments in the early Carboniferous)).

5:1 THE GEOLOGICAL QUESTION

The lead-zinc deposits of central Ireland are the product of hot (up to 250^{O}C), mineralised hydrothermal fluids which have been delivered to the sites of ore deposition. The candidate flow systems discussed in the Mass Balance Chapter (Chapter 2) have the following proposed or implied driving mechanisms: gravity-driven (local and/or regional); compaction (with or without a tectonic loading); and local basement-involved (free) convection. Flow systems driven by each of these mechanisms can be evaluated by numerical models.



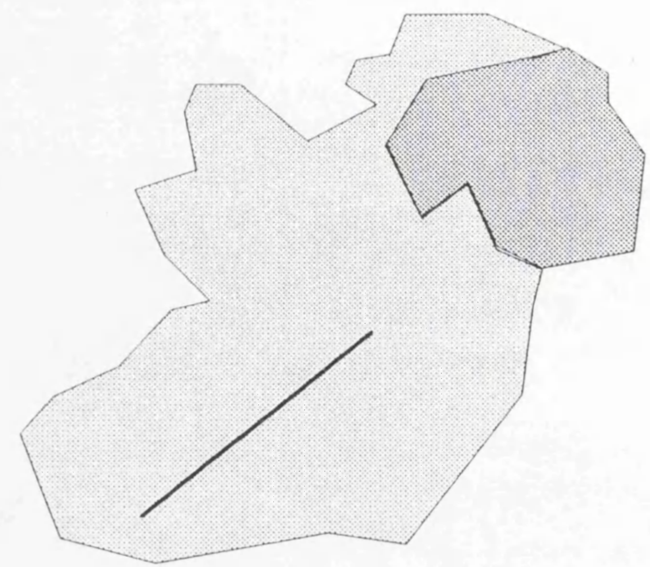


Figure 52. Schematic, Regional Cross Section Used for Fluid Flow Modelling, with Location Map of Ireland.

5:2 NUMERICAL SIMULATOR

Numerical models are used to test the flow systems that develop in the Midland and Munster Basins as a consequence of gravity-driven and convective drives. The available model can be used to simulate the development of topographically-driven or convection-driven flow systems, but it cannot simulate compaction or the effects of tectonic loading. However, the likely effects of both compaction and tectonic loading are discussed in light of the results of this and other studies, including reference to published works that consider these energy types.

There are no closed-form analytical solutions available for the governing equations that describe fluid flow, heat transport and geochemical mass transport through porous media. However, such systems can be discretised, and the equations can be solved numerically. In their simplest form, numerical methods involve assigning initial values to a sufficient number of variables for the equations to become solvable. Such solution techniques have been developed and utilised extensively in the past twenty years or so, to take advantage of the advances in computing capabilities.

Quantitative (numerical) 2-D simulations of transport through basinal sequences, with consideration of fluid-flow, heat and mass transport, were first published by Garven and Freeze (Garven & Freeze, 1984a; Garven & Freeze, 1984b) as part of an investigation of the role of groundwater flow in the genesis of stratabound ore deposits. Their stated purpose was not to use numerical modelling as an exploration tool, but rather as a means to better understand the general behaviour of the system being studied. Numerical modelling is used in that spirit in this study.

Garven and Freeze (1984b) and Garven (1989) provide thorough reviews of the theoretical background, and the reader is referred to these publications. The 2-D simulator used by these authors is informally called OILGEN, and has been adapted and used in the investigation of a range of geological heat- and fluid-flow problems (Garven, 1989; Ge and Garven, 1994; Lewis et al, 1994; Raffensperger and Garven, 1995; Haszeldine and McKeown, 1995).

OILGEN uses a mesh of quadrilaterals generated from a digitised geological cross-section to represent the shape of the model, and to represent the distribution of material properties. The quadrilaterals are divided into linear, triangular, finite elements for the numerical solution of the partial differential equations. Boundary conditions in the model are as follows: the ends are no-flow boundaries to fluids, heat, and mass transport; the base is a no-flow boundary to fluids and mass transport, but a uniform heat flux is specified across it; the upper boundary represents the water table (so only the behaviour of the fully saturated zone is simulated). It is a surface of free mass flow, is isothermal, and is isobaric.

A salinity-depth profile, a uniform top surface temperature, and a uniform basal heat flux are specified. Initial fluid properties are determined from the conductive temperature field, and iterative procedures are used to find a solution to the transport equations. Convergence is accepted when the temperature difference from the previous iteration is less than 1%. Water density and viscosity are determined from equations of state (Kestin et al, 1981).

Coupled or uncoupled heat- and fluid-flow options are available, as are steady-state or transient solutions. Darcy velocities are used to calculate average linear flow velocities. The temperature field, the head distribution, and the stream function are also calculated.

The discretised cross section must not contain more than 2500 quadrilateral elements or 9 discrete material types. These elements must represent all lateral and vertical variations in geometry, and in rock, thermal and petrophysical properties. All quadrilateral elements are assigned to a material type: in practice this means that the range of properties displayed by the region's sedimentary rocks must be represented by a single set of porosity, horizontal permeability, and vertical permeability values.

Although there is no need for elements to be of a similar size, in reality very large elements are poorly modelled, and tend to result in solutions that do not converge. In addition, layers of any given material type need to be at least two elements thick to provide a good solution. Because of phase changes in the behaviour of water at about 200°C (Kestin et al, 1981), temperatures in excess of this are reset to 200°C within OILGEN (Garven, pers. comm., 1995). This effectively places the lower boundary of the cross-section (for normal heat flow rates) at about 8 km depth.

5:3 THE GEOLOGICAL INPUT

5:3:1 The Cross Section

A cross section provides the geometric framework used in the simulation, and it is used to distribute material properties (Fig. 52). This section is discretised into a regular array of rows and columns of quadrilaterals, and the array is digitised. In this study one basic cross-section framework is generated and then adapted to reflect minor geometric changes. Major changes in the assignment of either material (rock) types to the quadrilaterals, or of the property values assigned to a material type, can be made without changing the cross-section framework.

There are a number of requirements that must be met by the cross-section used to generate the geological models. It must accomodate both the geographic limits of the potential flow systems and the geological elements involved in the development of these systems. It must also allow adequate discretisation of the included rock types into individual elements, and remain within the element-number and material-type limits of the simulator.

Because of the possibility that tectonically-driven flow from south of the Munster Basin reaches as far north as the Navan deposit, the chosen cross section extends from south of the palaeo-Munster Basin to the present-day Longford Down Inlier (Fig 52). The line of section is oriented approximately east-northeast to west-southwest. This was judged to be a suitable orientation for assessing flow which was a response to the Variscan orogeny. No preferred orientation has been suggested for local flow systems. Deep convective systems, being approximately radial, are modelled equally well in one orientation as another. Because deep basement-involved flow has been proposed, the section extends to a depth of eight kilometers, with basement rock occupying the lower part of the cross-section.

Several slightly different cross section surface (top water table) geometries are evaluated. These include: (1) a Variscan upland to the south of the Munster Basin, with surface slopes towards the Munster Basin; (2) several small (10m elevation) "uplands" bounding, or lying within, the Midland Basin; and (3) a regional south to north slope. The water table (top of the cross section) is otherwise taken to be at, or up to 100m below, sea level (see Section 5, Chapter 3, and below).

The cross-section is designed to reflect the salient features of Midland Basin geometry in both the early Carboniferous and in the Westphalian, as well as a simplified representation of the palaeo-Munster Basin at these times. Cross-sections of each restoration (Chapter 4) were generated along the intended cross section line and estimates made of the thickness of the stratigraphic column during the Westphalian.

The early Carboniferous restorations differ in detail, particularly in the thickness of the sedimentary rocks and number of faults, but all display a similar general shape and type of faulting. However, the degree of detail which can be incorporated is dictated by OILGEN's limits on grid and material properties, and so a fairly simple cross section geometry has been created. This section is intended to best approximate the Waulsortian restoration, but it is designed to allow variations in the sedimentary rock thickness so that the thicker Westphalian sedimentary column can also be modelled. The Munster Basin is represented by a 6km thick sequence of sedimentary rocks. The nature of these sedimentary rocks, and the distribution of faults in and around the Munster Basin, are derived primarily from MacCarthy and Gardiner (1987) and Graham (1983).

Given these considerations, the cross section created is about 120km long and 8km deep. Three material types are used in the basic case: (1) sedimentary rocks, (2) fractured basement, and (3) permeable faults. These categories are then subdivided as required, within the limits of the number of material types. The sedimentary rocks were originally subdivided into a clastic-dominated basal unit, and a carbonate-dominated unit, to assess whether preferential flow occurred the ORS, but the difference in properties assigned to these two rock types had no discernable effect on the results, and so this subdivision was abandoned.

5:3:2 Material Properties

5:3:2:1 Material Types

The three basic rock types -- fractured basement, sedimentary rocks and permeable faults -- are assigned to three different material property categories. The absolute values (of, for example, horizontal permeability) are varied from model to model, but the relative values of the properties assigned to these three materials is retained throughout: the sedimentary rocks have moderate porosity and horizontal and vertical permeabilities, the fractured basement has very low porosity and low to very low permeabilities, and the permeable faults have very low porosity but high permeabilities. Section 2:1:3 discusses geologically permissible ranges. Table 4 lists the variables used to define the material types, and the ranges assigned to these variables for each of the three basic material types.

5:3:2:2 Global Variables

Normal to slightly elevated heat fluxes of 65 to 75 mW/m^2 are used, together with a watertable (top of cross section) temperature of 20^oC. No salinity gradient information was available. Because of this lack of salinity distribution information, and because pure water undergoes phase changes at slightly higher temperatures than does saline water, a zero salinity gradient was used. This allows the models to be as deep as possible, Coupled heat- and fluid-flow, steady-state solutions are obtained for each simulation.

5:4 ASSUMPTIONS AND SIMPLIFICATIONS

The assumptions and simplifications made in the discretisation of a geological cross section have been discussed briefly, as have the geological simplifications made in generation of the cross-section. There is another set of assumptions made -- that of the match of the physical, mechanical, and chemical nature of the rocks and fluids being represented in the cross section to the simplifications inherent in the equations used in OILGEN.

Material Property	Sedimentary Rocks	Basement Rocks	Permeable Faults
Horizontal Permeability (md)	0.1 - 20.0	0.05 - 1.0	5.0 - 50.0
Vertical Permeability (md)	0.01 - 4.0	0.005 - 0.2	0.5 - 20
Porosity (%)	1.0 - 20.0	0.001 - 1.0	0.001 - 1.0
Thermal Conductivity (mW/m/°C)	2.5 - 4.5	2.5 - 4.5	2.5 - 4.5

Table 4. Ranges of material properties used for the three material types.

5:4:1 Two-Dimensional Flow

Perhaps the most obvious simplification is the use of a 2-D representation to simulate the behaviour of a 3-D system. Some flow systems may have the majority of their flow vectors contained in one plane, while others may have flow in a wide range of directions. It is not always possible to say *a priori* whether a flow system that has flow vectors in many directions is adequately represented by the values of vectors calculated in any given plane. In addition, even if a flow system has almost all its flow contained within a given plane, this flow may still be influenced by geological features out of that plane: these out-of-plane features cannot be represented in a two dimensional cross section. This problem can only be rectified by the development and use of a three dimensional heat- and fluid-flow simulator: such a simulator has been developed (Garven, pers. comm., 1995), but is not yet available for this study.

5:4:2 Continuous Porous Media

Multiphase fluid flow, heat transfer and chemical mass transport are adequately treated with continuum theory for porous media (Bear, 1972). The geology represented here strictly diverges from this state in that the the media used are discontinuous. This applies to both the fractures distributed throughout the basement, and to the permeable faults. A pervasively fractured medium can be treated as equivalent to a porous medium -- at least as long as the size of the elements is much larger than the fracture spacing (Garven 1995). This allows the fractured basement to be treated as a continuum, but permeable faults cannot obviously be categorised in this way.

The permeable faults in the basement of the Midland Basin are probably not open single fractures. Rather, they are likely to be zones of comminuted and chemically altered rock, through which an anastomosing set of very small open cracks has developed. Because permeability values are not known for either the fractures or the fault rock, and in the interests of simplicity, the permeable faults are treated as an equivalent continuum material type with low porosity but a high permeabilty.

5:4:3 Basin Type

OILGEN was originally formulated to investigate the hydrology of mature basins, but the Midland and Munster Basin region is continuing to develop during the time period being simulated. Sedimentation and primary compaction are still active, and synsedimentary faulting is probably common. The position and shape of the water table is changing, and there will be transient pore pressures caused by compaction, by uplift and by erosion. However, transient effects are probably localised, and the use of a steady-state solution is regarded as acceptable.

The upper surface of the model represents the water table. However, most of the top of the the geological cross section is at or below sea level. The present version of OILGEN treats this surface as isobaric, but could be adapted to better represent specified head values at its upper surface (Garven, pers. comm., 1995).

5:5 DATA INPUT AND OUTPUT

5:5:1 Generation of Input Parameters

The cross section is designed to have a consistent number of rows and columns. The positions of the rows and columns (the "mesh") are digitised, and the digitised points are converted into an appropriate format for OILGEN. The input files for OILGEN are generated using OILMENU. OILMENU is a graphical interface that displays the finite element mesh, allowing each quadrilateral to be assigned a material type number. OILMENU also allows the material properties of each of the material types to be set graphically. Basal heat flow rate, top-surface temperature, and the choice of a coupled or uncoupled solution are set in a similar manner.

5:5:2 Output

OILGEN's output takes the form of data files. However the results of the simulations can be displayed on-screen using OILPOST, and its more sophisticated cousin OILDRAW, which also produces hardcopy. OILDRAW displays all computed values in the framework of the cross section. Available displays include material type distribution, groundwater velocities, groundwater heads, temperatures, and the stream function. Each plot is annotated, as appropriate, with maximum plotted values and the value of the increments used in the plot. These plots are used to illustrate the results of the simulations, and are supported using values from the OILGEN output files if needed.

5:6 SIMULATIONS

Four groups of simulations were run. Three of the groups used the Midland and Munster Basins cross section (with variations in the surface shape as noted above), but with a different number of material types. The remaining group of simulations used a completely regular grid of rows and columns as its cross section. A large number of simulations are run for each set, with minor variations in values assigned the material types: only a representative sample of these simulations is included here.

The Midland and Munster Basins simulations are designed to allow investigation of the effects of both the distribution of material types <u>and</u> the values assigned to the material types and the boundary conditions. The regular grid is intended to investigate sensitivities of the calculation to variations in the grid geometry, and to provide a basis for the study of simple material type changes.

The first set of simulations, set 1, uses a regular grid geometry (Fig 53). It is good practice to investigate the behaviour of a numerical simulator by testing its response for a well known problem. Typically analytical solutions are used. In this case there were no analytical solutions available, so uniform elements were used and the reasonableness of their results assessed. These geometrically simple grids are also used at different points throughout the simulations to test sensitivities where a simple geometry is required. However, their main use is to investigate the stability of convective systems (see below).

The next three sets of simulations represent:

2. A very simple "generic" basin and basement geometry using sedimentary rock and fractured basement material types (Fig.54);
3. The geometry of the Munster and Midland Basins using sedimentary rock and fractured basement material types (Fig. 55);
4. The Midland and Munster Basin geometry, using sedimentary rock, fractured basement, and permeable fault material types (Fig. 56).

Examples of the results of each of these sets of simulations is discussed, and illustrated using OILDRAW plots of material type, water velocities, stream function, and temperature as relevant. Slightly different geometries and rock type properties are used in the plots illustrated for each set. The specifics of each plot are given in their captions.

5:6:1 Regular Grid

The regular grid series is used for two main purposes. It was originally intended to test the reasonableness of the behaviour of the simulator using very simple geometric and material type configurations. However, the inability of the Midland and Munster Basin

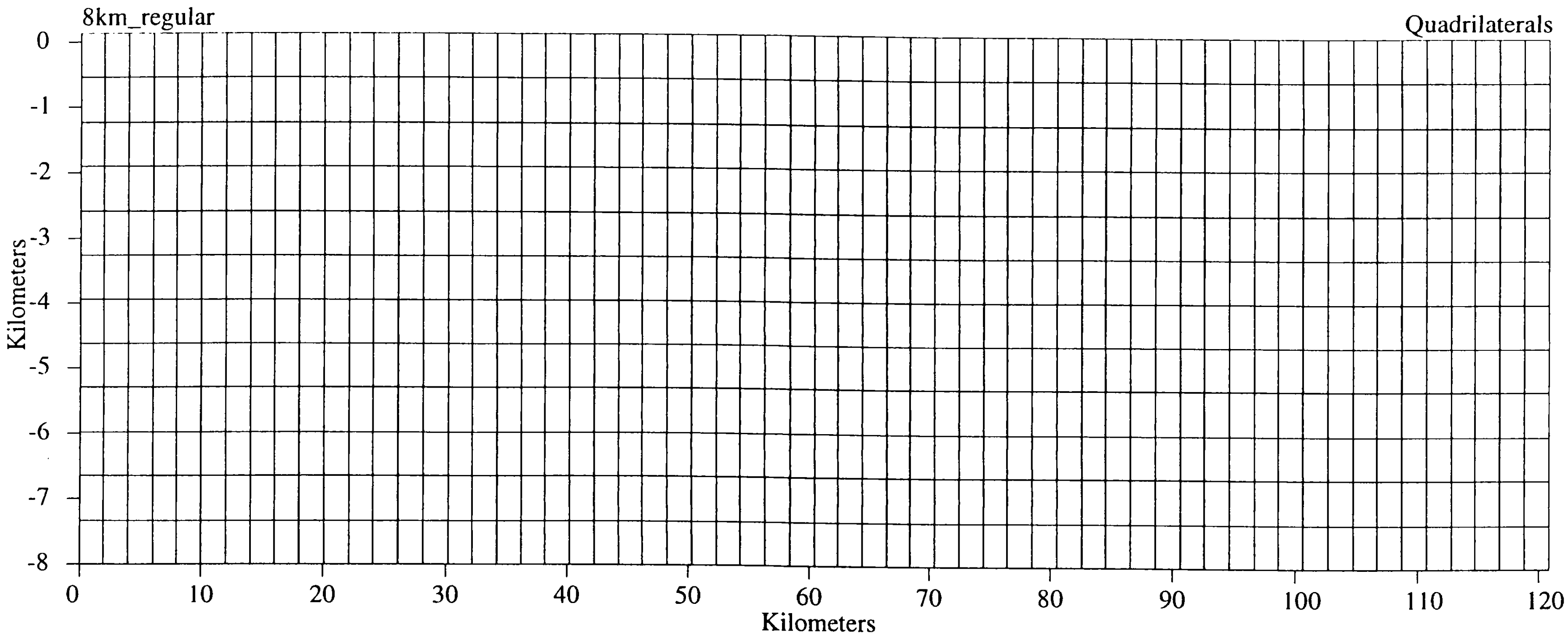


Figure 53. Geometry of regular grid of size 8km by 120km with flat surface (water table) at 20°C. Basal heat flow rate of $75mW.m^{-2}$. One material: porosity = 10%; horizontal permeability (kh) = 2md; vertical permeability (kv) = 0.2md.

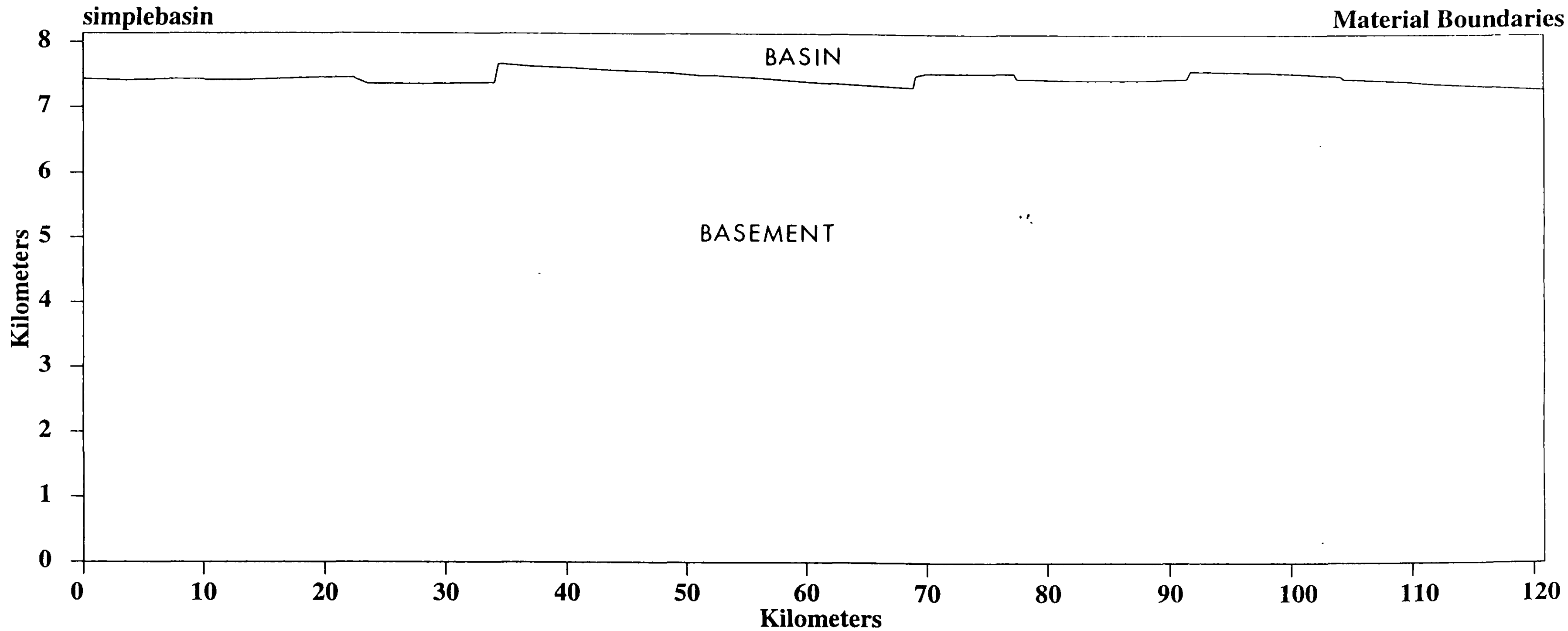


Figure 54. Material boundaries used for Simple Basin set of simulations. Grid is 8km by 120km, surface is 20°C and basal heat flow rate is 70mW.m^{-2} .Sedimentary rocks: porosity = 10%; kh = 5md; kv = 0.5md. Basement rocks: porosity = 1%; kh = 1md; kv =0.2md.

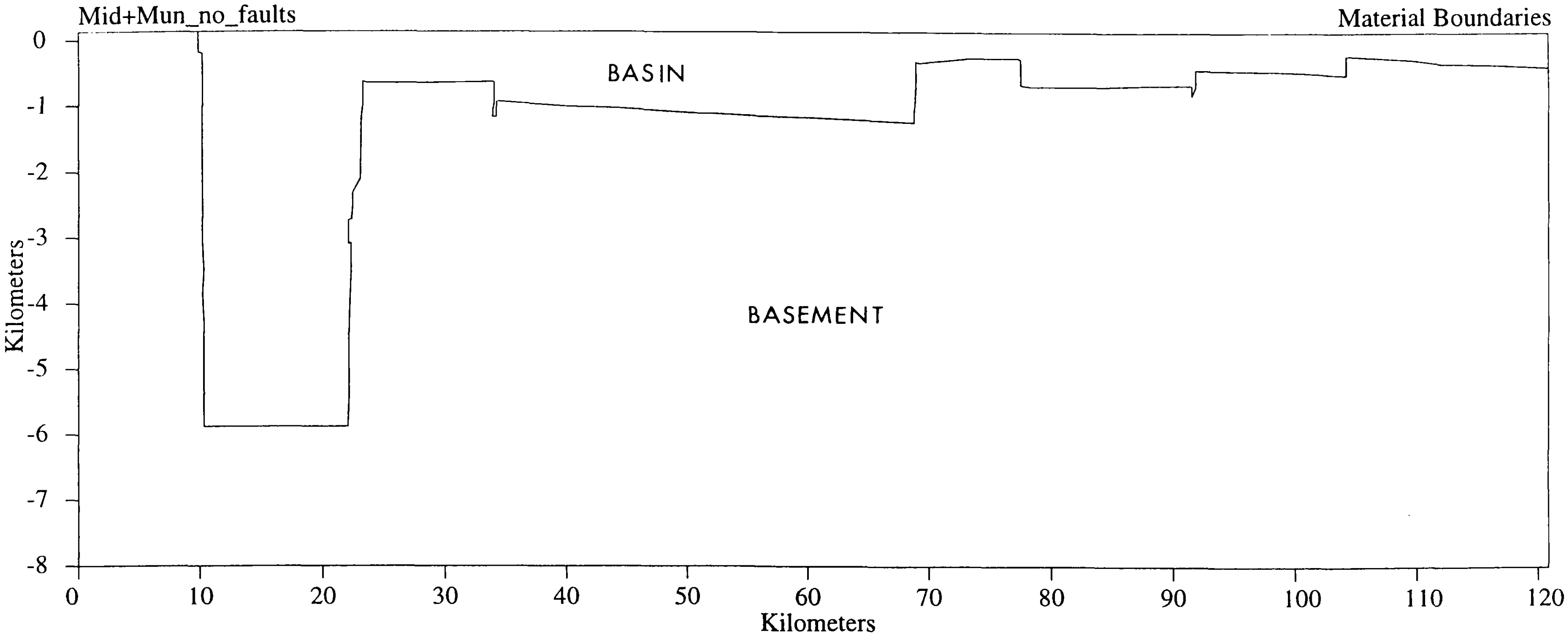


Figure 55. Material boundaries used for Midland and Munster Basins without fault simulations. Grid is 8km by 120 km, surface temperature is 20°C and basal heat flow rate is $70mW.m^{-2}$. Sedimentary rocks: porosity = 10%; kh = 2.5 md; kv = 0.5 md. Basement rocks: porosity = 0.5%; kh = 1md; kv = 0.2md.

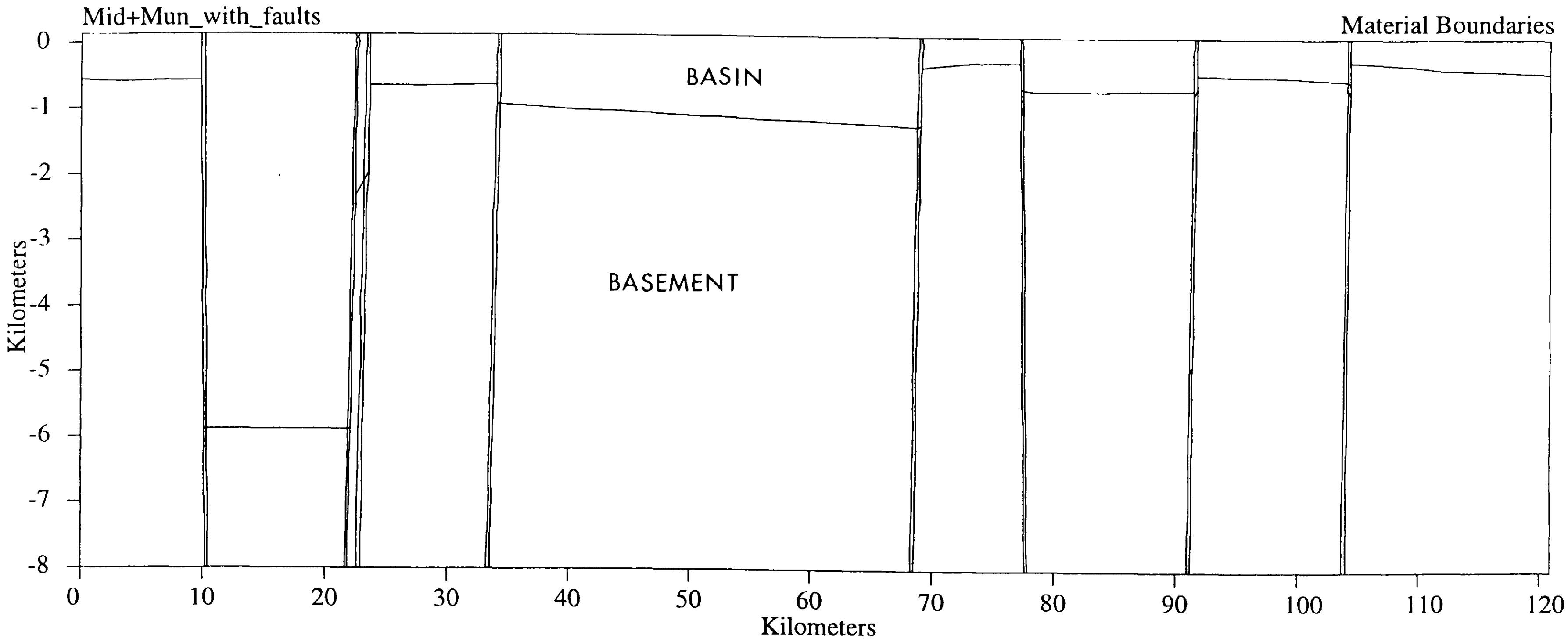


Figure 56. Material boundaries used for Midland and Munster Basins with fault simulations. Grid is 8km by 120 km, surface temperature is 20°C and basal heat flow rate is 70mW.m^{-2} . Sedimentary and basement rock properties as in figure 55. Sedimentary fault rocks: porosity = 0.1%; kh = 5 md; kv = 1.0 md. Basement fault rocks: porosity = 0.1%; kh = 25md; kv = 5md.

simulations to produce any regional flow systems, and the ubiquitous occurrence of convective systems (see below) has prompted a wider use. Therefore it is used to investigate: (i) the behaviour of completely regular grids; (ii) how surface topography affects flow systems in very simple geometries and with very simple material property distributions, and (iii) under what range of conditions convective systems occur.

5:6:1:1 Completely Regular Grids

Figures 57 to 63 show the results of two of many simulations using regular grids. Both use a single (but different) uniform material. The simulation shown in figures 53 and 57 to 59 (8km_regular) has one material with 10% porosity, 2md horizontal and 0.2 md vertical permeability, and has a 75mWm^{-2} thermal gradient. That shown in figures 60 to 63 (6km_regular_fine) uses a finer, thinner grid, 5% porosity, 5 md horizontal and 0.5 vertical permeability and a thermal gradient of 70mWm^{-2}. Neither simulations develop regional flow, but both develop fluid circulation, with updrafts spaced 25 to 40 km apart bringing hotter fluids to the near-surface. Such a response occurs over a wide range of modelling parameters in simulations using regular grids. However, the effects of circulation are not always obvious. Where the porosity, permeabilities and thermal gradient are very low fluid circulates so slowly that it does not produce a thermal perturbation. As the heat flow rate and porosity and permeabilities are increased, flow rates and thermal perterbations become larger; such that eventually the solutions do not converge.

5:6:1:2 Topography

A series of uniform grids were adapted such that right hand portion kept its flat top but the left hand portion was given a very gentle slope (Fig. 64). A number of different sloping to flat portion ratios were used. In each case there is regional flow under the sloping portion which extends for about 5 km into the flat portion (Fig 65). The remainder of the simulation is dominated by circulation systems that penetrate to the bottom of the model and are about 30 to 40 km across. The temperature plots for these simulations confirm that hot fluid is moving up and cold fluid is moving down (Fig. 66). The general flow pattern of these simulations is quite insensitive to rock properties.

These results support the conclusion that, at least in the absence of a tectonic driving force, a regional flow system requires a regional slope at the top of the water table, or at the top of a contained aquifer. The reverse situation is seen in the restorations of the Midland Basin region (Chapters 3 and 4), where both surface slopes and the top of each sedimentary unit dip in different directions, and are frequently further disrupted and tilted by faulting. Garven (1995) comments that a regional flow system developed in a regionally sloping, uplifted, basinal sequence tends to break into local flow systems when the regional topographic slope is disrupted by erosion. This study supports the requirement for a regional slope in order for a regional flow system to develop.

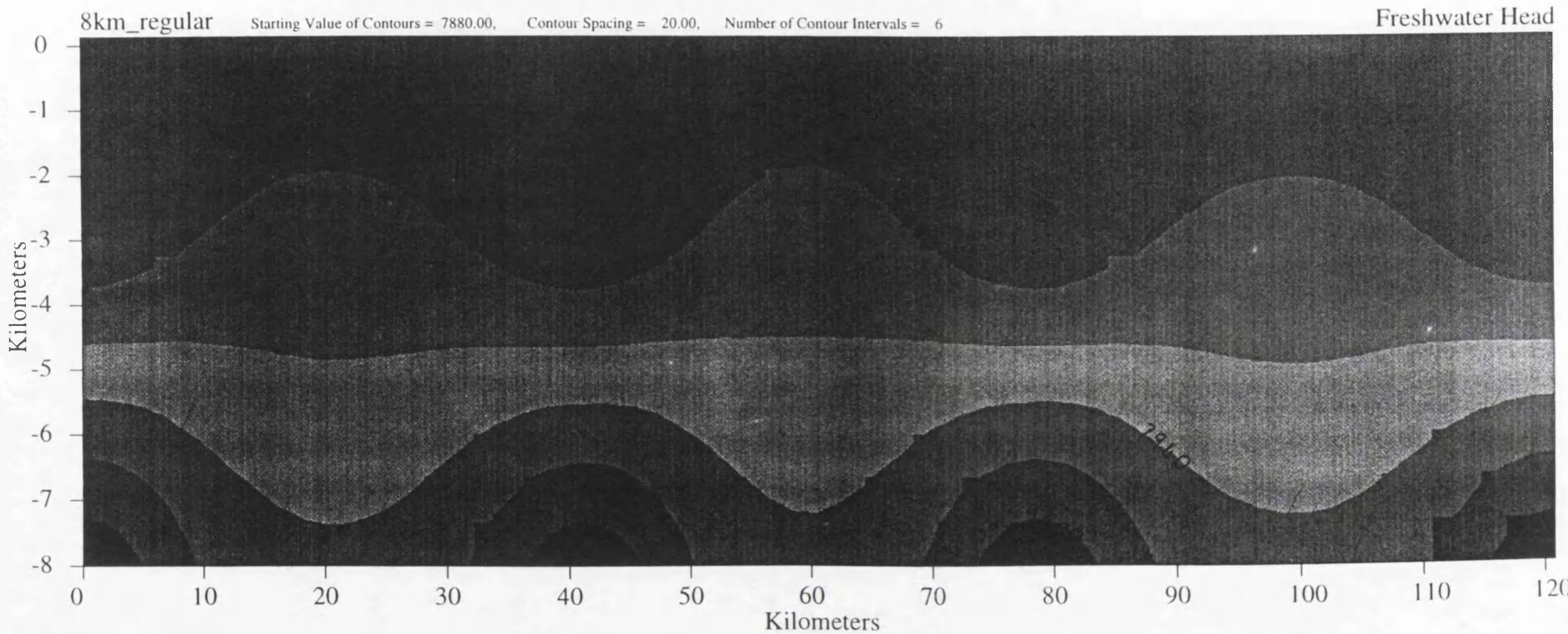


Figure 57. Calculated head distribution for regular grid with one material and flat surface.

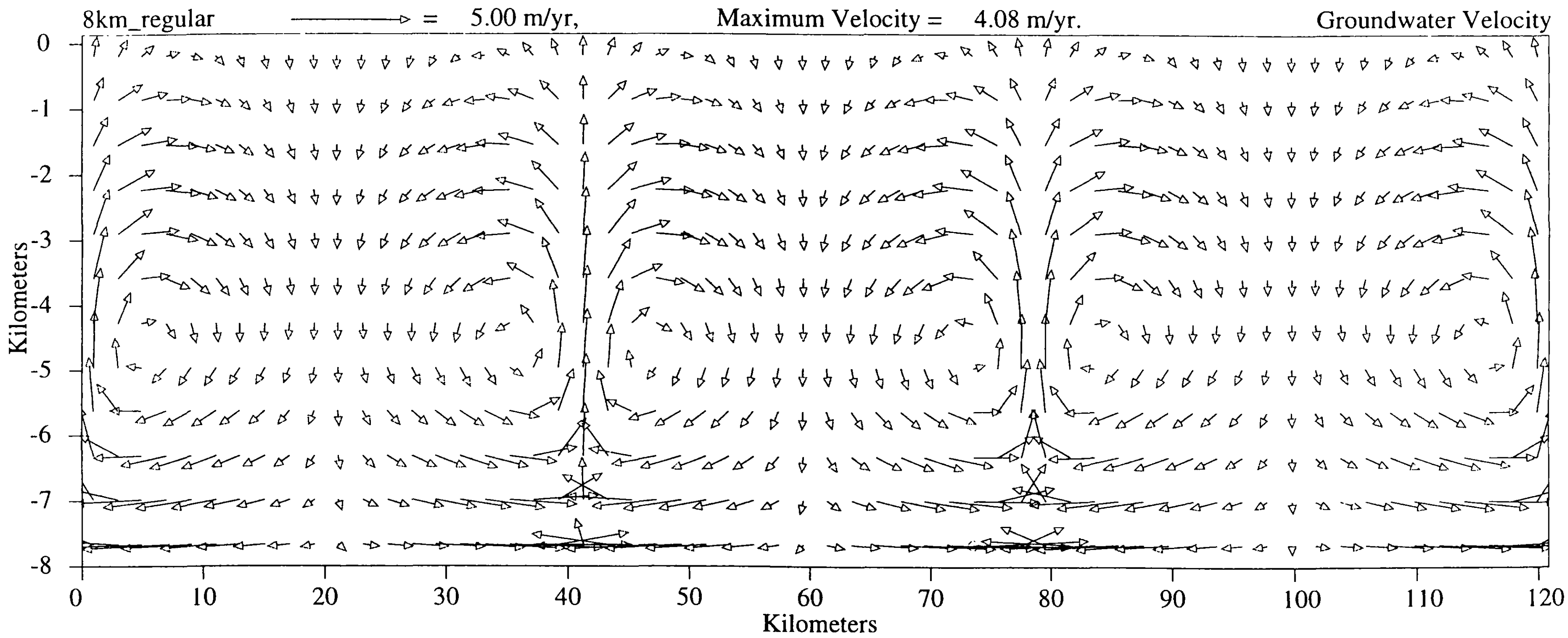


Figure 58. Calculated fluid velocities for regular grid with one material and flat surface.

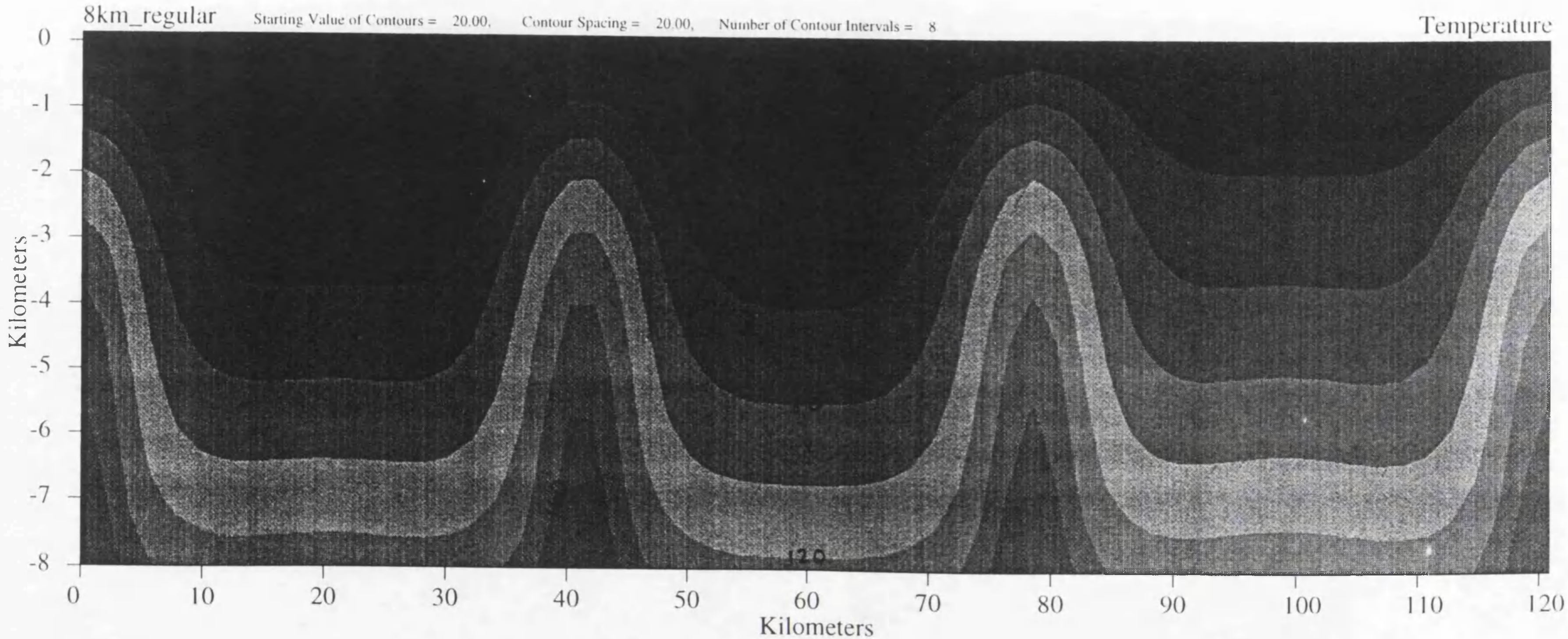


Figure 59. Calculated temperature distribution for regular grid with one material and flat surface.

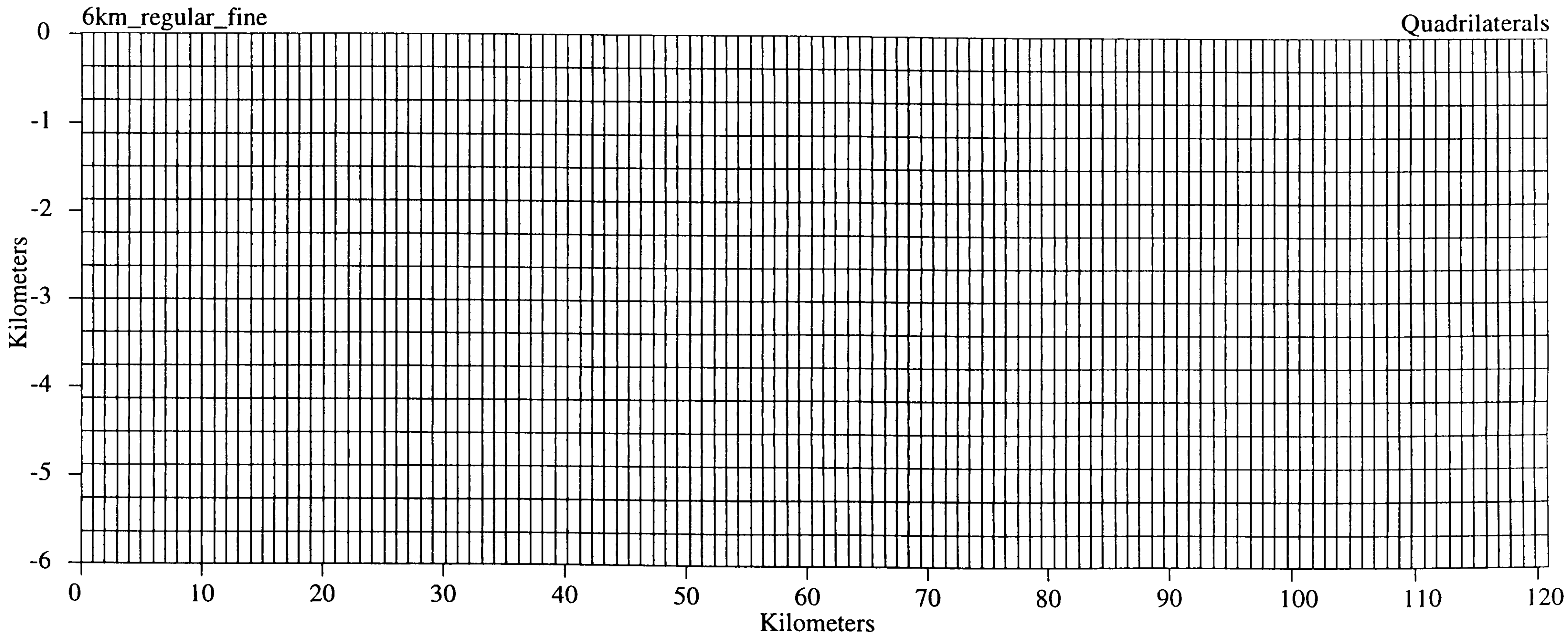


Figure 60. Geometry of fine element regular grid, 6km by 120km with flat surface at 20°C and basal heat flow rate of $70mW.m^{-2}$. One material: porosity = 5%; kh = 5md; kv = 1md.

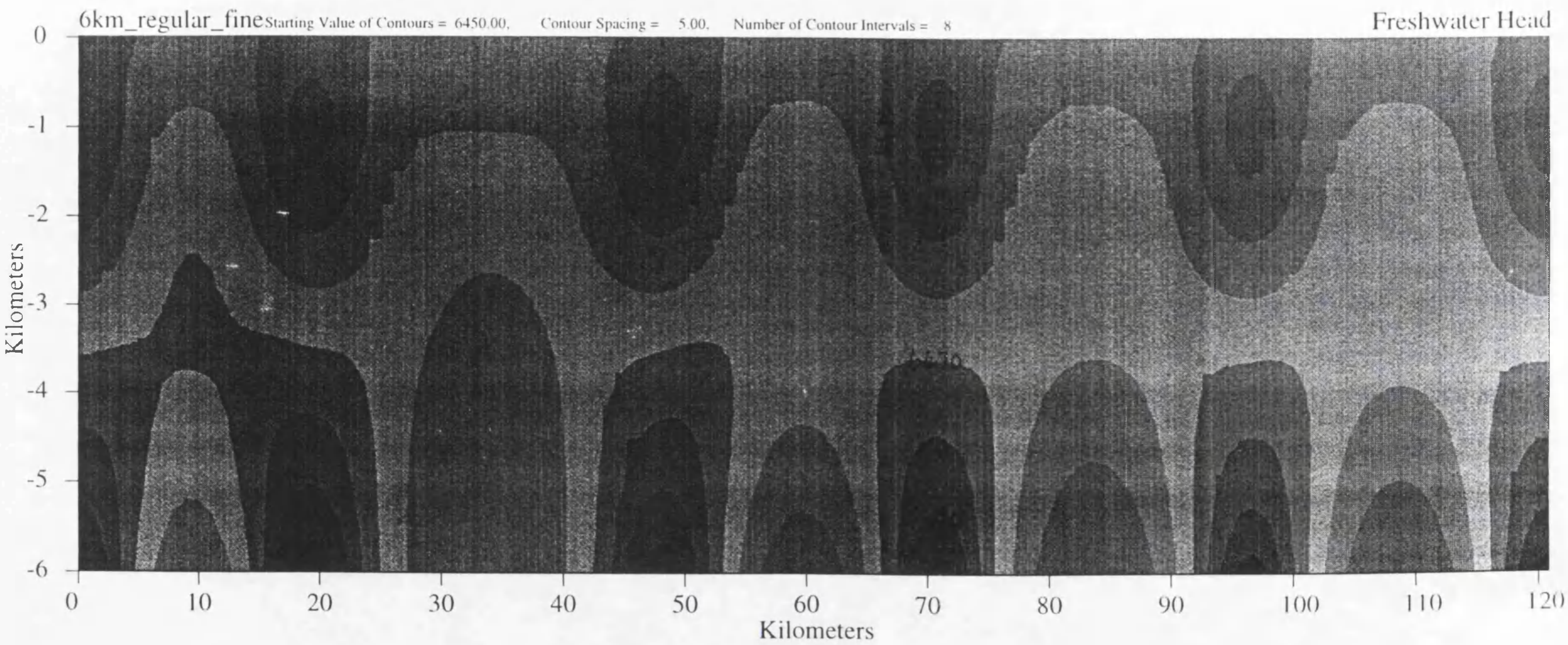


Figure 61. Calculated head distribution for fine element regular grid.

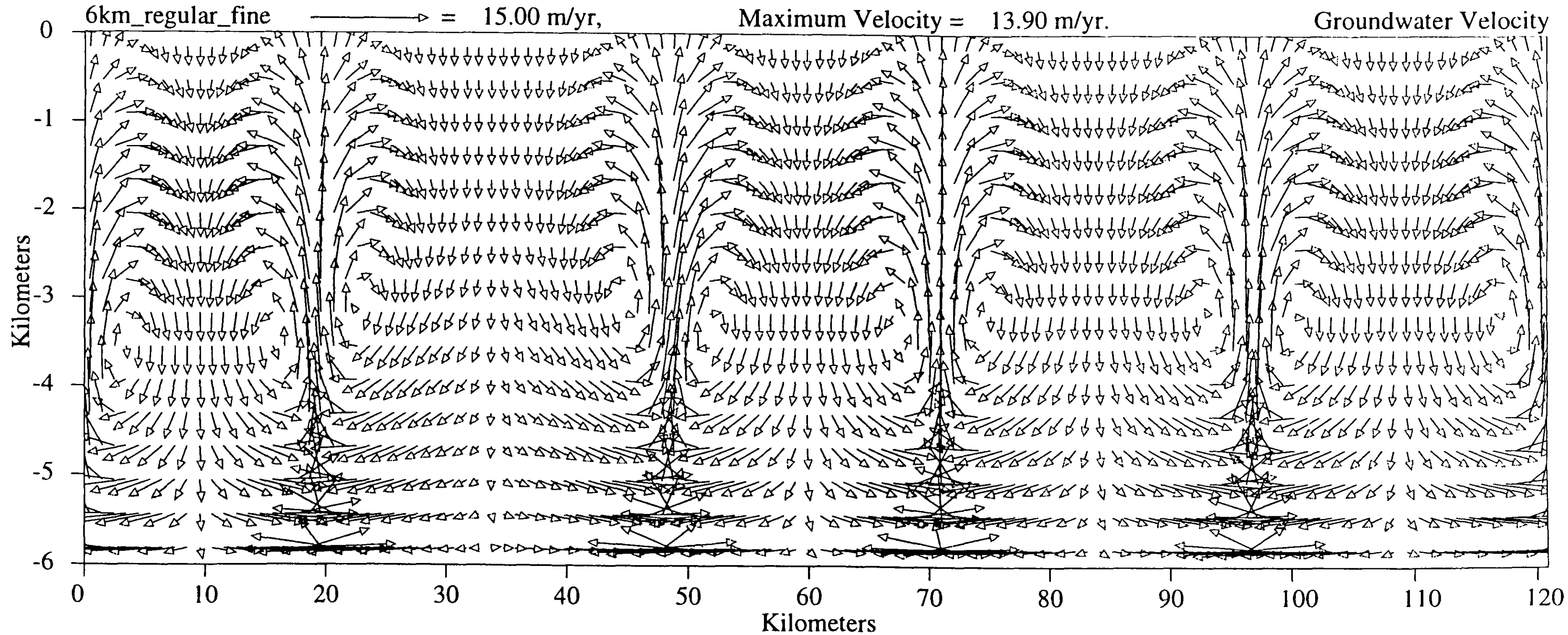


Figure 62. Calculated fluid velocities for fine element regular grid.

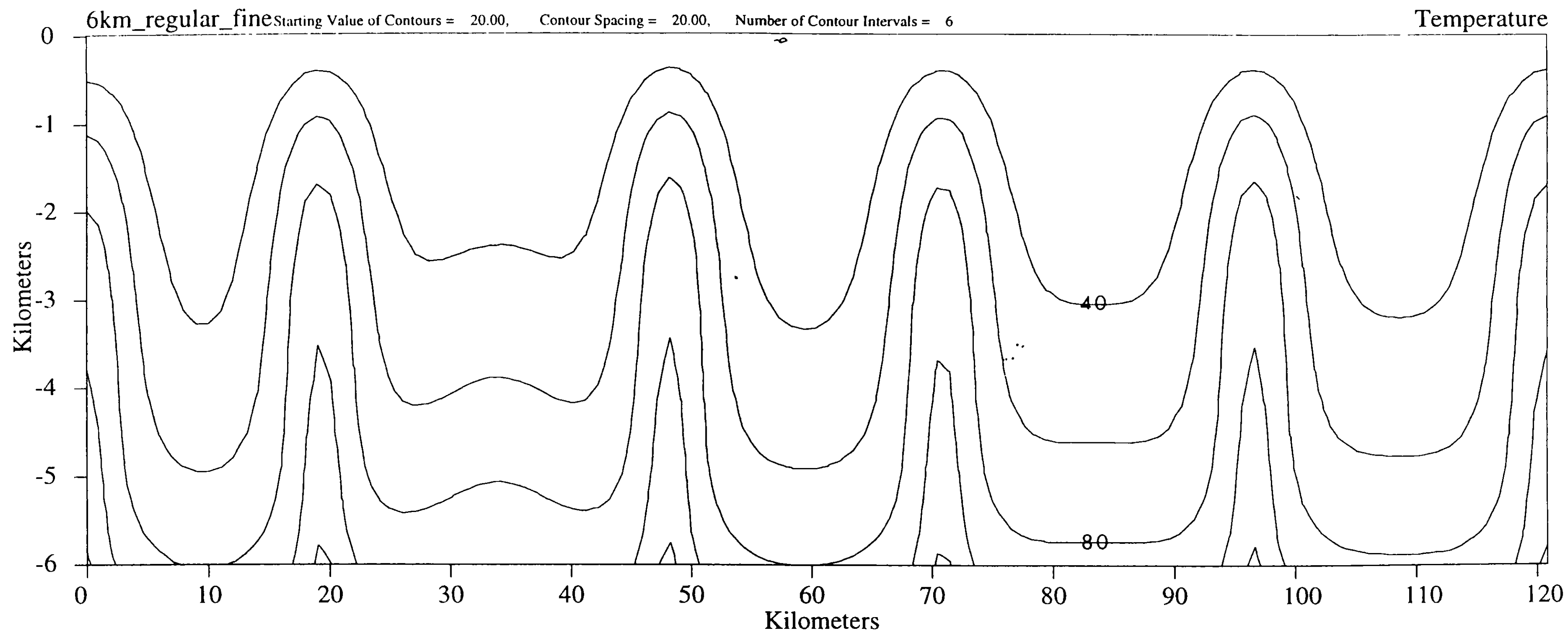


Figure 63. Calculated temperature distribution for fine element regular grid.

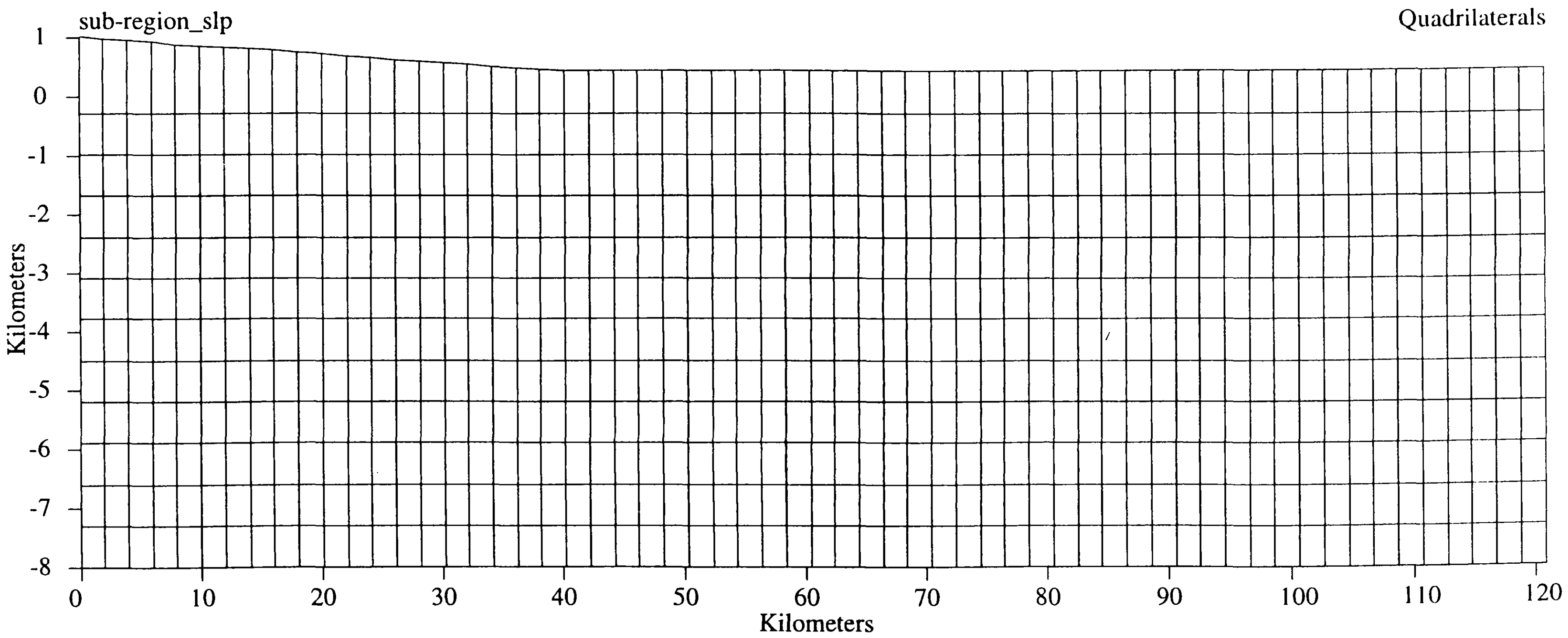


Figure 64. Geometry of regular grid with left hand side having a gentle uniform slope and the remainder of the surface flat. Grid is 8km by 120 km with basal heat flow rate of 70mW.m^{-2} Single material: porosity =10%; kh = 2md; kv = 0.02 md.

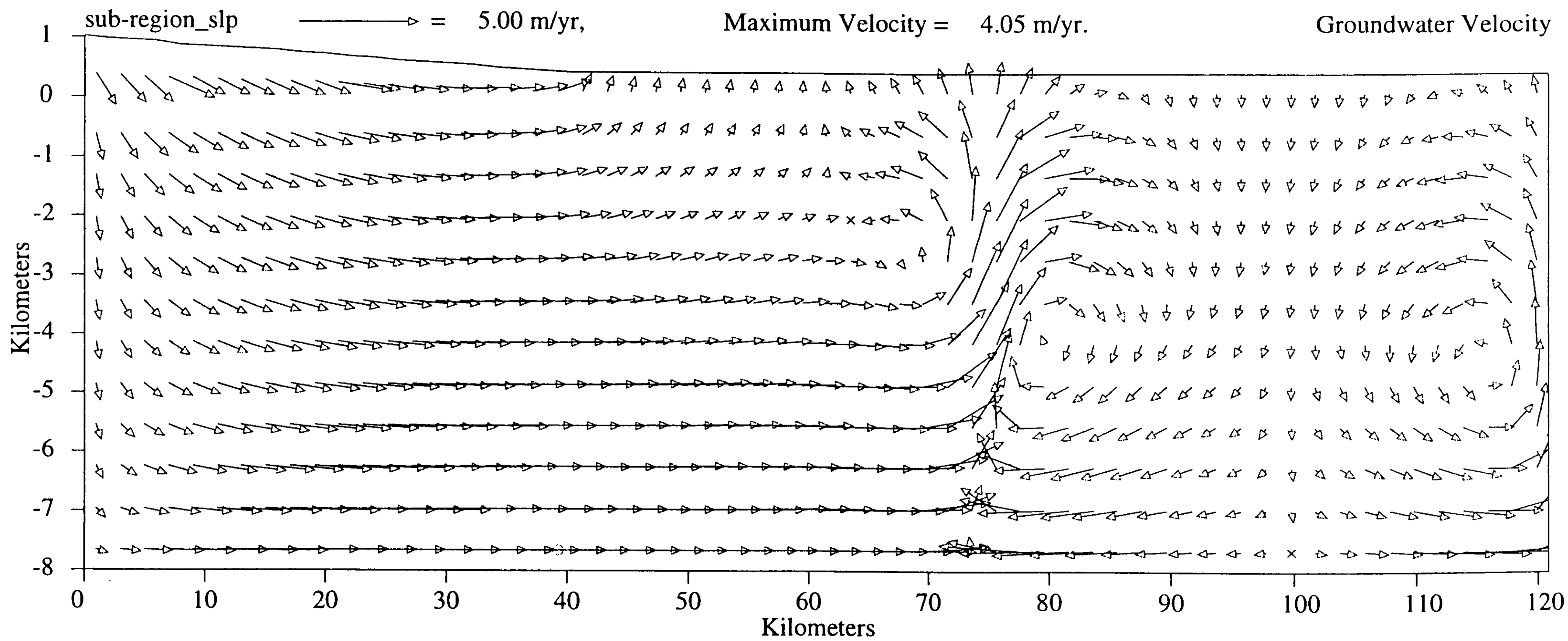


Figure 65. Calculated fluid velocities for uniform grid material with p. rtly sloped top.

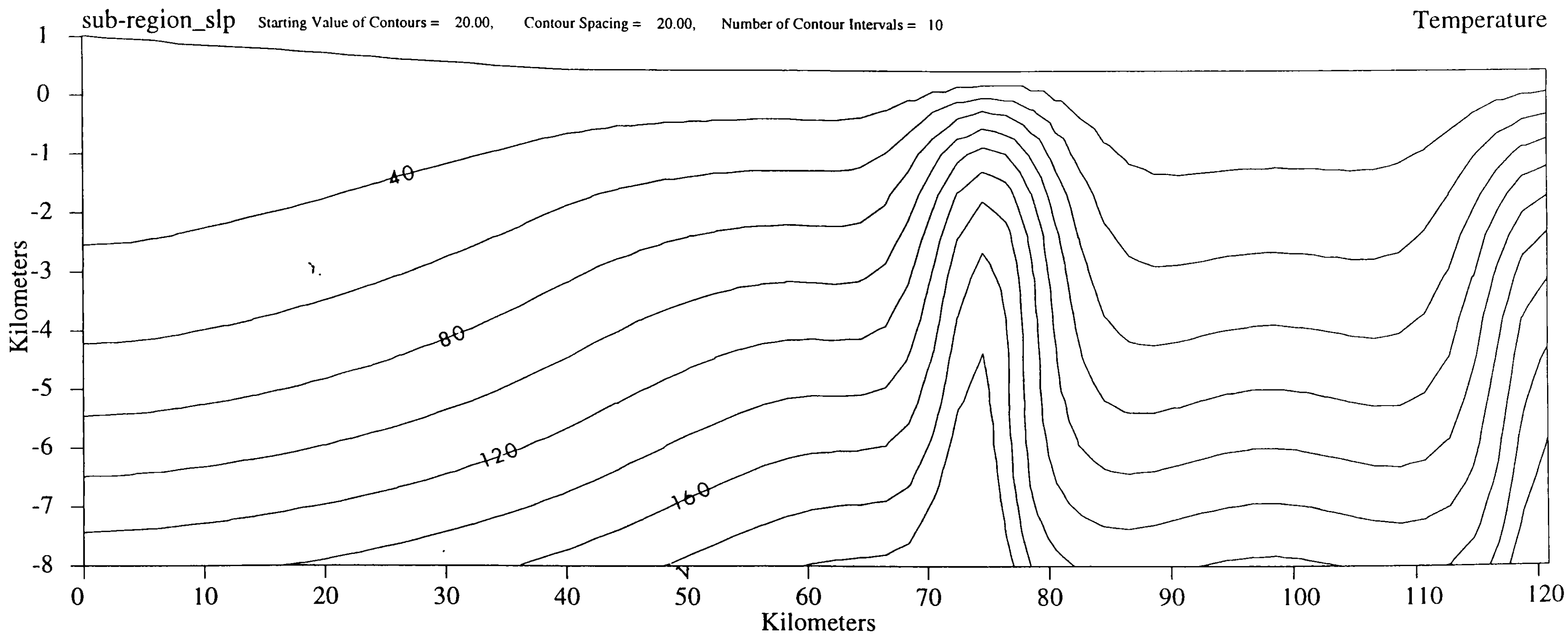


Figure 66. Calculated temperature distribution for uniform grid material with partly sloped top.

5:6:1:2 Circulation

Circulation (a geometric pattern) with most of the characteristics of convection (a process) develops in simulations which incorporate a uniform grid of only one rock type. Such simulations develop circulation over a wide range of material properties. The absolute flow rates and temperatures in any given element are highly dependent on the material properties: fluid and heat flow are much more rapid in better quality rock. But the fluid-flow pattern and temperature distribution pattern vary very little.

When two material types are used, large differences in assigned rock properties still produce circulation over a wide range of conditions. Multiple layers of very different material types suppress circulation, though this may well be a function of the grid element size (and so of the manner in which the system was discretised) rather than a property of the system itself.

The circulation pattern is difficult to suppress by changes in material property values, though flow rates and temperature values can vary widely with as material properties vary. Circulation is easily suppressed by topographically-driven flow in the vicinity of a surface slope, but the effect is only very localised to the vicinity of this slope.

5:6:2 Simple Basin

The simple basin set of simulations uses only 2 materials, sedimentary rocks and basement, in a simple basin and basement configuration (Fig. 54). The distribution of material types used in this set of simulations is not realistic, primarily in that it ignores the depth of the palaeo-Munster Basin. It does, however, approximate the shape of the palaeo-Midland Basin. The objective of this set of models is to investigate what flow systems would develop in a simple shallow basin (and its basement) in the presence of a variety of surface configurations (or uplands) and sedimentary column thicknesses. These uplands are intended to represent the geometric effects of a Variscan tectonic front to the south of the Munster Basin, and/or local uplifted fault-bounded blocks.

Representative samples of the results of this set of simulations using a flat water table are shown in figures 67 and 68, and with a local upland in figures 69 and 70. Where the margin of a (large or small) upland is abrupt, the resulting fluid velocity at the break in slope is often an order of magnitude greater than any other fluid velocity in that simulation. Where the break in slope is gentle, the velocity of cold fluids moving away from the upland is still fairly high, but again is only local to the slope. Where there is a regional surface slope over the southern portion of the cross section, a regional topographic flow system develops in that part of the model, but the regional flows extend only a few kilometres beyond the end of the regional surface slope. This is essentially the same result as that for the regular grid with a sub-regional slope shown in figures 64, 65 and 66.

Away from the uplifts and their margins other flow systems develop. The most well developed, and persistent, flow pattern in this set of simulations is a general downward

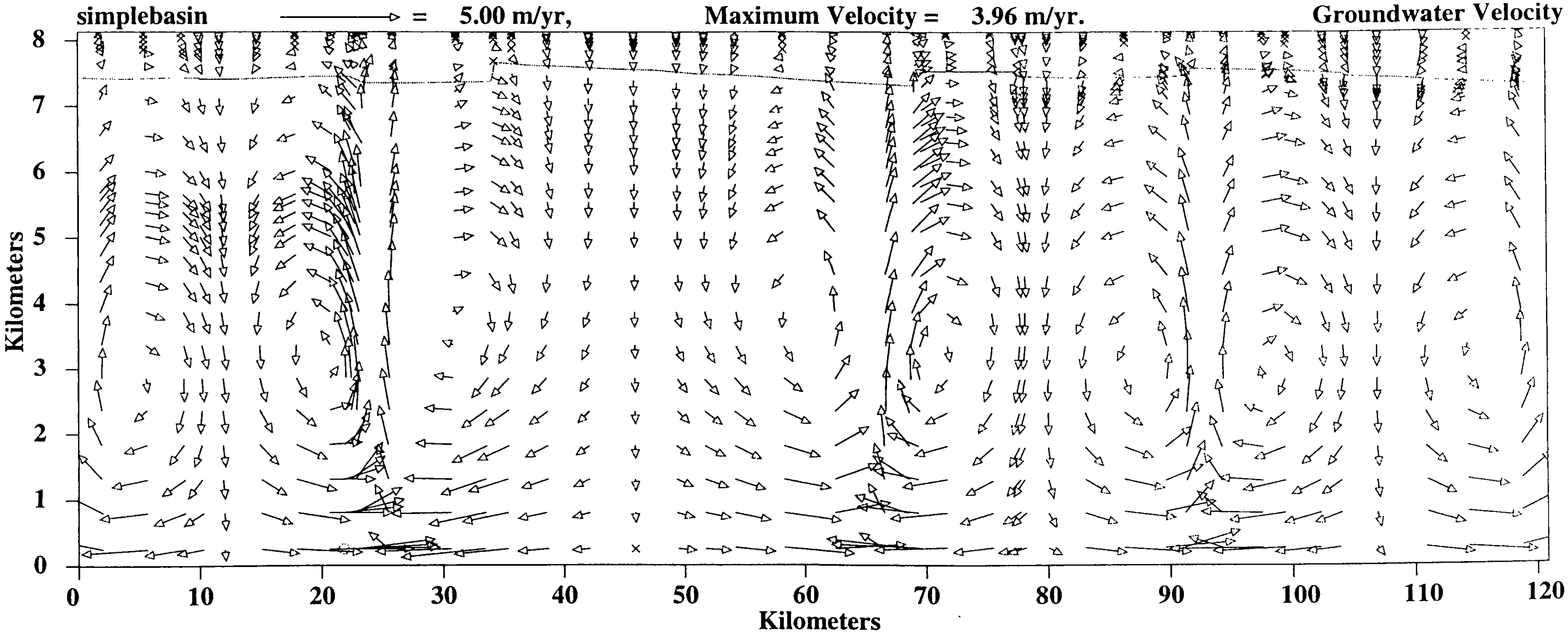


Figure 67. Calculated fluid velocities for Simple Basin simulation. Material properties as in figure 54.

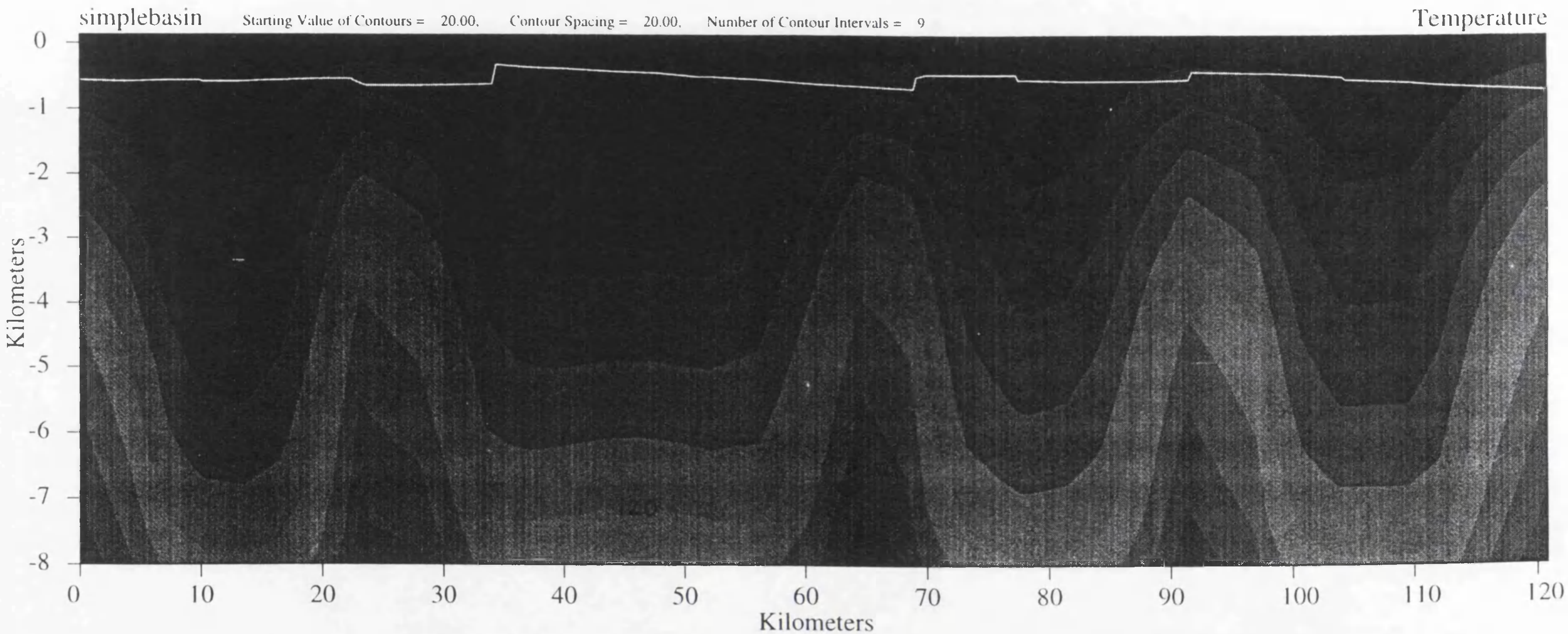


Figure 68. Calculated temperature distribution for Simple Basin simulation.

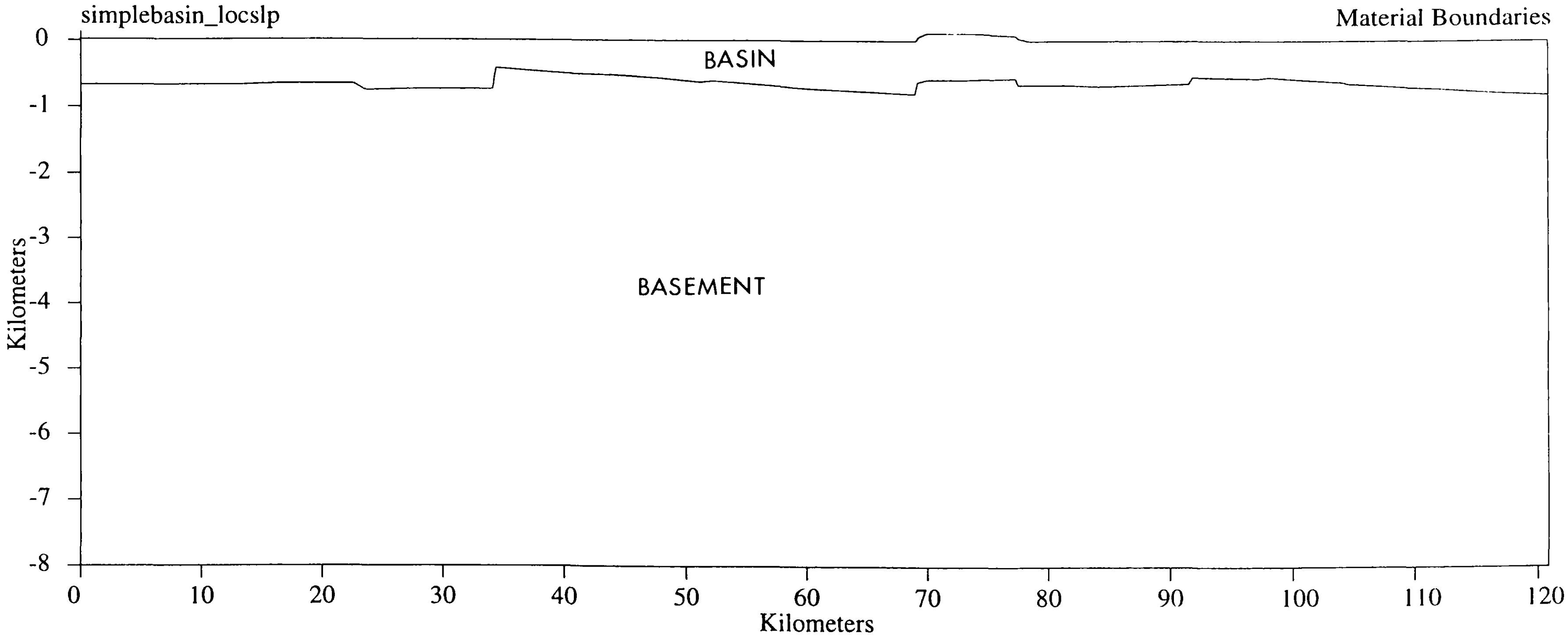


Figure 69. Material boundaries, Simple Basin simulation with local surface (water table) slope. Material properties as in figure 54.

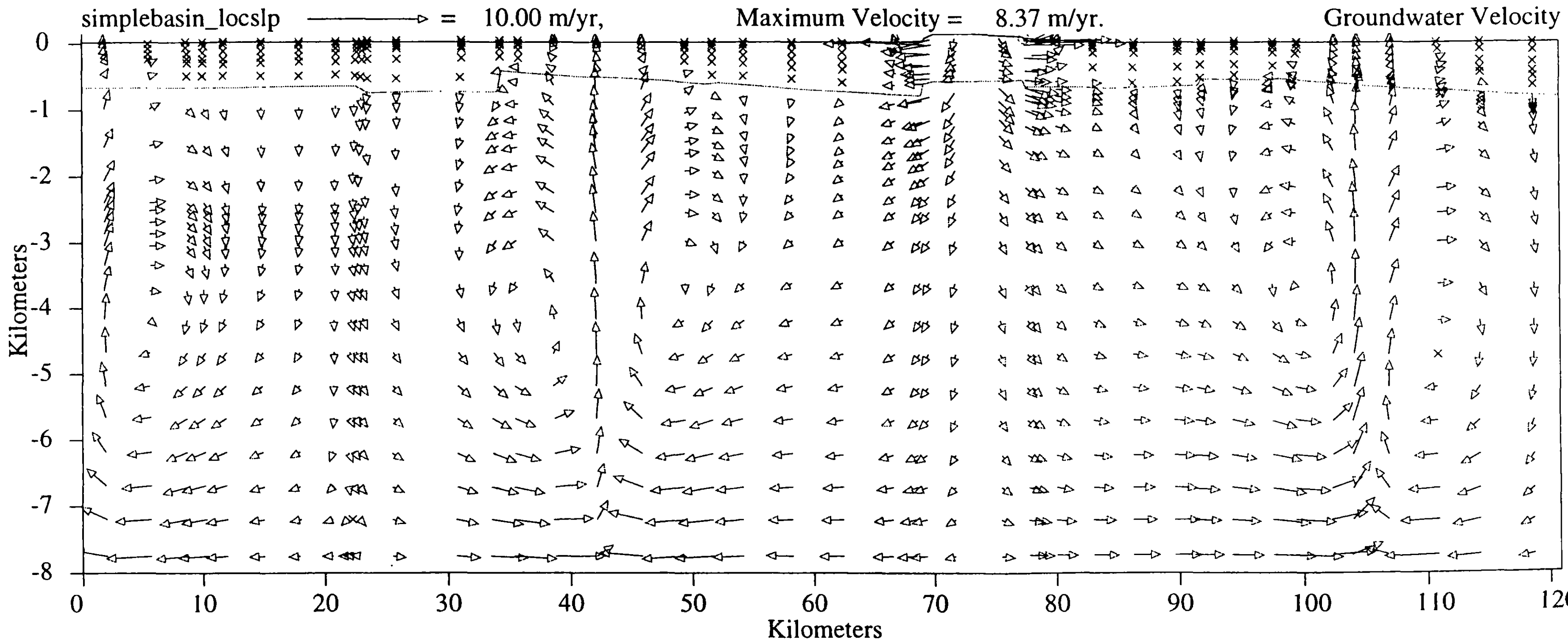


Figure 70. Calculated fluid velocities, Simple Basin simulation with local surface slope.

penetration of surface or near-surface waters to the base of the simulated cross section, where they are warmed and rise to the near-surface in fairly narrow updrafts (Figs 67 and 68). These bands of upwelling fluid are spaced about 30 to 40 km apart. The downward penetration of fluids is apparently suppressed near updrafts.

This circulating fluid-flow pattern displays most of the characteristics of free convective systems. However, there is no prominent near-surface lateral flow to complete the convective system, and hot fluids do not actually reach the surface (the boundary conditions prevent this).

5:6:3 Midland and Munster Basin

This set of simulations differs from the Simple Basin set in that the correct shapes of the palaeo-Midland and palaeo-Munster Basins are used to control the distribution of the sedimentary rock and fractured basement material types (Fig 55). That is, the palaeo-shapes of the Midland and Munster Basins are modelled. Various surface (water table) configurations have also been used here. Representative samples of the results of this set of simulations are shown in Figures 71 and 72.

The groundwater velocity plots (of which figure 71 is an example) show fluid circulation, typically (but not always) with upward fluid flow in the Munster Basin sedimentary rocks and downwards flow in the fractured basement to the south of the Munster Basin. The simulations also show two more fluid circulation systems in the Midland Basin and its basement. There is no evidence of lateral flow from the Munster to the Midland Basin, or of any other form of regional flow.

The general pattern of flow is very like that for the Simple Basin: there is local, shallow, cold flow away from upland(s), and several cells of fluid circulation (Figs 71 and 72). The updrafts are spaced about 35 km apart, though they tend to be at different locations from those in the Simple Basin set. It is not entirely clear if the slightly different flow pattern to the south of and in the Munster Basin is responsible for the change in the position of the updrafts.

The overwhelming impression is of a fluid- and heat-flow pattern that is very like that of the Simple Basin, with local cold flows near surface features, fluid circulation to depth and back to the surface, but no regional flow system, and no evidence of lateral flow from the Munster Basin rocks into the Midland Basin. These results suggest that the specifics of the basin geometries are not greatly important at the scale of these models, and so the lack of detailed stratigraphic data is not important to the study undertaken here.

5:6:4 Midland and Munster Basins with Permeable Faults

This series of simulations differs from the previous series only in that the faults are assigned to two fault rock material types depending if they were originally sedimentary or basement rocks (Figs 56 and 73, 74 and 75). The fault rock material types are given a

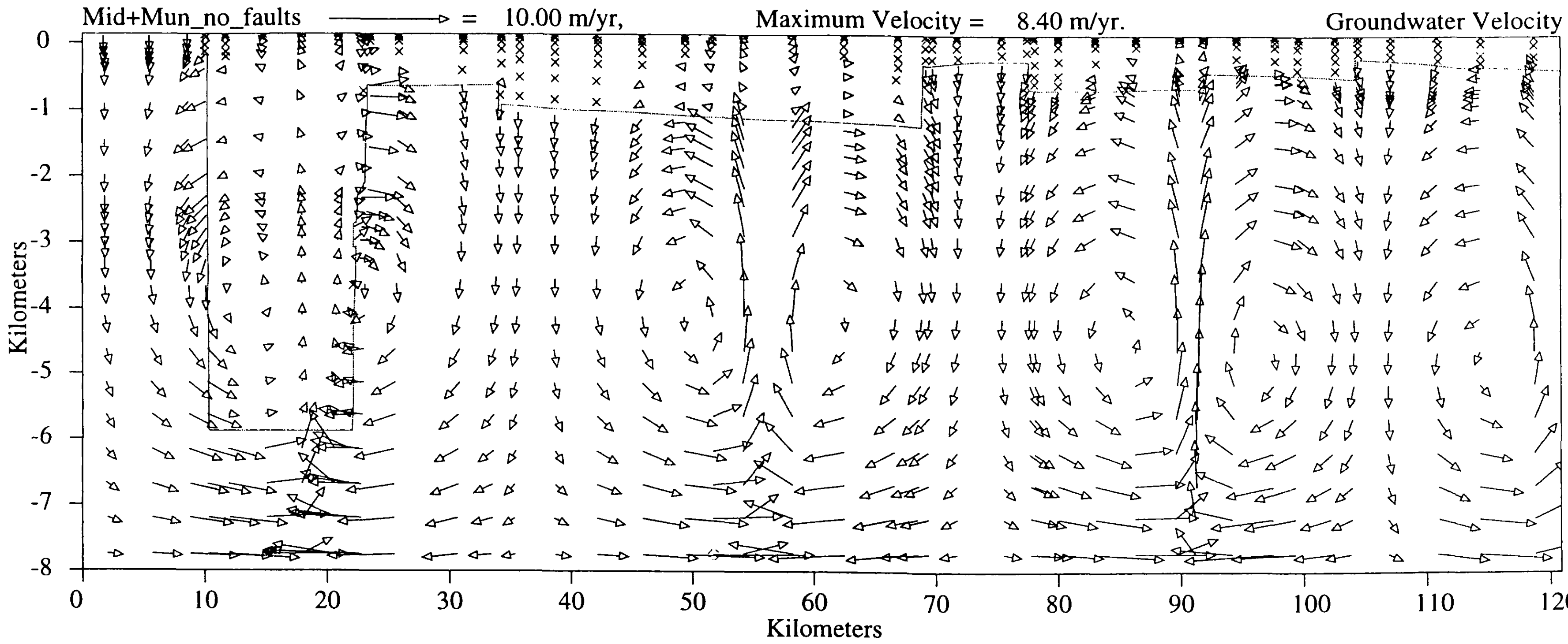


Figure 71. Calculated fluid velocities, Midland and Munster Basins no faults simulation. Material properties as in figure 55.

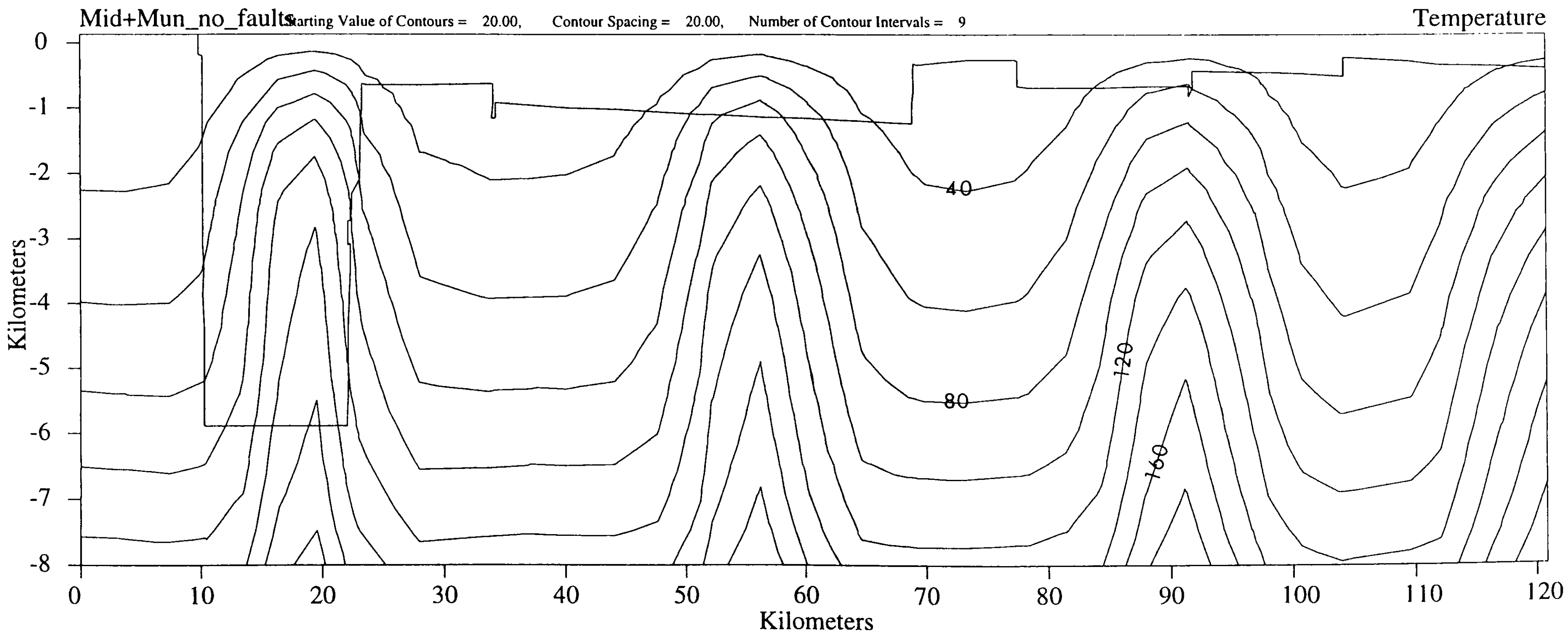


Figure 72. Calculated temperature distribution, Midland and Munster Basins no faults simulation.

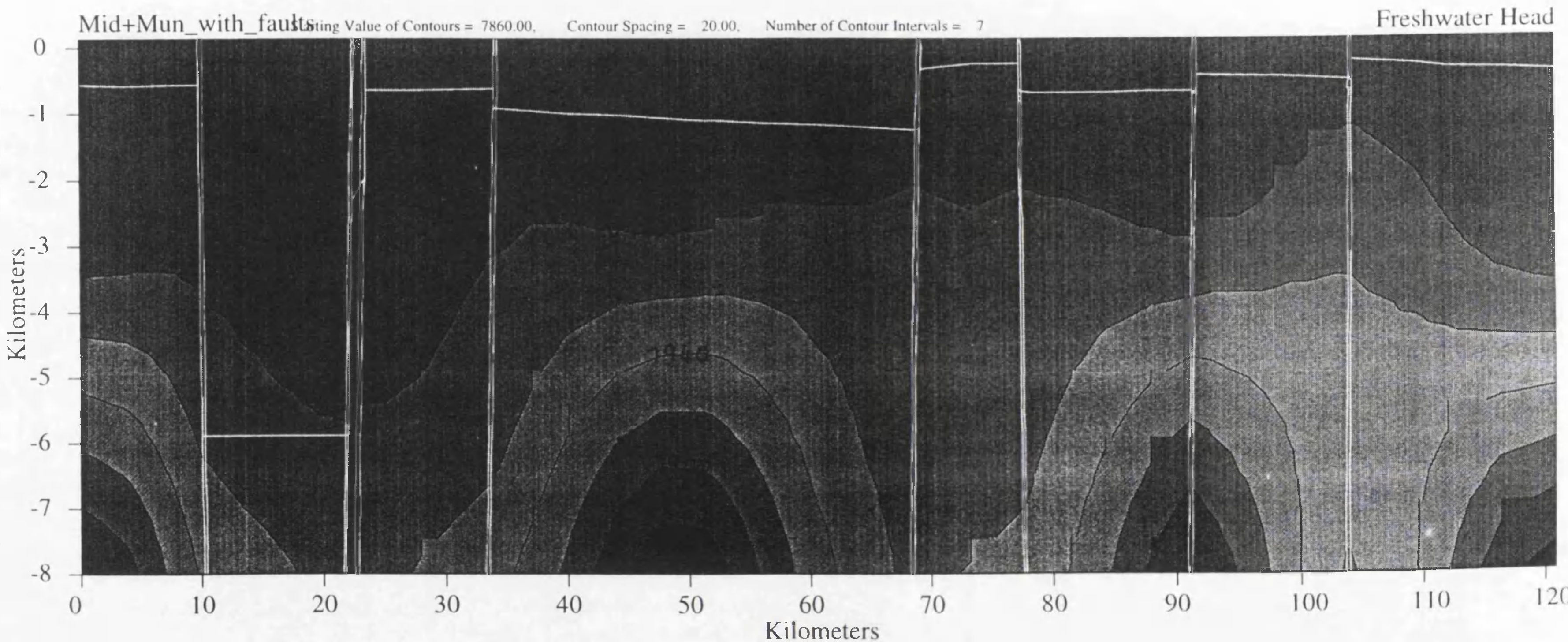


Figure 73. Calculated head distribution, Midland and Munster Basins with faults simulation. Material properties as in figure 56.

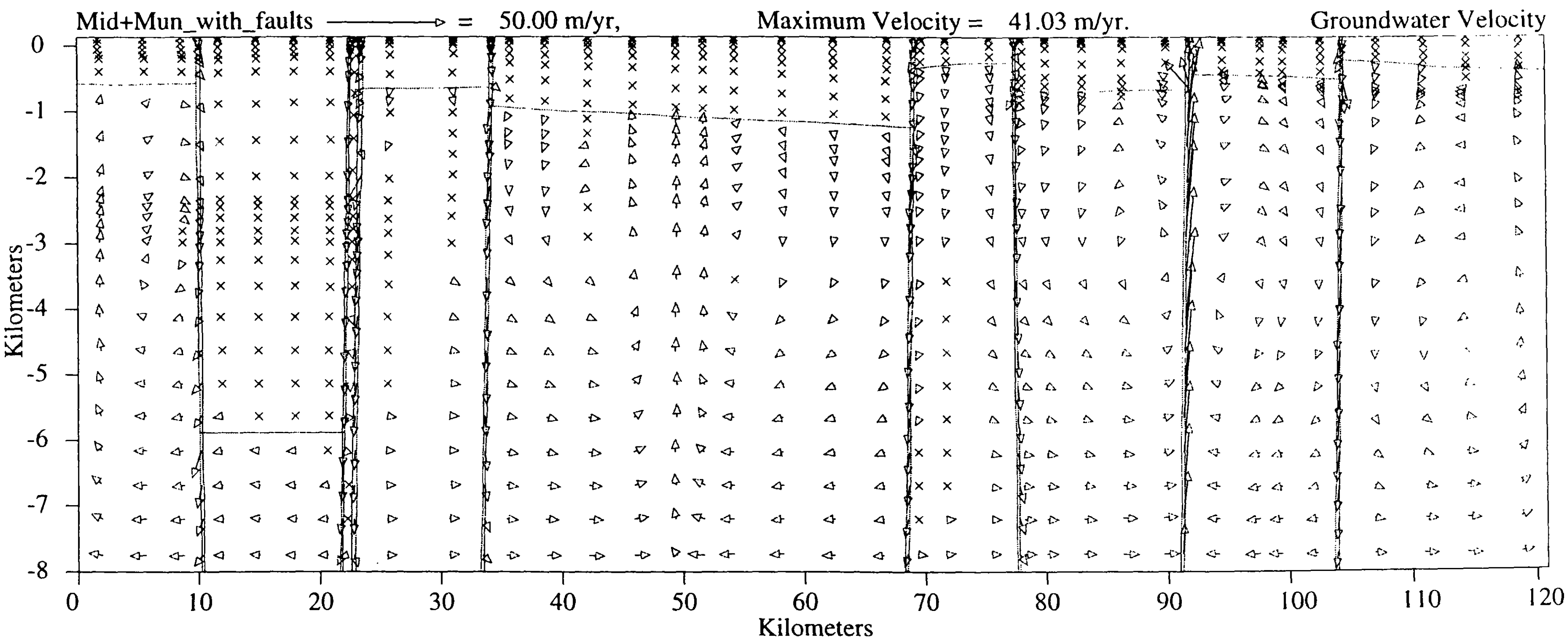


Figure 74. Calculated fluid velocities, Midland and Munster Basins with faults simulation.

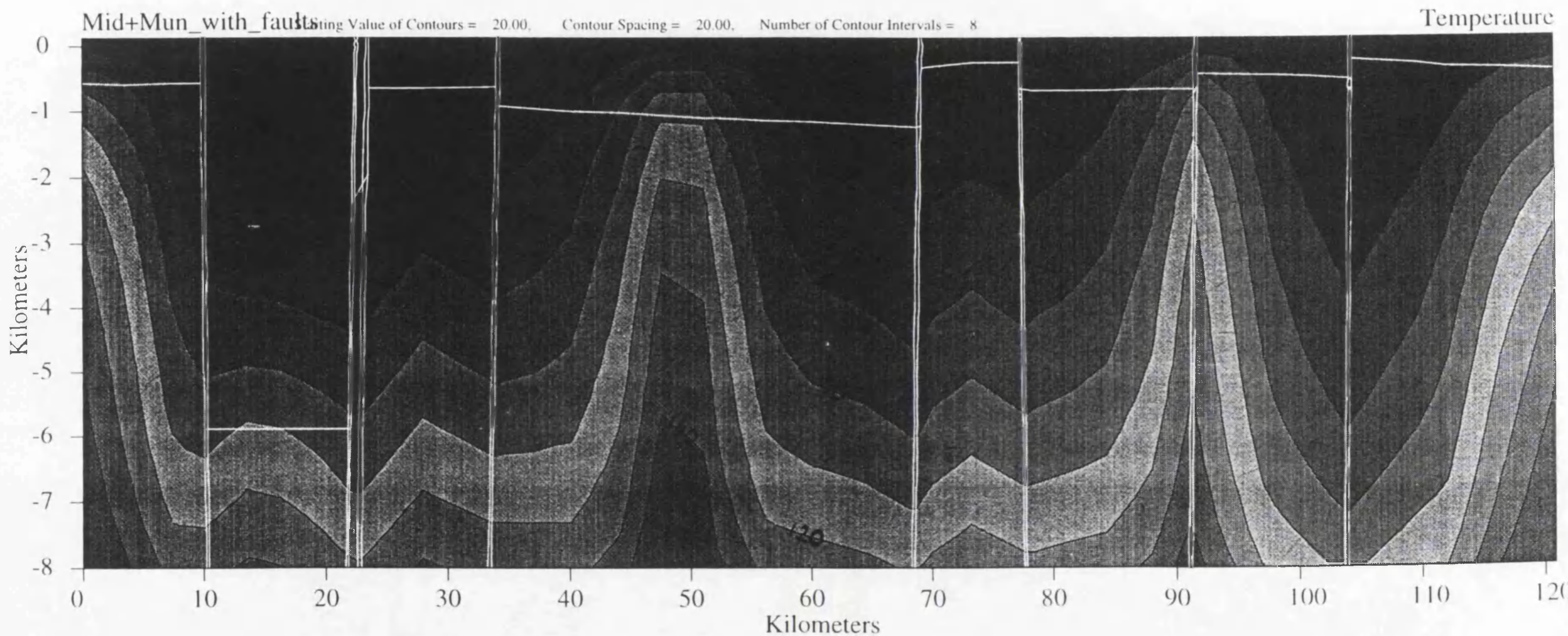


Figure 75. Calculated temperature distribution, Midland and Munster Basins with faults simulation.

range of high permeability and low porosity values. These fault rock types also differ from sedimentary and basement rocks in that their bulk vertical permeability is likely to exceed their bulk horizontal permeabilities. This is in marked contrast to the normal situation for sedimentary rocks (where horizontal permeability is taken to exceed vertical) and for most fractured basement (where horizontal and vertical permeabilities are taken as approximately equal).

In some cases there is virtually no difference in either the fluid velocity pattern or the temperature distribution between otherwise identical simulations with and without permeable faults. Compare the fluid velocity plots of figure 74 (with faults) and figure 76 (no faults) and the temperature plots with (Fig 75) and without (Fig. 77) faults. In other cases flow in the simulations with permeable faults is strongly controlled by the faults, and is very different from that in the otherwise identical no-fault simulations. This makes assessment of the role of faults in controlling flow patterns rather difficult at this stage. Part of the problem could be the need to keep vertical fault permeabilities fairly low: this can result in an unrealistically high horizontal to vertical permeability ratio for faults. If the vertical fault permeability is high (above approximately 10 md) the solution does not converge, probably because rapid upward flow exceeds the calculation step size. However, simulations with and without a strong control of flow by faults do not divide neatly into groups based only on vertical permeability. Further work into the role of permeable faults in such flow systems is needed.

5:7 GEOLOGICAL SIGNIFICANCE

The most obvious conclusions are that there is no regional flow, but that both very local cold flow below surface slopes, and local deep circulation, are ubiquitous. For a slope-induced regional flow from the Munster to the Midland Basin, or across the Midland Basin, a regional south to north slope is required. However, there is a great deal of geological evidence against the presence of such a slope during the Carboniferous (Cope et. al, 1992a), including the restorations reported in this thesis.

The flow systems that developed in the simulations are also insensitive to the changes from a simple basin, to the unfaulted Midland and Munster Basins, and are variable in their sensitivity to incorporation of permeable fault rocks in the Midland and Munster Basins simulations. Nevertheless, the propensity for circulating fluid systems to develop, in models with a wide range of geometries and properties, cannot be ignored.

The fluid circulation pattern has many of the characteristics of convection. Fluid moves downward over large areas, moves laterally at the base of the section, and moves up

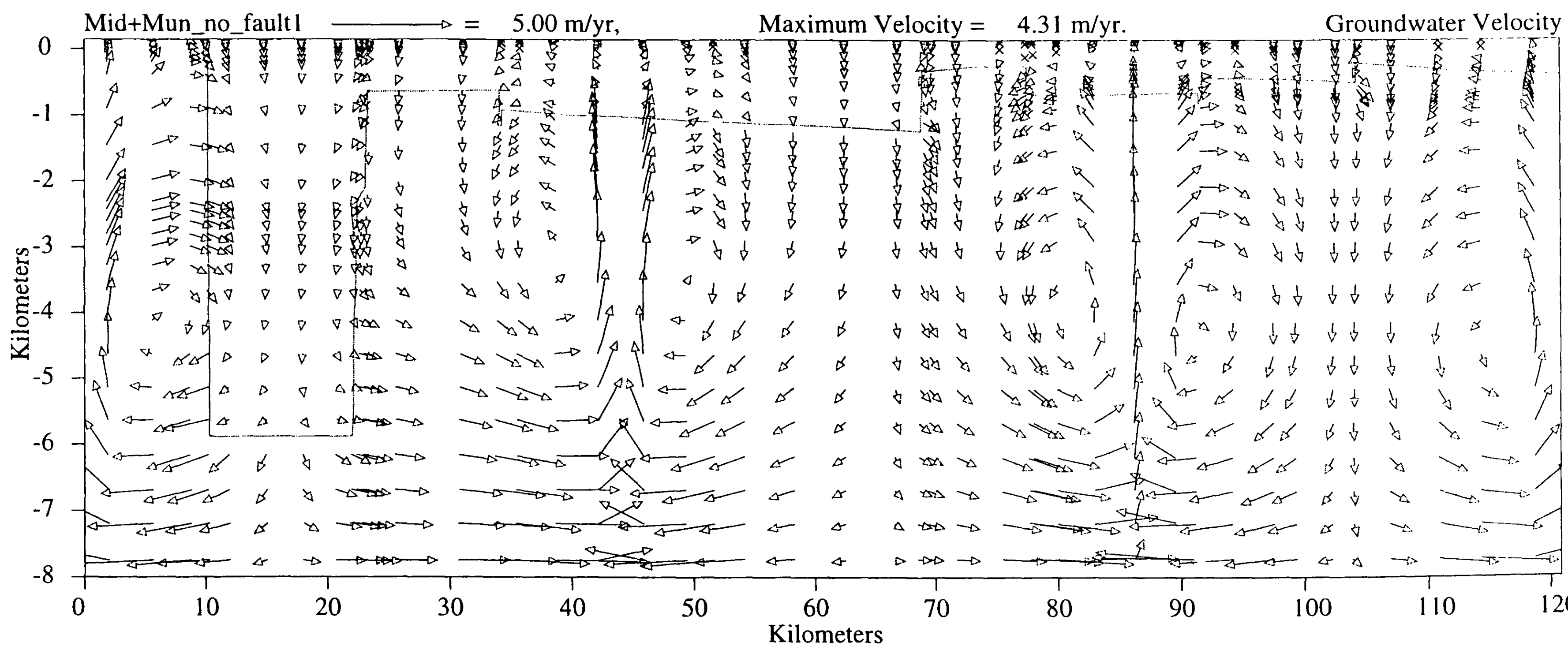


Figure 76. Calculated fluid velocities, Midland and Munster Basins without faults simulation using different set of material properties. Sedimentary rocks: porosity = 10%; kh = 7.5 md; kv = 0.75md. Basement rocks: porosity = 1%, kh = 2md; kv = 0.4md.

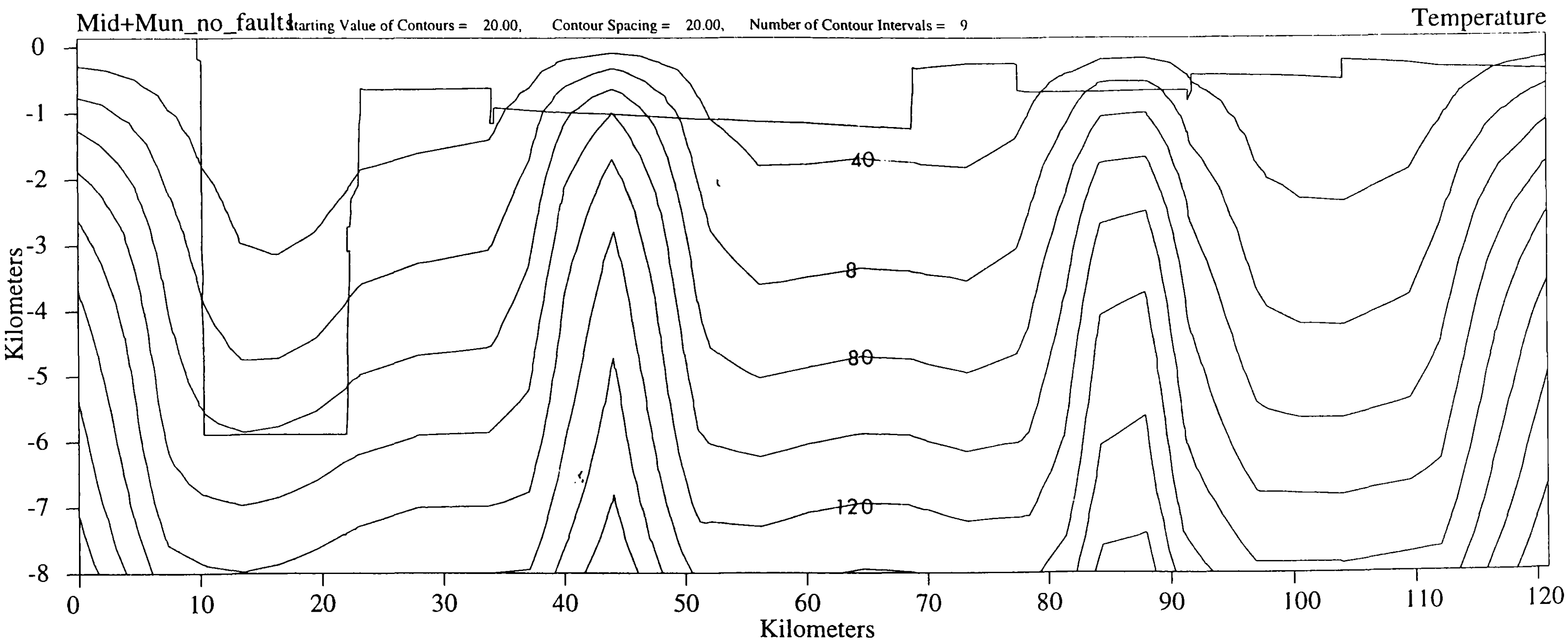


Figure 77. Calculated temperature distribution, Midland and Munster Basins without faults simulation using different set of material properties.

in narrow, regularly spaced zones. The downward moving fluid is cold and the updraft hot. There is only very slow lateral movement of fluid at the surface, possibly due to the inhibitions of the upper surface boundary conditions. The avearge spacing of the updrafts is fairly uniform for a given model depth, and increases as the depth increases, from about 35 km at 8 km depth, to 40 km at 10 km depth. This spacing approximates the 3:1 width:depth ratio typical of convective cells (Combarnous, 1975)

No simulation can possibly copy all the features of its geological counterpart. It is the role of the modeller to build a model which incorporates the most important components for the problem under investigation, and then to assess the simulations in light of what has, or has not, been incorporated, and in light of the inherent weaknesses of the chosen simulator.

5:7:1 Limitations of OILGEN

The major problems inherent in the use of OILGEN for this problem are its 2-D nature, and its inability to simulate compaction or tectonic loading -- both of which have been suggested as flow mechanisms. Compactive flow has been investigated by Bethke (1985), who demonstrated quite conclusively that compactive flow rates were very slow -- on the order of millimetres per year. In contrast, flow rates in the simulations reported here are metres per year. Also, compactive flow is upward and generally cold. The Mass Balance chapter has shown that the volume of compactive fluid available at the end of the early Carboniferous was not sufficient to source all the known deposits. Though some small effect on the flow path due to compaction cannot be eliminated, compaction is not a serious candidate driving mechanism.

Overcoming the inability to model tectonic loading is more difficult. The Midland Basin region does show evidence of the presence of fluids hotter than would be expected from simple burial (Clayton et al., 1989). However, much of this evidence is from rocks adjacent to known hydrothermal deposits, and may have occurred at any time up to the present. It is not suprising if the temperature is elevated in these areas. Information obtained away from known deposits suggests temperatures generally lower than those near deposits, but the cumulative regional thermal state is still somewhat elevated.

The effects of the Variscan orogeny, or of fluids associated with this orogeny (Fitzgerald et al, 1994), are regarded as the most likely source of this "extra" heat. However, no specific ways in which the orogeny could have been responsible for this heat transport have been suggested. Oliver (1986) proposed a hypothetical hydrogeologic model in which a compressional tectonic belt expels fluid out of foreland basins onto the platform margin. He suggested that these tectonically-driven fluids could transport heat and dissolved solids. Shi et. al (1989) simulated deformation and flow in the Oregon accretionary prism kinematically, finding high pore pressure development in the rocks below the tectonically emplaced rocks. The thermal perturbation produced in such a situation has been investigated by Deming et al. (1991), though the thermal effects produced in their studies were quite small, occurring only over limited areas, and being of a few degrees in magnitude.

Ge and Garven (1994) developed a 2-D simulator which incorporates tectonic compression and induced fluid flow. They model a poro-elastic material using a plane strain condition, and investigate the effects of stress changes on the hydraulic head distribution and the flow velocity field. Thermal and chemical effects are ignored in this study. These authors used a geological cross-section with an aquitard overlying an aquifer, with a putative thrust belt at the thick end of the sedimentary sequence. The tectonic effects, in the form of the weight of the thrust sheets and horizontal tectonic compression, are represented by distributed horizontal and vertical forces along the boundaries between the thrust sheet and sedimentary basin.

Ge and Garven (1994) found that, for their simulations, tectonic compressions created periods of transient flows in the simulated foreland basin, with excess flow rates of 10^{-3} to 10^{-1} m/yr for thrust sheets 1 to 10 km thick. Most of the excess pressure generated dissipated in 1,000 to 10,00 years. They concluded that the propagation of thrusting across a foreland basin could eventually move basinal fluids long distances. They also concluded that the volume of fluid involved in tectonic squeezing is relatively small, and is unlikely to have contributed significantly to regional fluid migration and ore formation.

Ge and Garven's (1994) simulations are not directly applicable to the fluid and heat fields developed in the Midland and Munster Basins region in the latest part of the early Carboniferous, when the Variscan front had reached southern Ireland (Cope et al., 1992a). This is in part because their cross section geometry is quite different from that used here. However, their cross section is probably more suitable to regional fluid migration than is the cross section used here, and the small volume of fluid which moved under tectonic influence would probably be even smaller if this cross section was subjected to a similar analysis. In light of the lack of movement of fluids from the Munster Basin any distance northwards (except by convection), the modelled effects of the tectonic compression and weight of the overburden associated with the Variscan tectonic front probably would not move hot fluids northwards into and across the Midland Basin. However, Ge and Garven's simulator does not incorporate the thermal effects of tectonic loading, and the possibility remains that such thermal effects could affect the resultant heat- and fluid-flow pattern.

It appears that, in the absence of a regional topographic gradient or regionally tilted aquifer, local cold flow from topographic highs which are very limited in their extent, and deep convective systems about 30 to 40 km across, are the most likely flow systems -- that is provided that the simultions bear a good relationship to the geology they represent. A regional topographic slope is very unlikely in Carboniferous Ireland, as is a unidirectionally tilted aquifer. The Midland Basin is much more likely to have frequent reversals of slope, both at the surface, and within the sedimentary succession, because of the synsedimentary block faulting. This reduces the likelihood of regional flow even further than would be anticipated by paleo-surface reconstructions.

Transient effects from both local uplift and from sediment compaction are likely. It has not been possible to model their effects, but as compactive flows are thought to be very slow and cold, the transient effects are probably not large. Transient flows caused by uplift could occur, though if they have any relationship to the flows from uplands that occur in the steady state simulations, their effects will again not be major. Local deep convection with a thermal driving mechanism appears to be the dominant fluid flow system. It is swamped in the vicinity of topographically-driven flow, but is otherwise pervasive over a wide range of rock properties.

5:8 SUMMARY

It is probable that convective systems deliver hot mineralised fluids to the near-surface. This study is a regional study: it has not investigated the details of flow on the local scale. The role of faults in the structural and sedimentological evolution of the region has been demonstrated in Chapter 4, but it was not possible to demonstrate their vital importance in the fluid flow system. Never-the-less, factors which could well be important to fluid flow paths developed at the local scale include the details of the geometry and the distribution of fractures and faults and the geochemical environment.

CHAPTER 6

DISCUSSION

This chapter discusses the discoveries made during this investigation of the flow systems that developed in the region of the early Carboniferous Midland Basin, Central Ireland. It also addresses how the research contributes to the understanding of the problem. The initial general question -- what controls the location of deposits? -- can now be replaced by more focused questions: what has been learned about the structural setting of the deposits, and what flow system(s) provide the mineralised fluids?

The question of "what flow systems" is the aspect of the study that is most clearly answered, and it is treated first. The subject of the basinal setting is then considered.

6:1 WHAT FLOW SYSTEM(S) CAUSED THE MINERALISATION?

The mass balance study (Chapter 2) investigates whether the proposed fluid flow systems could provide sufficient lead, zinc and water to have created the known deposits. The numerical modelling (Chapter 5) investigates what flow systems could develop in a cross-section representing the Midland and Munster Basins and their basement during the Carboniferous. The methods available for undertaking these two studies are not totally compatible, and so the flow systems investigated in the two approaches were not identical. However, synthesis of the results of both these approachs allows conclusions to be drawn as to the viability of: compactive flow in the Midland Basin, with and without the Munster Basin, and with and without a tectonic driving mechanism; local and regional topographically-driven flow; and deep convection. The results from both studies are synthesised below for each investigated flow system. In each case, relevant information on the Midland Basin region's structural evolution (Chapters 3 and 4) is incorporated.

6:1:1 Compaction-Driven Flow

By definition, a compactive driving mechanism displaces original pore fluids from sediments, and it does not permit pore-volume replacement. Even if the definition is relaxed, compactive flow cannot involve very much replacement fluid. In general, neither the local nor the regional (Midland Basin) compactive flow volumes are large enough to meet the fluid volume required to produce the known deposits. But if the compactive fluid volume that could be generated from the Munster Basin sediments is added to the Midland Basin compactive fluids, fluid mass balance may just be achievable.

Is such a scenario reasonable in a wider geological context? Mass balance requires that all of the Munster Basin compactive fluids would have to be transported into the Midland Basin, and that when the fluids arrive at the deposit sites, they are at temperatures of at least 150^{o}C, and quite probably above 250^{o}C. This requirement cannot be met for at least two reasons. Firstly, compactive flow is almost invariably cold and slow (0.1 to 1 mm per year: Bethke, 1985), and, in the volumetrically important upper parts of the sedimentary section (Shinn and Robbin ,1983), fluid flows are likely to be directed upwards, not laterally. As sedimentation rates are generally low for the Midland Basin, and fairly low for the Munster Basin in the Carboniferous, flow rates are likely to be towards the lower end of these estimates, and temperatures may well be cooler than in "average" conditions typical of sedimentary compaction. Secondly, compactive fluids are produced as sedimentation and burial occur, and a large portion of the Munster Basin rocks are of Devonian age and so would not be expelling fluids in the Carboniferous (MacCarthy and Gardiner, 1987). So, only a very small proportion of the total fluid volume of the Munster Basin could have been expelled and transported during the Carboniferous to the Midland Basin sediments. If the contribution from the Munster Basin sediment compaction is reduced to reflect only the Carboniferous portion of the basin fill, fluid mass balance is not achieved.

Fluid-inclusion studies have demonstrated that the temperatures at the sites of mineralisation reached 250^{o}C or greater (Sampson and Russell, 1987; Banks and Russell, 1992). Both Sampson and Russell (1987) and Banks and Russell (1992) attribute the 250^{o}C temperature to the mobile fluid. They argue that the lower calculated fluid temperatures (150^{o}C upwards) are probably the result of the mobile fluid mixing with the much cooler local fluid. It is very difficult to see how compactive fluids, which at the point of generation are cool, can reach 250^{o}C after transport through rocks which rarely, if ever, are at depths of more than 3 or 4 kilometres, and generally are within 1 kilometre of the surface.

No specific study of the compaction-driven flow has been undertaken in this study, but reference to other studies (Bethke, 1985; Ungerer et al., 1990) supports the argements made here regarding the role (or lack of it) for the expulsion of fluids during compaction of the Munster Basin. Additionally, as the simulations which were performed do not produce any flow from the Munster Basin into the Midland Basin, there is no support for heating and entrainment of Munster or Midland Basin fluids by any other flow systems. However, compactive fluids were certainly produced in these basins, and were probably entrained by more active flow systems, both local topographically driven flow, and convection.

Therefore, while the compactive fluids were produced, and they clearly went somewhere, they are not the primary source of mineralising fluids which created the Irish lead-zinc deposits.

6:1:2 Other Possible Regional Flow Systems

Large basins in other parts of the world have been modelled as developing regional fluid flow systems. These regional flow systems appear to be the result of a regional surface gradient (Garven and Freeze, 1984b; Garven, 1989). Garven (1989) comments that this situation typically occurs in foreland basins which have been subjected to uplift at their margin, and which have therefore developed a regional topographic slope away from the tectonic belt.

The Midland Basin region was still developing through the Carboniferous with marine conditions dominating. The Variscan tectonic front reached southern Ireland by about Westphalian time (Cope et al., 1992a), and this orogenic belt has been suggested as the source of the hot mobile fluids (Fitzgerald et al, 1994). There is abundant evidence against a regional northerly slope across the Munster and Midland Basins during the early Carboniferous, both in the literature, and in the restorations completed as part of this study. But since there is reason to suggest a tectonic front south of the South Munster Basin at about Westphalian time, could there have been an earlier associated topographic high?. Could the combined topographic and tectonic loading effects of a Variscan uplift which remained south of the Munster Basin have produced a flow system that would have driven hot fluids into the Midland Basin?

The simulations which incorporate a regional northerly topographic gradient across much of the Munster and Midland Basins produce a regional flow system very similar to that in, for example, the foreland basin of western Canada (Garven and Freeze, 1984a, 1984b). However, the mobile fluids are quite cool in both Garven's simulations and those with long topographic slopes reported here. The simulations of the Midland and Munster Basins with a topographic slope extending across a large part of the cross-section display a regional gravity-driven flow system that does not extend more than a few kilometers away from the end of the sloping surface. This simulation is significant in that it shows a similarity to the work of Garven and Freeze (1984a, 1984b) in that a regional topographic slope is incorporated, but it also suggests that any regional flow is closely tied to the continuation of that slope. When a topographic high, which is restricted to locations south of the Munster Basin, is added to the simulation, it produces a gravity-driven flow system, but the flow system does not extend more than a few kilometers away from the upland, and it does not cross the Munster Basin. The mobilised fluids are also cool.

The OILGEN simulator does not incorporate the effects of tectonic loading. Two-dimensional simulations of tectonic loading, reported by Ge and Garven (1994), use a somewhat different cross section to that used in this study, but these authors concluded that the fluid-flow effects caused by tectonic loading were minor in comparision to those of other flow systems. While it is not possible to say with certainty that a minor tectonic component in one simulation would also be a minor component in a different simulation, there is sufficient similarity between the cross-section modelled by Ge and Garven and that modelled in this study, to suggest that the effects of tectonism would also be small in the Irish example. If this is true, it seems unlikely that the combined effects of topography and tectonism could create a regional flow system capable of moving fluids into, and across, the Midland Basin region.

6:1:3 Local Topographically-Driven Flow

Local, basin-only systems just pass the metal mass balance test (Chapter 2), but, as these can only be driven by a topographic head, they can accommodate multiple pore-volume replacements. Therefore they cannot be eliminated entirely (from a mass balance viewpoint) as the means to supply mineralised fluids to the smaller deposits. How do they fare in the wider geological context? Typical flows from local uplifts in the simulations extend less than 5 km away from the upland margin. This means that the fluids pass through a much smaller source-rock volume than has been assumed in the mass balance calculations. If the simulations represent the size of a typical local flow system, then local basin-only flow systems could provide sufficient metal for only the smallest deposits. Such fluid systems are not likely to provide fluids which are heated to anything approximating 250^{o}C unless they penetrate several kilometres into the basement. The simulations confirm that topographically driven fluids remain cold, and that they do not descend to depth. Therefore, local basin-only flow systems are not a likely source for mineralising fluids.

Nevertheless, there will have been cold local flow systems where there was a sufficient topographic head to drive flow. Such situations arise when fault blocks become exposed, and are clearly indicated by diagenetic and lithologic evidence of exposure (oolites and dolomitisation). It is possible that local, topographically-driven flow systems might actually inhibit mineralisation close to topographic highs by diluting the effectiveness of hot mineralised fluids, or by forcing the zone of fluid mixing deeper into the subsurface. If such conditions of (presumably) fresh water influx fail to provide a sufficient sulphur supply, the mineralisation may be inhibited entirely.

6:1:4 Convection Cells

The local deep systems can achieve metal balance even for the largest deposit, Navan, but they may require a few hundred pore volumes to produce an average deposit. Perhaps a few tens of pore volumes are required if very high solubilities are assumed.. Deep convection has been proposed as the driving mechanism for local deep flow (Russell, 1968; 1978). Any number of fluid replacements are permissible by this mechanism -- at least from a mass-balance viewpoint -- and the delivery of hot fluids to the near-surface is illustrated by the simulations reported in Chapter 5.

The mass balance analysis suggests that perhaps 500 fluid replacements are necessary. Is this number at all reasonable? If the duration of mineralisation is assumed, the fluid velocity needed to produce several hundred pore volume replacements can be calculated. It is assumed that one fluid volume replacement corresponds to one fluid circulation in a convective system. If a deposit forms over a 1 million year period and it requires 500 fluid circulations, then the average fluid velocity is about 1m per year. If the lead and zinc solubilities are an order of magnitude lower or higher, then the required average speed is 10 m or 0.1 m per year, respectively. If mineralisation occurs over only 100,000 years then the velocities increase by a factor of ten. Velocities of 0.1m to 10 m per year are within the range of reported geological fluid flow rates in the upper crust (Cathles and Smith, 1983) but values much in excess of 10 m per year are rarely reported. The simulations described here produce flow rates for convecting fluids close to 1 m per year. Thus the rates of flow indicated by these simulations are reasonable.

The simulations also produce a hot updraft of fluid. When the updrafts approach the surface, the ascending fluids become only warm, and then they cool to the surface temperature. This cool surface fluid is a consequence of the specification of a uniform surface temperature boundary condition. Nevertheless, the pattern of hot ascending fluid is born out by the simulations, and less restrictive models are expected to produce updrafts that remain hot all the way to the surface. Convective flow is the only system capable of explaining the character of the Irish lead-zinc deposits.

6:2 BASIN DEVELOPMENT

6:2:1 Geometric Changes During Carboniferous Basin Development

This study has not been able to prove that the structural style of the Midland Basin region in the Early Carboniferous is that of tilted, but otherwise undistorted, fault-bounded blocks of basement rocks with overlying folded or faulted sedimentary rocks. However, this style is fully compatible with the available constraints.

Some of the faults used in the reconstruction and restorations have been identified by surface mapping, but many have not been positively identified. Fault identification in this study is based on changes in structural elevation or thickness, with the "faults" being inferred to lie in areas where the rate of change of structural relief, or thickness, is most rapid. In particular, a pattern of regions of very similar isopached thickness separated by regions with large thickness changes, emerges for all the isopached units.

Faults identified in this manner are unlikely to be always correctly positioned, and may not occur as single faults, but perhaps as fault zones. In some cases "faults" in the sedimentary section may actually be folds over faults in the basement. Nevertheless, there is much evidence to support the dominance of this style, and a fault-bounded block style needs to be seriously considered when evaluating the tectonic causes of this basin.

Both the restored geometries, and the changes between the stages of basin evolution, demonstrate that subsidence of the basin was not uniform, either in location, or in the rate of subsidence. There is no obvious subsidence-shape function that even approximates the actual pattern, and no obvious sea level curve that explains this distribution of rocks. These issues also need to be taken into consideration when evaluating the tectonic setting of the Midland Basin region, and of central and southern Ireland in general in the Early (and possibly Late) Carboniferous.

6:2:2 Lithology Changes Related to Structural Development

The development of the Midland Basin region by fault-bounded block movement produces a somewhat uneven rate of subsidence (Chapter 4), and it might be expected that sedimentation will reflect rapid lateral and temporal changes in the position of the sediment/water interface. In the time represented by the Waulsortian and Chadian restorations, oolite shoals have developed on the tops of some blocks, and dolomites on the tops of others or in the immediate down-dip vicinity. Both these occurrences suggest a near-surface position of the top of these blocks, and/or exposure. Exposure has implications for the influx of fresh, meteoric pore waters, and thus for the early development of diagenetic dolomite cements. Since there are differences between hydrothermal dolomite and the cements associated with meteoric influx, it may be that a careful analysis of the dolomites will prove to be useful in interpreting whether or not dolomitisation is an important precursive event for ground preparation prior to mineralisation.

Other factors which could result from fault-bounded block movement include rapid changes from shallow to deep-water sedimentation, with the attendant possibility of anoxic conditions developing in local deeps. Anoxic conditions may be favourable for the development of brine pools, a circumstance invoked by Boyce et al. (1983) as a necessary component of mineralisation at Silvermines. Some of the rapid facies changes that occur in the Midland Basin may be readily explained as being the product of localised structural changes.

There is a growing body of evidence for the development of slumping and submarine mass-wastage, and their associated debris flows deposits, in association with lead-zinc mineralisation. These processes are readily attributed to contemporaneous faulting located nearby (Boyce et al., 1983, Ashton et al., 1986; 1992; Ford, pers. comm., 1995). This evidence provides further support for the high-amplitude, short-wavelength structural changes identified in this study.

One of the consequences of high rates of sedimentation, which can result from the rapid downdrop of fault-bounded blocks, is localized (time and space) high rates of compaction. Rapid compaction can lead to either local overpressure or to short-duration, localised compactive flows (Couples et al.,1995). Fluid flows resulting from temporally- and spatially-varying compaction could constitute a locally-significant component of mass transport, but these are unlikely to have a major impact on the conclusions reached concerning the flow systems responsible for mineralisation. This is because the sites of local, rapid subsidence (and sedimentation) only function as such for short times, and affect only a small volume of the basin fill. The mass balance approach will not permit such localised systems to be responsible for producing significant mineralisation.

6:2:3 Fault-Block Corners

The empirical relationship between fault-bounded block corners and lead-zinc mineralisation has been addressed in Chapter 4. But the physical characteristics that may make corners favourable sites for mineralisation have not yet been considered. Corners of fault blocks, particularly of (upthrown) outside corners, may be sites of higher strain, and thus sites of higher degrees of deformation. In addition, the geometric requirements for fault displacement may cause extra dilatancy at irregularities such as corners, especially if regional motion alters slightly through time. If the deformation is dilatant, then corners may be sites for enhanced for fluid flow. This potential enhancement could occur only around the time of fault movement, or it could last for long periods. This is a subject for further study.

Fault-bounded block corners have the potential for another impact on mineralisation. Boyce et. al (1983) have suggested that synsedimentary mineralisation at Silvermines took place in fault-controlled brine-filled depressions on the Carboniferous sea floor. The development of corners could also result in the formation of a fault-controlled local depression, so helping the development of the brine pools which Boyce et al. (1983) have invoked as a necessary component for ore formation.

6:3 TECTONIC SETTING OF THE MIDLAND BASIN

No clear tectonic model is dictated by the reconstructions created in Chapter 4. There is no special or consistent point where subsidence is localised throughout the early Carboniferous; there is no spatial or temporal pattern to depositional deeps versus depositional shallows; and the shape of the basin does not develop in any obvious progression. The "classic" basin types are each considered below.

If an extensional origin is assumed, then the basin should: exhibit rift-phase sedimentation localised to a basin deep, with possible rift-shoulder-derived coarse material being deposited at distinct fault-bounded basin edges; possess axial drainage patterns along the length of the basin; probably show a degree of asymmetry, but this is not required; and, after active rifting ceases, a thermal-sag phase of sedimentation should develop, with potentially a considerable accumulation of younger materials that do not show a relationship to active faulting. These characteristics are not observed in the Midland Basin.

If a wrench environment is assumed, then the basin may be expected to: have both significant ups and significant downs; depending on whether the wrenching is transtensional, transpressional, or pure, the relative proportions of ups and downs might be altered; rapid facies changes, and locally-derived sediment supplies, are to be expected, along with fault-controlled sedimentary distributions; and the trends of structures need to form distinct patterns. These characteristics, especially those of the structural shapes, do not seem to be compatible with the reconstructions. The possibility of the Midland Basin being created in a wrench setting can be discounted.

If it is assumed that the basin is formed in a compressional setting, then: it should take the form of a foreland basin; its sediment should be largely supplied from the rising orogenic belt, or possibly from cratonward; there should definitely be debris from the orogenic belt; and there should be strong asymmetry to the basin geometry geometry (deepest near the mountains). These characteristics do not agree with the data described for the Midland Basin.

So, the "classic" basin environments do not apply to the Midland Basin. Indeed, aspects of its evolution, as indicated by the reconstructions and the associated lithofacies distributions, seem to rule out each of the normally-accepted modes of basin formation. Perhaps such contradictory situations are more common than is often assumed (Dickenson, 1993). However, deriving the tectonic setting for the Irish Midlands is not the goal of this project. That investigation must be undertaken in a different study. All that is necesary here is to indicate that it would be unwise to force any of the classic interpretations onto this basin, since doing so would result in predictions that contradict the results obtained by this study.

When that tectonic/geodynamic study is undertaken, it will be useful to place the Midland Basin in its wider context. This, presumably, will need to consider the possibility that the Midland Basin is the down-dip continuation of the Early Carboniferous Northumberland Basin of northern England and southwestern Scotland. The investigation will also have to consider the context in which the Northumberland Basin has been interpreted, and its relationships to other Carboniferous basins that are well-known in England and Scotland (Fraser et al., 1994). It will also be important to ensure that the interpretation considers other Carboniferous basin development across North America (Couples et al., 1992), since Ireland was a part of that craton in the Carboniferous. It may prove to be the case that the Irish Midland Basin provides an important link between the studies of northern European basins and those of North America.

CHAPTER 7

CONCLUSIONS

This study represents a regional investigation of both the basinal setting of the known ore deposits, and the flow systems that could have formed them. It has used knowledge of the deposits -- particularly the mass of the metals, and the temperatures and chemistries under which deposition occurred, to determine the volume and characteristics of the hydrothermal fluid systems that transported the metals to the sites of deposition. The study has contributed to understanding the development of lead-zinc mineralisation in central Ireland by relating the possible hydrothermal systems (those that pass the tests of mass balance) to the setting in which they operated.

The geological portion of the study reveals that basin development was primarily by the movement of fault-bounded blocks of basement, with concomitant accumulation of heterogeneous sedimentary sequences in the spaces that were created. An empirical correlation suggests that fault-block corners are favourable sites for syngenetic or epigenetic mineralisation. Deep, local, convective hydrothermal flow is the only viable heat- and fluid-flow system that is compatible with the geologic setting, and with the requirements posed by information from the deposits themselves. The study has suggested new paradigms which could now serve as exploration tools. Some of these are of use in a regional sense, while others are of use on the more local scale of individual orebodies.

Although it is unlikely that this study has provided a definitive explanation for Irish mineralisation, future investigations can now proceed from a firm base of characteristics (from this work and other studies) which must be addressed by any models that are subsequently proposed. These characteristics are:

1. The mineralised fluids are at temperatures of about 250^{o}C when they reach the sites of mineralisation.
2. The mineralised fluids are the carriers of the lead and zinc and about 15% of the sulphur: the remainder of the sulphur is biogenic, and is locally derived.
3. The local fluid is a cold brine.
4. The sites of mineralisation may be at the surface or somewhat deeper, but they are within about 1 km of the surface.
5. The lead is primarily basement-derived.

6. The deposits are mostly sediment-hosted with some vein-hosted mineralisation, which is primarily in basement.
7. All deposits formed close to faults, and most formed at the corners of fault blocks.
8. There was compaction-driven fluid, but it is not the mineralising fluid.
9. There was no regional flow system.
10. There was gravity-driven flow from emerged fault blocks, but their flow was only very local, shallow, and cold.
11. There was deep local convection which brought hot fluids to the near-surface in a focused updraft.

Appendix A

This Appendix accompanies Chapter 2 and contains simplified versions of the equations used to calculate metal- and fluid-balance (see also Fig. 4, Chapter 2). The complete equations incorporate: individual calculations for lead and zinc; corrections for fracture/fracture and fracture/matrix intersections; unit conversions; density corrections, etc as required.

Metal mass which reaches each mineralised site (Md):

Md = (metal now in deposit + metal in halo) * depositional efficiency **1**

NB: For regional cases, Md calculated for each deposit individually, and then summed.

Metal mass removable from source rock (Ms):

Metal mass removeable from source rock matrix **(Msm):**

Msm = flow system volume * participating rock fraction * (1 - porosity) * metal concentration in rock * fraction of metal removed. **2a**

Metal mass removeable from source-rock fracture walls **(Msf):**

Msf = Fracture surface area * alteration zone depth * metal concentration in rock * fraction of metal removed **2b**

Ms = Msm + Msf **2**

Water volume required for each deposit (Fd):

Fd = **Md** * maximum solubility at deposit site. **3**

NB: 1. Separate calculations made for lead and zinc, with 10% variation allowed. Larger value used in subsequent calculations.
2. Correction made for water delivered to deposit at less than maximum metal solubility.

Pore volume of source rocks (Fp):

Pore volume of rock matrix (**Fpm**):

Fpm = flow system volume * participating rock fraction * porosity **4a**

Pore volume of fractures (**Fpf**):

Fpf = fracture surface area * fracture aperture **4b**

Fp = Fpm + Fpf **4**

Fluid required to extract source-rock metals (Fs):

Fs = **Ms** * solubility **5**

NB: 1. Solubility varies by rock type and conditions

2. Separate calculations made for lead and zinc with 10% variation allowed. Larger value used in subsequent equations.

Water volume required to transport metals (Ft):

Ft = Larger of **Fd** or **Fs** **6**

Compaction-driven fluid volume (Fc):

Fc = surface area of flow system * change in sediment thickness due to compaction **7**

NB: Change in thickness of sedimentary column determined by BasinMod.™

Number of pore volumes (Pv):

Pv = Ft / Fp **8**

Number of compactive volumes (Pc):

Pc = Ft / Fc **9**

APPENDIX B

Appendix B consists of the large 1:350,000 scale maps of the reconstructed top-basement, and the sedimentary units. These maps are contained in a packet at the back of the document. All 7 maps use the Irish National Grid and are produced to the same format:

1. Faults are in blue
2. Contours are in red, are in metres, and are spaced at at either 100 m or 200 m as needed to display the configuration. Subsea values are negative.
3. Deposits are given in green: S = Silvermines; T = Tynagh; N = Navan; L = Lisheen; G = Galmoy.

APPENDIX C

THE THEORY AND METHODS OF CONTOURING AND GRIDDING

This Appendix addresses the difficulties encountered in representing the shape and position of geological volumes and surfaces in a form that can both be interpreted by a geologist from a map, and that can be used for mathematical operations. The method used must also allow properties of that surface or volume to be represented mathematically along with the shape and positional information.

In practice these requirements are only partly met by the techniques available to us. Structure-contour maps represent a geological surface (or two or more maps represent a volume) in a way which is meaningful to a geologist, but in a way that is not fully specified. Mathematical operation is performed by defining values at regularly spaced grid nodes. The value assigned each grid node represents some property such as elevation, thickness or averaged porosity through a given thickness.

Gridding is most commonly done from subsurface data for which there is not yet a structural interpretation. However, the geologist can create a grid from a structure-contour map: this is the approach taken in this study. In either case, the elevation information is gridded; if the required surface shape is already known, surface orientation information is also used. The resulting grids can then be contoured for (2-D) display purposes, and be used to computer-generate 3-D displays.

C:1 DIFFICULTIES OF CONTOURING

Historically the most common method of representing a geological surface is by using a structure-contour map. This method is adapted from cartography and represents points of equal elevation by a continuous line. Normally a number of equally-spaced depth or elevation values are used for the contours. A fault is represented by a line if it is vertical, and by a polygon if it has a normal displacement. Reverse faults are generally represented by ornamented lines, with a portion of the overlapped surface (including the fault cut-off) obscured from view and either not contoured or contoured with dashed lines.

The generation of a structure-contour map to represent a geological surface is by no means an automatic process. The input data may take several forms, and can include: elevations or depths of the surface at specified points (point XYZ data); location of faults (either as traces or as planes); offsets at faults; and dip and strike or other orientation information. Construction of the map also requires the choice of a structural style (such as that of a fold and thrust belt, an extensional region, or several generations of folding in a metamorphic belt). In some situations the structural style is known, but even in these cases, every geologist will produce a different map. When the structural style is unknown, the maps that result from assuming different styles can be wildly different.

C:2 THE NEED FOR GRIDDING

The experienced geologist has little difficulty in visualising the general three-dimensional shape of the geological surface which is represented by a structure-contour map, even when the map is fairly complex. However, there are two major problems which can arise from using structure-contour maps. First, the geometry is not fully specified by the creator of the structure-contour map. Strictly speaking, the interpretation is a series of lines representing the map position at which the surface is at a certain elevation. If the "map" has been well created, most geologists would come up with a similar interpretation of the shape of the surface between the contour lines. But even the most able contourer has difficulty with complex folded or faulted surfaces.

The second problem arises from the first. Because the "surface" is only specified along the contour lines, it is not possible to operate on it mathematically. For example, the thickness of a Jurassic unit cannot be properly removed from the top of a Triassic horizon mathematically using structure-contours on the top and base of the units unless those contours are very closely spaced.

Mathematical operation on a surface requires a more complete specification of the X,Y,Z shape of the surface. Geological surfaces are complex shapes and can only very rarely be represented by tractable analytical functions. The normal method is to generate a (regular) X,Y grid and calculate, using a gridding algorithm, a Z value at each node of the grid. Surfaces represented by grids with the same X and Y spacing (and covering the same area) can then be added, subtracted etc. Faults can be used in the gridding algorithms such that they prevent data from one side of a fault being used in calculating elevations on the other side.

This is not an ideal system. as the surface shape is still not fully specified, but it does allow a reasonable reperesntation of the surface shape, particularly if a suitable grid spacing is chosen.

C:3 CREATING A GRID FROM DATA

The data which can be used in generating grids is very similar to that used to produce a structure-contour map. Individual points which have depth data are almost always used; if the shape of the surface is already determined, the surface orientation information is usually input by digitising the structure contours (see below). More advanced gridding packages also use faults, which are digitised as lines (if vertical) or polygons (if inclined). However it is not possible to **directly** input the geologist's experience (see "Problems Specific to this Study" below) . Finding the "tricks" which incorporate the geologists knowledge is the biggest difficulty encountered in computer generation of surfaces.

There are other problems which need to be addressed. These are covered below:

Unlike a structure-contour map, a grid has to contain a value at every node within its limits. But it is possible to arrange that a certain region is effectively excluded from gridding if the geologist feels that the uncertainty is too great. The excluded region is represented by grid nodes containing null values which result in "holes" in the grid. A null value is normally a very large number, which the software is told represents "missing". In certain circumstances this an acceptable solution, though use of null values to operate on any other grid. results in null values in the second grid also

Even if a grid node overlies a data point, the calculated Z value may not exactly match the value of the original data point. This lack of matching applies equally to input contours. If this problem is anticipated, it is normally possible to design the data input to minimise this problem (for example by very close spacing of the digitised points of a contour line). Also, the gridding algorithm (see below) can be chosen so as to minimise this problem.

Faults introduce a whole class of complexity. This is particularly true if there are isolated fault blocks. Faults can be used to segment the data available for gridding, so that the data is applied only to the fault block which contains it. In practice this can result in too little data to produce grid values in some fault blocks. The geologist has to decide whether there is a regional trend throught the area, with faulting imposed on it. If this is the case, it may be possible to chose an algorithm which performs its first pass without the faults, and refines the grid using faults in its second pass. If there is no regional trend, the grid can be hand-edited.

Producing grid values near the edge of the gridded area can be difficult because, by the way it is defined, the gridding algorithm cannot use data from outside its limits. Extrapolation, rather than interpolation methods are used, but the best results are usually obtained by extending the initial gridded area outside the area of interest, and then clipping the grid to the desired limits.

C:4 THE GRIDDING ALGORITHMS

Values are calculated for each point of a grid using a gridding algorithm. There are a wide range of algorithms, with different strengths and weaknesses. The appropriate algorithm depends on: the type and distribution of data available; the closeness-of-fit required; the presence or absence of faults; and the structural style to be modelled.

The basic process of gridding takes a "patch" of XY space around each grid node and uses different algorithms to interpolate (or extrapolate at area margins or close to faults) a value at the node. The gridding algorithm chosen controls: the shape and size of this "patch", the method used to average the data points included in the "patch"; and the minimum number of data points for a valid calculation. The "patch" is then moved over 1 increment and the process repeated. The resulting node values are then "smoothed" to remove the "patchy" effect. Smoothing can be done using a range of averaging methods.

Typical gridding algorithms include:

1. Convergent Gridding. Grid node values are converged upon by iteratively "snapping" control points to nearby nodes using a distance-weighting technique such that control points nearer to the node have a larger influence on the node's value. Convergent gridding can use faults. This algorithm is stable, and good for general-purpose gridding.

2. Least-squares Gridding. A least-squares fit is made through the relevant control point and a plane is generated. The Z value of this plane is assigned to the node. Most gridding proceedures also use distance-weighted averaging in the generation of this plane, and smooth the first-pass Z values using a biharmonic filter. Most forms of this gridding algorithm can use faults. Least-squares gridding is useful for dense data, but is not suitable for interpolation or extrapolation over long distances. It also does not handle contour data very well.

3. Trend gridding. Trend gridding is used to derive the regional trend of a surface. It is usually used to identify anomalies in surfaces, such as paleo river channels. This is done by generating a "residual" grid by subtracting a trend grid from a "normal" (eg. convergent) grid. Trend maps do not honour individual data points, but show a broad regional shape. Trend gridding allows the Geologist to control the order of fit. A first-order fit results in a sloping plane; a second-order fit incorporates curvature components, and so picks out more features of the surface. The higher the order of fit, the closer the fit to the original data.

There are other types of gridding algorithms available. Not all algorithms are designed to represent a surface. Some are more suitable for mapping the distribution of different rock types, fauna types etc.

C:5 PROBLEMS SPECIFIC TO THIS STUDY

The gridding process is used in this study to produce pre-determined surface geometries. The software used in this study, CPS3™ is not designed to accommodate this need and difficulties are encountered, particularly because of the use of the tilted fault block structural style. In addition, the use of grids to represent unit thicknesses, rather than surface elevations is not straightforward.

C:5:1 Representing Planar Segment Interpretations

Gridding algorithms are designed to take distributed depth data and generate a surface which both reasonably honours that data and has no abrupt changes which are not forced by the data. There is no direct method to input surface orientation information. The "smoothness" of the grid values is normally achieved by designing in a small change in Z value from one grid node to the next. This tends to result in curved (splined) contour lines. The structural style used at top-basement level is that of uniformly dipping fault blocks. In order to produce an accurate representation of uniformly dipping segments, the **input** contours have to be digitised at closely spaced elevation intervals and the contours themselves have to be closely spaced, even if this requires very small depth (or value) increments. This method forces a better fit to the required interpretation.

C:5:2 Problems with Surface and Isopach Continuity

CPS3™, along with most other gridding packages, is designed to generate and operate on surfaces. When it is used for isopachs several problems arise. The isopachs of several units go to zero within the gridded area. CPS3™ copes with the absence of a surface by assigning null values to the relevant grids nodes, but this means that those nodes cannot be operated on, even if every other surface in the calculation is complete. This can be dealt with by converting the nulls to zeros, or to very small values, as CPS3™ has difficulties contouring zeros. Never-the less it is still very difficult to produce a reasonable contour map showing where an isopach reaches zero thickness.

APPENDIX D

TABLES OF UNIT THICKNESSES

D:1 Table of Measured ORS Thicknesses

(X and Y locations use Irish National Grid (km))

X	Y	Thickness (m)
254.8	256.5	51.
271.1	221.2	33.
273.4	216.3	38.
216.7	228.9	97.
214.9	179.6	133.
214.4	179.0	138.
197.5	182.0	148.
193.4	175.7	105.
207.9	216.8	110.
198.2	185.9	229.
200.2	184.7	229.
225.8	185.7	274.
241.5	210.8	348.
230.5	211.9	220.
183.1	173.2	100.
183.3	177.3	100.
181.1	171.9	110.
182.1	171.6	110.
171.4	169.9	116.
172.7	169.7	112.
182.4	148.1	307.
183.4	146.8	288.
141.0	153.5	348.
141.8	181.6	144.
143.5	179.6	163.
168.5	212.3	271.
169.6	213.3	271.
170.0	211.7	258.
168.9	210.2	266.
174.0	211.6	251.
178.7	213.5	138.
147.0	204.8	125.
155.8	184.4	157.
174.4	188.3	119.
175.6	189.2	112.
175.5	187.1	123.
177.1	191.3	122.
258.9	239.9	82.
182.8	180.8	98.
148.6	218.4	0.
291.7	231.0	35.
283.9	230.6	50.

Table of Measured ORS Thicknesses
(cont.)

X	Y	Thickness (m)
260.4	253.1	40.
255.0	257.1	40.
265.9	240.3	50.
272.2	223.3	50.
269.7	221.1	40.
271.8	220.3	30.
227.1	249.1	130.
221.2	244.7	120.
234.8	240.7	80.
230.2	235.4	100.
220.4	231.3	125.
217.1	229.9	125.
215.0	224.2	135.
212.1	225.6	125.
209.7	223.9	125.
208.4	223.3	125.
205.1	229.9	125.
207.3	232.0	125.
213.3	235.4	125.
212.7	236.6	110.
214.8	240.5	130.
204.9	235.8	150.
194.1	232.4	125.
192.8	228.5	140.
218.1	243.4	110.
213.6	177.7	125.
210.7	175.5	135.
205.5	188.5	225.
200.8	184.3	225.
242.2	212.5	350.
184.5	177.5	100.
187.3	174.8	115.
186.8	173.6	105.
189.7	173.2	110.
178.7	150.3	300.
132.8	154.5	365.
134.6	155.8	370.
146.2	168.9	335.
146.7	180.1	150.
146.4	182.1	140.
166.2	218.6	140.
168.2	217.2	205.
170.6	217.1	195.
174.5	215.8	180.
171.5	210.8	255.
171.1	213.5	260.
174.0	213.4	190.
174.9	213.9	225.
176.3	216.4	175.

Table of Measured ORS Thicknesses
(cont.)

X	Y	Thickness (m)
178.2	212.6	200.
178.2	212.1	210.
181.0	213.3	190.
179.5	211.2	180.
181.4	210.1	180.
176.6	209.3	195.
181.0	206.2	180.
182.3	205.6	140.
184.0	206.2	195.
155.8	184.4	120.
171.3	187.1	150.

D:2 Table of Measured Navan Thicknesses

(X and Y locations use Irish National Grid (km))

X	Y	Thickness (m)
291.7	231.0	225.
283.9	230.6	275.
260.4	253.1	375.
265.9	240.3	425.
269.7	221.1	250.
234.8	240.7	200.
205.1	229.9	185.
194.1	232.4	175.
192.8	228.5	150.
218.1	243.4	250.
187.6	231.1	155.
272.2	223.3	250.
271.8	220.3	221.
227.1	249.1	400.
221.2	244.7	248.
213.3	235.4	173.
212.7	236.6	173.
204.9	235.8	59.
242.2	212.5	181.
169.6	249.4	121.
271.1	221.2	139.
170.7	255.8	18.
272.2	223.3	250.
271.8	220.3	221.
227.1	249.1	400.
221.2	244.7	248.
213.3	235.4	173.
212.7	236.6	173.
242.2	212.5	181.
169.6	249.4	121.
258.9	239.9	400.

D:3 Table of Measured ABL Thicknesses

(X and Y locations use Irish National Grid (km))

X	Y	Thickness (m)
279.9	248.4	1060.
300.2	228.4	51.
251.4	258.8	177.
281.0	282.8	150.
283.9	269.5	125.
284.0	268.7	64.
297.8	274.8	49.
297.8	274.6	50.
254.5	279.9	196.
262.1	272.9	245.
277.1	265.1	129.
227.1	249.1	253.
221.2	244.7	141.
230.2	235.4	377.
217.1	229.9	290.
217.2	229.3	19.
217.5	228.9	106.
200.6	226.2	283.
202.5	260.6	25.
198.2	185.9	334.
184.5	177.5	281.
183.1	173.2	277.
182.1	171.6	206.
178.7	150.3	308.
132.8	154.5	252.
141.0	153.5	236.
146.2	168.9	266.
238.1	281.6	137.
230.7	278.8	155.
223.9	272.6	162.
235.0	266.1	80.
235.4	265.9	144.
234.8	264.5	182.
213.1	280.6	97.
201.2	279.4	64.
218.6	266.0	197.
169.6	249.4	145.
162.5	219.0	199.
168.2	217.2	272.
169.6	213.3	309.
171.5	212.4	186.
147.0	204.8	117.
258.9	239.9	207.
266.9	259.4	175.
265.9	240.3	225.
258.2	261.2	170.
234.8	240.7	340.
194.1	232.4	290.
192.8	228.5	300.

Table of Measured ABL Thicknesses
(cont.)

X	Y	Thickness (m)
206.5	246.8	250.
218.1	243.4	250.
237.5	262.0	200.
166.2	218.6	250.
291.7	231.0	686.
260.4	253.1	215.
250.0	256.0	168.
268.0	262.5	176.
210.5	250.4	243.
202.4	260.4	62.
210.7	175.5	504.
205.5	188.5	454.
187.3	174.8	257.
186.8	173.6	259.
189.7	173.2	277.
146.7	180.1	192.
208.7	262.8	63.
218.6	266.3	205.
219.2	266.0	189.
187.6	231.1	284.
159.8	215.3	198.
178.2	212.1	242.
181.4	210.1	347.
176.6	209.3	351.
181.0	206.2	358.

D:4 Table Measured Waulsortian Thicknesses

(X and Y locations use Irish National Grid (km))

X	Y	Thickness (m)
182.111	171.583	42.
235.001	266.078	75.
235.396	265.874	15.
234.825	264.511	29.
237.467	262.027	112.
208.698	262.883	85.
209.141	263.039	100.
218.552	266.028	143.
218.636	266.336	133.
219.186	265.993	177.
148.61	218.38	17.
168.23	217.175	177.
178.66	212.814	11.
181.375	210.055	26.
176.63	209.295	28.
181.03	206.155	4.
146.965	204.81	26.
217.562	243.140	320.
193.926	228.075	265.
203.017	260.283	66.
258.342	261.322	158.
207.173	245.477	258.
251.108	258.592	74.
260.393	253.004	169.
275.744	273.789	5.
297.303	274.049	134.
282.238	270.672	7.
285.095	269.114	28.
269.251	262.880	20.
275.667	246.735	518.
265.615	239.763	226.
288.472	230.153	278.
301.199	230.153	70.
296.004	226.776	19.
216.523	230.153	240.
218.082	231.192	214.

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