The age, origin and tectonic significance of Mesozoic sediment-filled fissures in the Mendip Hills (SW England): implications for extension models and Jurassic sea-level curves

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Abstract – In the eastern Mendip Hills, on the northern margin of the Wessex Basin, SW England, the Carboniferous Limestone is cut by numerous fissures that are filled with Mesozoic sediments (sedimentary dykes, neptunian dykes). The fissures contain a record of Triassic–Lower Jurassic sediments that are only sparingly preserved in their normal stratigraphical position between the Carboniferous Limestone and the unconformably overlying Upper Inferior Oolite of Bajocian age. Detailed analysis of cross-cutting relationships, facies analysis, biostratigraphy, lithostratigraphy and strontium-isotope ages of relevant Mesozoic sediments has allowed the construction of an Upper Triassic–Lower Jurassic fissure-fill stratigraphy for the eastern Mendip area. Most fissures were clearly formed by rapid influx of unlithified sediment from the land surface or sea floor. Some smaller cavities, or larger cavities with restricted access to the unconformity, were apparently filled by sediment that trickled down into the fissure system. The vast majority of the Mendip fissures are interpreted as having formed as a response of the Carboniferous Limestone, north of major basin-bounding faults, to pulses of tectonic extension during Ladinian–Norian/Rhaetian, late Hettangian–early Sinemurian, late Sinemurian–early Pliensbachian, mid-Pliensbachian, late Pliensbachian and Bajocian times. Triassic–earliest Jurassic fissures have a broad spread of strike from E–W to NW–SE to N–S, accommodating extension in a roughly NE–SW direction. Younger Jurassic fissures show well-defined E–W and N–S trends with the former becoming dominant through time. Total extension of ∼ 4.7% N–S and ∼ 0.6% E–W was produced by the formation of Triassic–Jurassic fissures within the Carboniferous Limestone. Such patterns of extension are thought likely to be characteristic of the subsurface geology in much of southern England and Wales. Major implications of this study are that: (1) the presence of seismically unresolvable sediment-filled fissures in supposedly rigid fault blocks can lead to a significant underestimate of regional extension based on the restoration of motion on normal faults on seismic-reflection profiles, and (2) the isolation of pulses of tectonic activity with a temporal resolution of 10^5–10^6 years may provide a means of identifying a tectonic signal in relative sea-level curves derived from the Jurassic sedimentary record.

Keywords: extension, fissures, neptunian dykes, sedimentary dykes, Mendips, Triassic, Jurassic, Mesozoic, sea-level changes.

1. The geological setting of the Mendip fissures

The Mendip Hills consist of four *en-echelon* periclines of Palaeozoic rocks (Fig. 1), on the northern edge of the Wessex Basin in southern Britain: the Blackdown Pericline, the North Hill Pericline, the Pen Hill Pericline and the Beacon Hill Pericline (Green & Welch, 1965). The main field area for this study is the Beacon Hill Pericline, the most easterly and southerly of the four, which forms an approximately E–W ridge. At its eastern end, the Palaeozoic fold plunges beneath the Jurassic strata of the Upper Inferior Oolite (Bajocian) and Fuller's Earth (Bathonian). The southern edge of the Beacon Hill Pericline is cut off by the Leighton Fault, which forms the northern edge of the Wessex Basin (Fig. 2). Over much of the area Palaeozoic

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rocks are overlain, with spectacular unconformity, by Upper Inferior Oolite of Bajocian age (Arkell, 1933). The Mendip fissures comprise Triassic and Jurassic sediments cross-cutting Upper Palaeozoic strata and, more rarely, the Upper Inferior Oolite.

2. The stratigraphy of the Mendip area

2.a. Palaeozoic stratigraphy

In the core of the Beacon Hill Pericline, to the west of the Downhead Fault, Silurian volcanic rocks of late Llandovery age (Fig. 2) and sedimentary rocks (Wenlock) are exposed in a thin strip. The Silurian is unconformably overlain by Upper Devonian Old Red Sandstone. The most extensive Palaeozoic rocks in the Mendips area are the Carboniferous Limestone Series, which gives the area most of its distinctive scenery
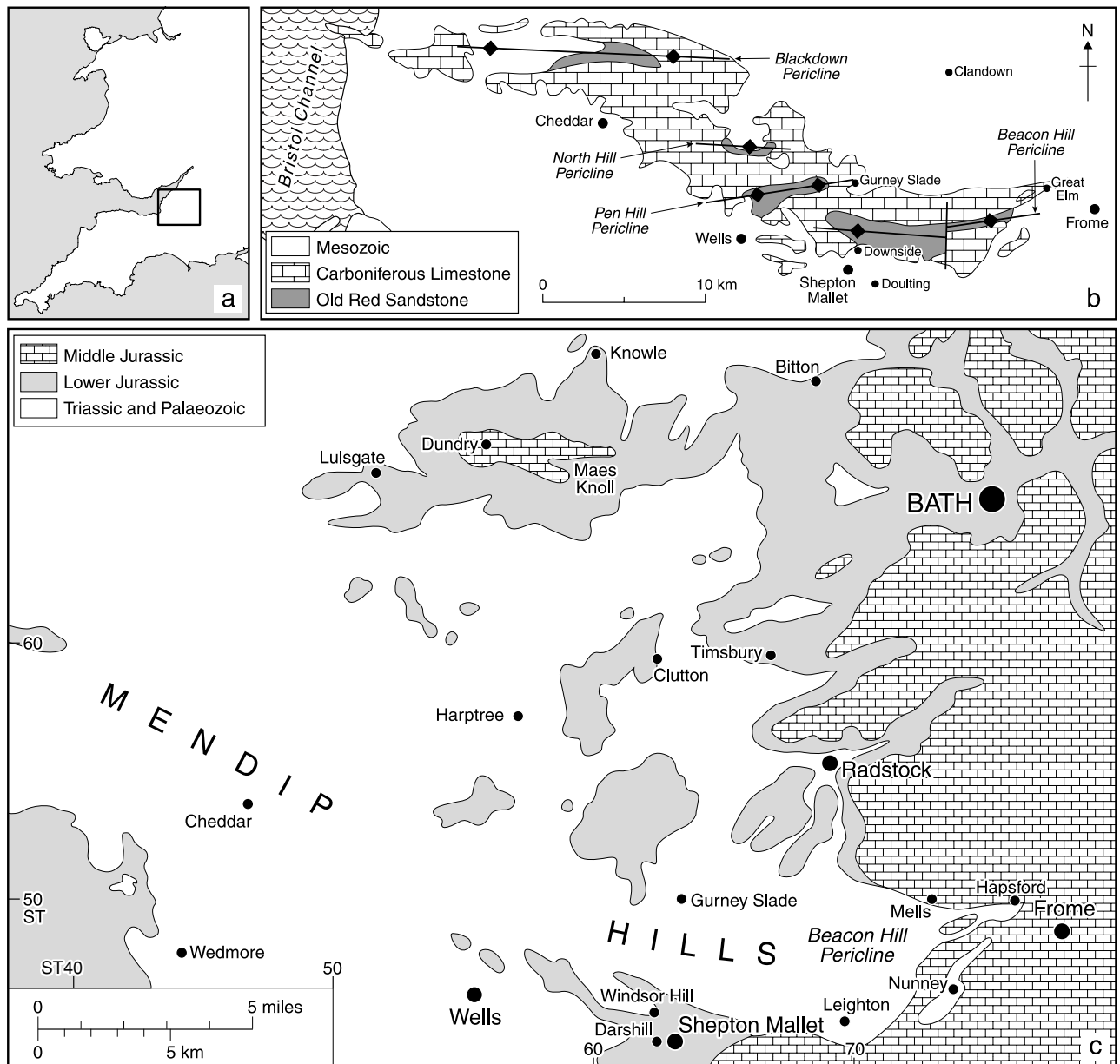
Figure 1. (a) Map showing location of the Mendip area in southern England. (b) Simplified geological map, after Green & Welch (1965), of the four Mendip periclines. (c) Map of the Mendip area showing the position of the Beacon Hill Pericline, the principal Jurassic and older outcrops and key place names mentioned in text. Modified from Donovan & Kellaway (1984).

and is heavily quarried (Fig. 3). The total thickness of the series is approximately 900–1100 m. It is divided into the following four groups from the base up: Lower Limestone Shale Group; Black Rock Group; Clifton Down Group; Hotwells Group. The facies are typical for the Carboniferous Limestone of the Bristol Channel area (Green & Welch, 1965). The southern edge of the Palaeozoic outcrop is marked by the Leighton and Cranmore faults (Fig. 2).

2.b. Mesozoic stratigraphy

The oldest Mesozoic rocks in the eastern Mendips are Triassic conglomerates, up to 90 m thick, which

represent the marginal facies of the red marls of the Mercia Mudstone Group, found to the north and south of the Mendips (Fig. 4). These rocks are known locally as the Dolomitic Conglomerate and are commonly found in palaeo-valleys that dissect the flanks of Palaeozoic folds (Halstead & Nicoll, 1971). These Triassic sediments, interpreted as scree and alluvial-fan deposits, are commonly eroded so as to exhume the Triassic landscape of wadis and gorges on the sides of desert hills, as described for the Triassic of Glamorgan (Tucker, 1977, 1978). The most common facies contain clasts of Carboniferous Limestone and other Palaeozoic rocks, up to a metre in diameter and typically well rounded, set in a matrix of red marl or sandstone.
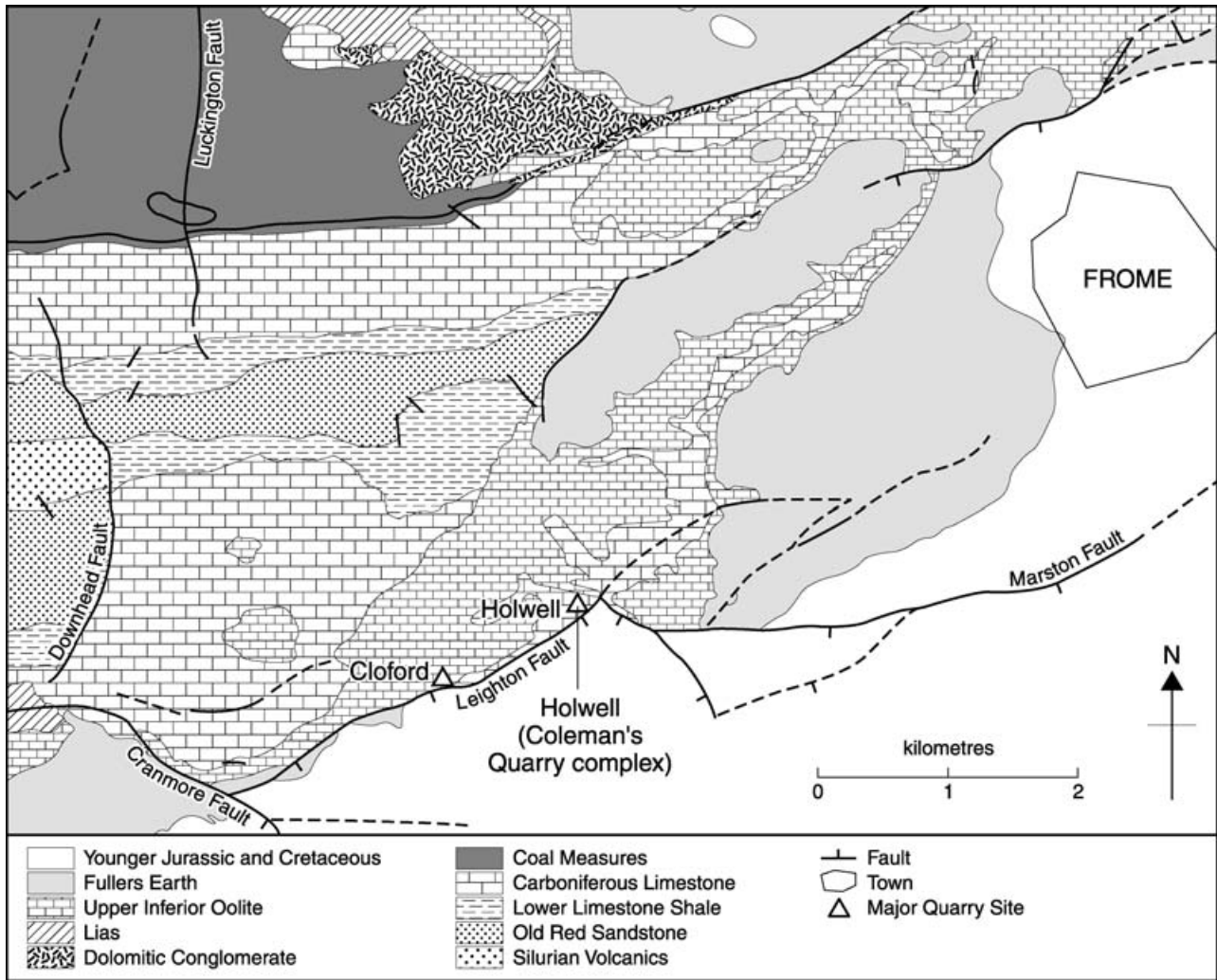
Figure 2. Simplified geological map of the area around the Beacon Hill Pericline. After British Geological Survey (2000).
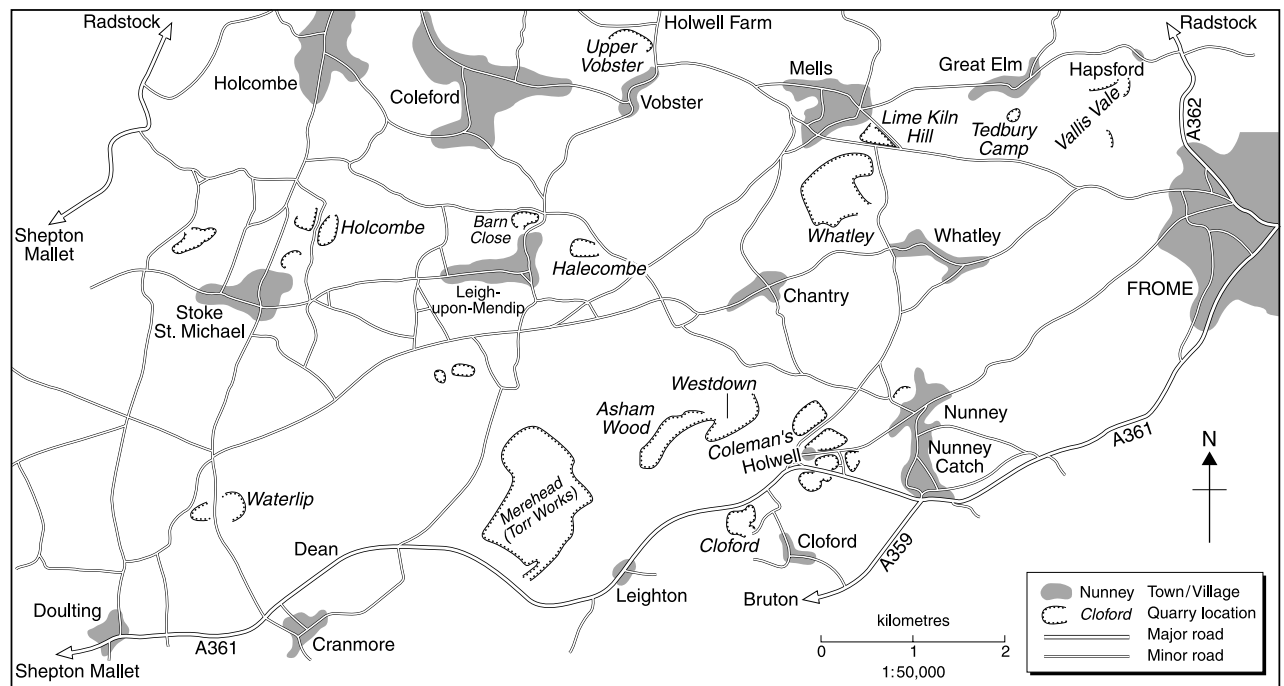

Figure 3. Map of the active and disused quarries in the Carboniferous Limestone of the eastern Mendips and key place names mentioned in the text. Map records the outline of the quarries in the 1990s.

STAGE	AMMONITE ZONES	AMMONITE SUBZONES	WESSEX BASIN (DORSET COAST)	CENTRAL SOMERSET BASIN	RADSTOCK SHELF	MENDIPS SHEPTON MALLETT	MENDIP FISSURE-FILL STRATIGRAPHY
SINEMURIAN — UPPER SINEMURIAN	raricostatum	aplanatum	BLACK VEN MARLS	'LOWER LIAS CLAY' / CHARMOUTH MUDSTONE FORMATION	ARMATUM BED		Fill-type 4
		macdonnelli			? - - - ?		
		raricostatoides			RARICOSTATUM CLAY		Fill-type 3
		densinodulum				PYLLE CLAY	
	oxynotum	oxynotum					
		simpsoni					
	obtusum	denotatus					
		stellare					
		obtusum	BLACK VEN MARLS		OBTUSUM NODULES		
SINEMURIAN — LOWER SINEMURIAN	turneri	birchi	SHALES WITH BEEF		TURNERI CLAY		
		brooki					
	semicostatum	resupinatum			SPIRIFERINA BED		
		scipionianum			BUCKLANDI BED		
		lyra			Derived ammonites found in higher beds		
	bucklandi	bucklandi					
		rotiforme	BLUE LIAS	BLUE LIAS		DOWNSIDE STONE	Fill-type 2.2
		conybeari					
HETTANGIAN	angulata	depressus					
		complanata					
		extranodosa					
	liasicus	laqueus					
		portlocki					
	planorbis	johnstoni			CORN GRITS		
		planorbis					

PERIOD	STAGE	GROUP	FORMATION	MEMBER	MENDIP FISSURE-FILL STRATIGRAPHY
TRIASSIC	RHAETIAN	PENARTH GROUP	LILSTOCK FORMATION	LANGPORT MEMBER	Fill-type 2.1
				COTHAM MEMBER	
			WESTBURY FORMATION		
	NORIAN	MERCIA MUDSTONE GROUP	INCLUDES DOLOMITIC CONGLOMERATE		Fill-type 1
	CARNIAN				
	LADINIAN				

Figure 4. For legend see facing page.

Finer-grained lithologies comprise red-green, sandy marls, typically interpreted as lacustrine (Tucker, 1977, 1978). There are only isolated remnants of the Triassic cover preserved in the eastern Mendips around Mells, Great Elm and in Cree's Quarry (Coleman's Quarry complex), Holwell (Figs 2, 3). The Dolomitic Conglomerate is poorly dated, but probably ranges in age from late Ladinian to Norian.

The Rhaetian Westbury and Lilstock formations of the Penarth Group overstep the Dolomitic Conglomerate onto the Palaeozoic. The dark shales of the Westbury Formation represent the oldest Mesozoic marine sediments and include thin conglomeratic beds at localities close to the Mendips (e.g. Hapsford Bridge: Duffin, 1980). At this locality (Fig. 3) a littoral facies, containing bored and encrusted pebbles and abundant phosphatic vertebrate remains, overlies limestones of the Clifton Down Group. Most recorded occurrences of the Westbury Formation are in depressions in the surface of the Carboniferous Limestone where it has been protected from erosion. A 'bone-bed' is locally recorded at the base of the section (Green & Welch, 1965), but the fossil material is usually distributed throughout the clays and conglomerates. Quartzose sandstones are developed further west around the Isle of Wedmore together with a grey/brown, clastic limestone known as 'Wedmore Stone' (Green & Welch, 1965), and at Harptree (Fig. 1), close to exposed Old Red Sandstone (Arkell, 1933).

The overlying Cotham Member of the Lilstock Formation ('Cotham Beds') consists of pale cream, calcareous mudstones and includes the famous stromatolitic 'Cotham Marble'. Close to the Mendips, these beds contain finely ripple-laminated units and pebble lenses. The Langport Member of the Lilstock Formation comprises up to 2.5 m of light grey micrites, often referred to as the 'White Lias' and contains a relatively diverse fauna, including bivalves. The top of the White Lias is commonly marked by a hard, splintery limestone with a bored, eroded top, known as the 'Sun Bed' (Green & Welch, 1965).

Lower Jurassic rocks are poorly represented in the eastern Mendips but, as is the case with the Rhaetian, Lower Jurassic sediments are found in some areas as isolated outliers on the unconformity with the Carboniferous Limestone (e.g. Moore, 1867; Jenkyns & Senior, 1991) and a stratigraphy for the area can be pieced together from this fragmentary record. The area around the eastern Mendips can be divided into three distinct regions. The region to the south is the northern edge of the Wessex Basin; in general

terms, 'normal' facies and 'normal' thicknesses of the sediments in question were deposited in this area throughout Early Jurassic times. To the north, the Radstock Shelf was an area of moderate sediment accumulation and subsidence that bears a condensed sequence of Lower Jurassic fossiliferous clays and limestones (Tutcher & Trueman, 1925; Kellaway & Welch, 1948; Green, 1992). The Mendips formed an area of positive relief that had a dramatic effect on sediment thickness and facies, and was described as a fault-controlled 'swell' by Sellwood & Jenkyns (1975). The region formed an island archipelago (Arkell, 1933) for much of the Early Jurassic and contains even thinner (locally absent) littoral facies of this age. The area is widely regarded as a westerly extension of the London Platform (Donovan, Horton & Ivimey-Cook, 1979). The Jurassic stratigraphy of this and adjacent areas is summarized in Figures 4 and 5.

The Hettangian and Sinemurian stages (Fig. 4) are mainly represented in the eastern Mendips by the Downside Stone, a littoral facies of the Blue Lias consisting of massive, shelly limestone with conglomeratic portions. Away from the Mendips, to the north and south, the Downside Stone passes laterally into normal Blue Lias facies of interbedded blue/grey clays and limestones. The Downside Stone is best seen in the Shepton Mallet area (Green & Welch, 1965), where it is overlain by the Charmouth Mudstone Formation (Pylle Clay Member of Bristow *et al*. 1999). Most of the Downside Stone is of *planorbis–bucklandi* Zone age (Hettangian–Sinemurian). On the Radstock Shelf, Hettangian rocks are limited to the *planorbis–liasicus* zones and the entire *angulata* and *bucklandi* zones are missing; the facies consist of thin, clay-rich gritty limestones and interbedded shales. The Sinemurian comprises a sequence of condensed limestones and clays with many intervals absent or only represented by reworked ammonites.

The Bucklandi Bed (of late *semicostatum* Zone age) is a massive grey limestone, up to 0.75 m thick, containing many phosphatized, derived ammonites. The Spiriferina Bed is a nodule band with many derived fossils (mainly *Spiriferina walcotti* and ammonites) and forms the base of the Turneri Clay (Tutcher & Trueman, 1925). This unit of grey-blue clays is up to 1.2 m thick on the Radstock Shelf and thickens northwards as it passes into normal Lower Lias Clay facies. During the *obtusum* Zone most of the clays deposited were subsequently eroded to leave the Obtusum Nodules, although clays can be seen in some sections in the north of the area, around Timsbury

Figure 4. Stratigraphical scheme for the Triassic and Hettangian–Sinemurian (Lower Jurassic) of the Mendip area, showing suggested fissure-fill stratigraphy. Data from Cope *et al*. (1980*a*); Green & Welch (1965); Whittaker & Green (1983); Donovan & Kellaway (1984); Copp (*in* Duff, McKirdy & Harley, 1985); Hesselbo & Jenkyns (1995); Page (1995); Cox, Sumbler & Ivimey-Cook (1999); British Geological Survey (2000) and Donovan (pers. comm. 2002).
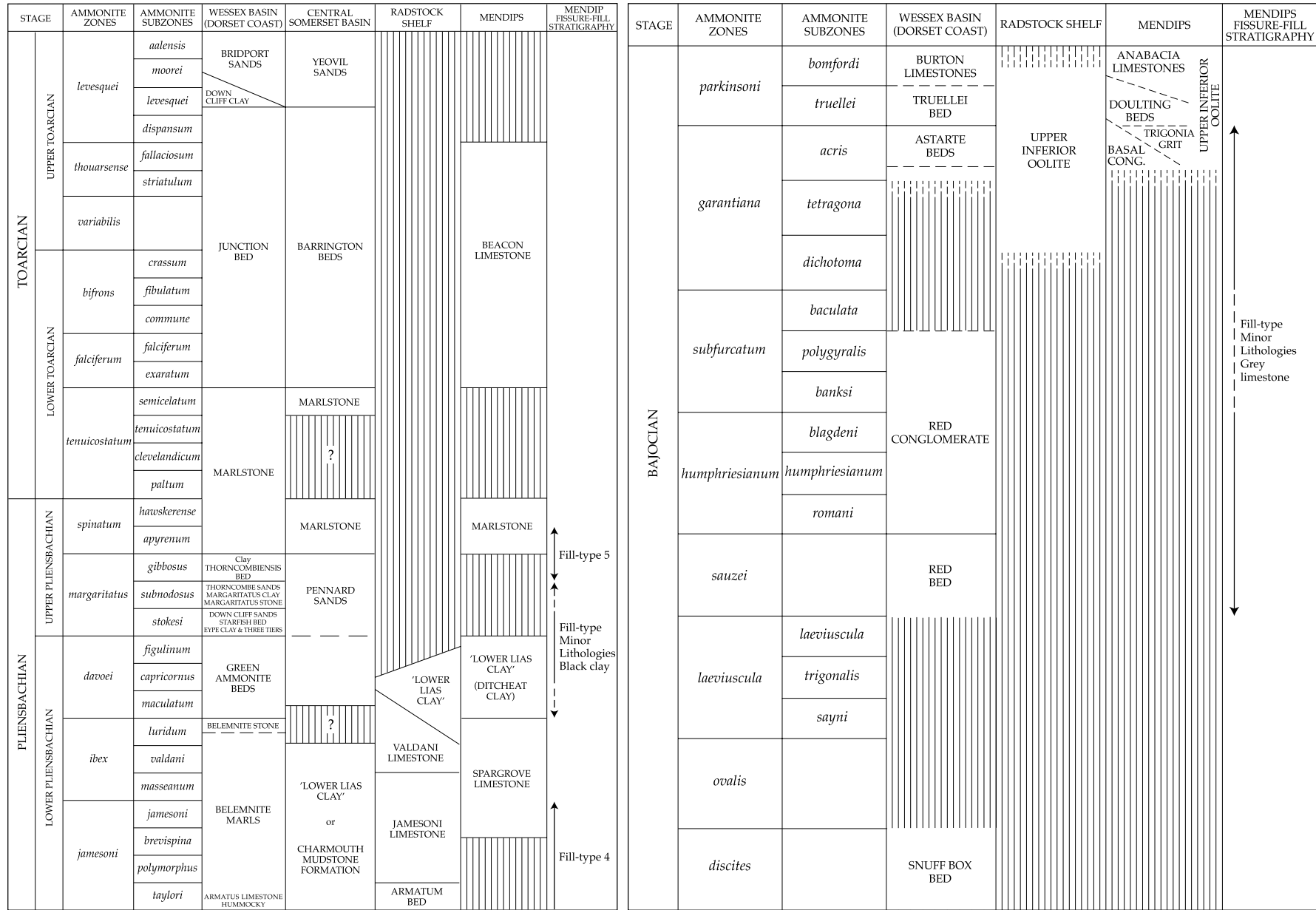
Figure 5. Stratigraphical scheme for the Pliensbachian–Toarcian (Lower Jurassic) and Bajocian (Middle Jurassic) of the Mendip and adjacent areas, showing suggested fissure-fill stratigraphy. Data from Cope *et al.* (1980*a*,*b*); Green & Welch (1965); Whittaker & Green (1983); Donovan & Kellaway (1984); Copp (*in* Duff, McKirdy & Harley, 1985); Jenkyns & Senior (1991); Howarth (1992); Callomon & Cope (1995); Bristow *et al.* (1999); Cox, Sumbler & Ivimey-Cook (1999); British Geological Survey (2000) and Donovan (pers. comm. 2002).

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(Fig. 1; Tutcher & Trueman, 1925). There is then a major gap in the sequence on the Radstock Shelf, which encompasses the *denotatus* Subzone, *oxynotum* Zone and *densinodulum* Subzone. The Raricostatum Clay contains ammonites of the *raricostatoides* and *macdonnelli* subzones and is commonly reduced to a nodule band or derived fossils in the overlying Armatum Bed. The Armatum Bed is a ferruginous limestone known for its well-preserved ammonite fauna. Some of the ammonites are derived and represent the *oxynotum* and *raricostatum* zones.

The Pliensbachian on the Mendips–Radstock Shelf area is represented by limestones (Spargrove Limestone) and equivalents and the overlying 'Lower Lias Clay' (Fig. 5). Both the Armatum Bed (*taylori* Subzone of the *jamesoni* Zone) and the overlying Jamesoni Limestone are fine-grained, creamy biomicrites with ammonites, bivalves, brachiopods and abundant echinoderm debris, typically iron-stained (Donovan & Kellaway, 1984). The Jamesoni Limestone is highly condensed, with four ammonite subzones (*polymorphus–masseanum*) recorded from a 1.2 m section in Clandown Colliery Quarry, near Radstock (Fig. 1; Tutcher & Trueman, 1925). These two units are highly transgressive and overstep progressively older rocks southwards, until they come to rest on Carboniferous Limestone at Vobster (Fig. 3). The Jamesoni Limestone is mapped as pinching out about 750 m further east (Donovan & Kellaway, 1984). Pink crinoidal limestones, resting unconformably on Carboniferous Limestone, dated at a level 'about that of the passage of the Lower into the Middle Lias' were recorded by Moore (1867) from several Mendip localities. Jenkyns & Senior (1991) described these facies from a temporary exposure at Leighton (Fig. 3), where they are intercalated between the Carboniferous Limestone and the Upper Inferior Oolite; brachiopod faunas suggest a Pliensbachian age.

The Valdani Limestone overlies the Jamesoni Limestone in a restricted area to the north of Radstock and is a hard, coarse-grained, limestone with a ferruginous base (Donovan & Kellaway, 1984). The *davoei* Zone is represented by the Striatum and Capricornum clays, which are exposed above the Valdani Limestone at some localities, and reach a maximum thickness of about 36 m, on Timsbury Sleight (Fig. 1). To the northwest, around Clutton (Fig. 1), these clays rest on *liasicus* Zone sediments, and comprise 21 m of blue clays with 'ironstone nodules'. They thin rapidly southwards and are reduced to a thickness of 2.75 m by Upper Vobster (Fig. 3) and overstepped by Upper Inferior Oolite south of Holwell Farm (Figs 2, 3; Donovan & Kellaway, 1984). The Marlstone is a 1–2 m thick, crinoidal limestone containing ferruginous ooliths which crops out just to the north of the Mendips around Dundry and to the south around Mells and Shepton Mallet in the Doulting–Cranmore area (Figs 1, 3; Arkell, 1933; Donovan & Kellaway,

1984; Jenkyns & Senior, 1991). This unit contains a sparse ammonite fauna indicative of the *spinatum* Zone (Richardson, 1906, 1909), although elsewhere in Britain the age has been shown to extend into the basal Toarcian, *tenuicostatum* Zone (Howarth, 1980). Upper Pliensbachian sediments are absent from the Radstock Shelf.

Toarcian sediments (Fig. 5) are only exposed in two areas within the scope of this study. In the Mendip area, the Junction Bed (Cephalopod Bed) or Beacon Limestone is found beneath the Upper Inferior Oolite around Doulting (Fig. 3), just south of a westerly extension of the Cranmore Fault (the Bodden Fault). The *falciferum–striatulum* subzones are represented by 1.5–3 m of sandy (quartzose) and ferruginous fine-grained limestones (Green & Welch, 1965). Copp (*in* Duff, McKirdy & Harley, 1985) reported Junction Bed between Cloford and Merehead quarries (Fig. 3), and Jenkyns & Senior (1991) demonstrated the effect of the Cranmore Fault on the thickness of Toarcian sediments of *tenuicostatum–thouarsense* Zone age in the same area. No Aalenian is recorded from the Mendip area. The Upper Inferior Oolite, of late Bajocian age (Fig. 5), is the only Jurassic unit that passes over the Mendips with little variation in thickness or facies; it rests on Carboniferous Limestone with spectacular unconformity, locally remarkably planar but typically bored by annelids and *Lithophaga* and encrusted by oysters (Cole & Palmer, 1999). Formation of this unconformity and deposition of the overlying uppermost Bajocian limestone was attributed to the effects of the 'Vesulian Transgression' by Arkell (1933).

3. Sediment-filled fissures in the Mendip area

The amateur geologist Charles Moore (1859, 1867) was the first to recognize and study the sedimentary fissures in the Mendips. The best-known of Moore's localities is the area around the hamlet of Holwell, just southwest of Nunney, near Frome (Figs 1, 2): ' . . . its various-coloured limestones give a very picturesque effect; and I have no doubt that the first conclusion drawn would be that everything there was Carboniferous Limestone; but a closer examination would show this to be an error' (Moore, 1867, p. 483). He studied the complex of small quarries in great detail and recorded many 'Liassic Veins' which were left standing proud of the active faces by the quarrymen. Moore's (1867) drawing of the sedimentary dykes cutting the Carboniferous Limestone at Holwell, with his colourful descriptions, is shown in Figure 6.

Moore (1867) said little about the origin of the fissures except to express a doubt that they simply represented caverns in a Jurassic sea-cliff. Most research in the twentieth century concentrated on the fissures as a source for well-preserved vertebrate fossils (Savage, 1993). At Holwell, Kühne (1946) discovered
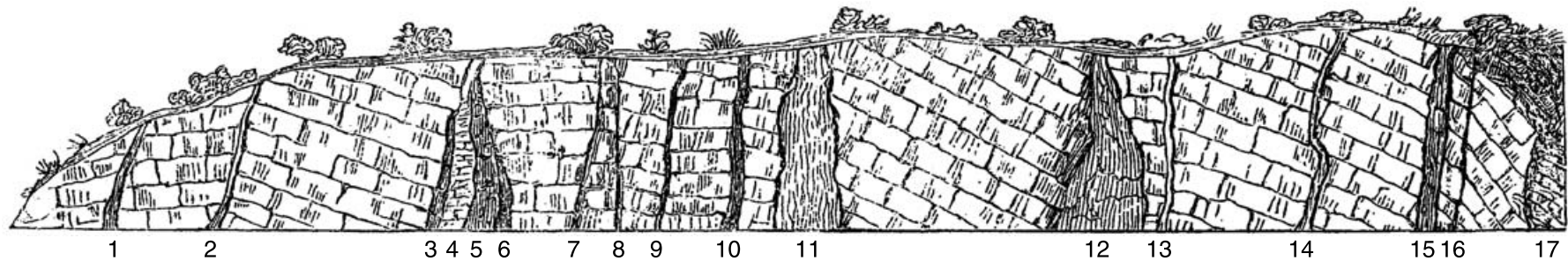
Figure 6. Moore's (1867) drawing of the fissures at Holwell. Width of quarry face is approximately 70 metres. Moore's colourful descriptions of the fissure-fills are as follows: 1, 'Liassic vein, 2 feet'; 2, 'Vein of carbonate of lime &c., 1 foot'; 3, 'Vein of ferruginous stone, Liassic, 10 inches'; 4, 'Liassic stone, 2 feet, 6 inches'; 5, 'Vein of crystalline carbonate of lime, 4 feet, 4 inches'; 6, Liassic vein, variegated or red from oxide of iron, 2 feet, having in the centre a vein of spar showing traces of galena . . . followed by another vertical band of yellower limestone, having on its weathered sides multitudes of *Pentacrinite* stems, the infilling at this point being almost made up of them'; 7, 'Vein of carbonate of lime, 5 inches'; 8, 'Vein of carbonate of lime, 3 inches'; 9, 'Vein of carbonate of lime, 1 foot'; 10, 'Irregular Liassic infilling, with thin veins of ironstone, 3 feet'; 11, 'Liassic infilling, having on the south a thin vein of carbonate of iron, 3 inches, next a band of deep-red and yellow conglomerate, 1 foot, succeeded by crystallized carbonate of lime 2 feet, and Liassic conglomerate, 6 feet: 9 feet 3 inches'; 12, 'Vertical vein of Lias, very various in colour (cream-coloured, yellow, pink, green, or blue) showing by its occasional thinly laminated structure that it was in fact very slowly deposited. This encloses fragments of Carboniferous Limestone. In this vein may be found occasional nests of Rhaetic remains mixed with *Rhynchonella variabilis*, *Terebratula punctata*, and *Delphinula nuda*, Moore, and a crustacean claw of Liassic age. At the base of the quarry it attains a thickness of 13 feet'; 13, 'Vein of spar, occasionally enclosing Liassic stones, mottled or stained with oxide of iron, 6 inches'; 14, 'Irregular bed of clay with Carboniferous Limestone and siliceous pebbles, and fish and other remains of Rhaetic age'; 15, 'Dyke of conglomeratic Lias, passing to the top, with occasional patches of greenish crystalline rock of the same age; 2 feet 6 inches'; 16, 'A nearly vertical vein, the sides of which are composed of red, chocolate, or variegated impure limestone, sometimes with a central fissure stained with oxide of iron, or containing ironstone, at others filled with crystallized carbonate of lime, 9 inches'; 17, ' . . . vertical face of limestone containing *Spirifera Walcottii*, *S. Münsterii*, *Echini*, &c., unquestionably of Liassic age . . . seen to pass down as a vertical dyke . . . which appears to be about 6 feet thick. It is composed of a wavy, thinly laminated, yellow or bluish material, occasionally conglomeratic, and somewhat resembling marble'.

20 mammalian teeth (Microleptids and Triconodonts) in a light-brown sandy clay fissure that contained a mixture of Rhaetian, Hettangian, Sinemurian and Bajocian fossils. He also discovered the remains of *Oligokyphus* in a Lower Lias fissure in Windsor Hill Quarry (Fig. 1). Robinson (1957) reviewed the research and discussed Kühne's other finds in Triassic fissures containing a red/green matrix at a number of localities in the Mendips and in South Wales, where Carboniferous Limestone is similarly overlain unconformably by Triassic and Jurassic sediments. She was the first to attempt a classification of the fissures and propose mechanisms for their formation. To this end, she subdivided the fissures into four groups. The first consisted of 'neptunian dykes' or cracks on the sea floor formed 'as a result of small tensional forces operating on the limestone in the area' and slowly filled with sediment from above. Moore's (1867) fissures were placed in this category. The second, termed 'sagged-cover' dykes, were formed from pre-existing sediments that were 'let down' into fractures as semi-cohesive units to line the walls of the fissure (cf. Jenkins 1925, 1930). The fissure at Gurney Slade (Fig. 1) was described in these terms and the fauna studied indicated a late Hettangian age for the Jurassic part of the fill. Subaerial Triassic fractures filled by debris from the land surface were placed in a third category. The fourth and most important class of 'fissure deposit', in terms of their vertebrate fossil content, were palaeo-caves that contained the remains of an 'upland' sauropsid reptile fauna in Triassic sediment. The concept of a distinct 'upland' fauna in Triassic palaeo-caves was challenged by Marshall & Whiteside (1980) who demonstrated that a cave system bearing an 'upland' faunal assemblage was partially filled by sea water during the Rhaetian and could not therefore represent a cave from a highland area.

In Lulsgate Quarry, near Bristol (Fig. 1), a fissure containing blue clay with septarian nodules and a *turneri* Zone fauna was described by Donovan (1958). Fissures from the central Mendips were examined by Green & Welch (1965), who reported limestones of different facies of probable late Hettangian age, early Pliensbachian age, and greenish-grey marly clays and limestone of *jamesoni–ibex* Zone age. The Holwell fissures were described, somewhat simplistically, by Halstead & Nicoll (1971) as karstic slots formed during the Triassic, and filled during the Liassic transgression over the Mendips. Copestake (1982) proved an early Sinemurian age for siltstone-bearing fissures at Holwell and Cloford (Figs 2, 3) based on their contained microfauna. Copp (*in* Duff, McKirdy & Harley, 1985) described the fissure deposits using Robinson's (1957) classification as a basis for discussion. He defined six categories of fissure: three terrestrial and three marine. In addition to Robinson's (1957) two categories of terrestrial fissure, he added 'karstic features' in which Triassic sediment was trapped in pockets

or grykes on an eroded Carboniferous Limestone landscape interpreted as formed by the collapse of cave systems; the overlying cover was assumed to have sunk into the space whilst retaining its internal structure (cf. Pedley, 1974). Copp's three types of marine fissure were (1) open fissures slowly filled with contemporaneous marine sediment; (2) injection fissures filled with material that was sucked in as the sea floor cracked open, commonly on more than one occasion; (3) subaerially produced karstic features filled with younger marine sediment at a later date.

The relevance of the Mendip fissures to the Mesozoic history of the Wessex Basin was underscored by Jenkyns & Senior (1991), who viewed these features as a component of regional Jurassic extension. Their description of a temporary exposure near Leighton (Figs 1, 3) was the first to show identical Lower Jurassic sediments in both fissures and normal stratigraphical position, beneath the Upper Inferior Oolite to the north of the Leighton Fault. The interpretation of sediment-filled fissures as an integral part of Mesozoic regional extension and basin development forms the basis for this paper.

4. The geological evidence for sedimentary fissures in southwest England and Wales

4.a. The Brixham fissures

Permo-Triassic sandstone-filled fissures in the Devonian limestones on the foreshore at Brixham, in Devon, were first described by Pengelly (1866) and later by Lloyd (1933). A thorough study by Richter (1966) showed that the two generations of fissures are both characterized by two main orientations: one trending approximately N–S and another ENE–WSW. He concluded that the fissures were formed tectonically and that the resultant extension of the host rock was around 1% N–S and 0.3% E–W. The fissures were interpreted as filled by fluvially transported material from above; some fills show well-developed bedding. The fissures are spatially linked to normal faults cutting the Triassic, and both features are roughly parallel. The margins of the fissures are sharp and show no signs of solutional modification and, where the younger fissures cut the older, a karstic origin for the features is impossible.

4.b. Fissures associated with faults in the Wessex Basin

Sediment-filled fissures in Jurassic sediments have been described from many localities in the Wessex Basin, where their occurrence has usually been spatially linked to syn-sedimentary faults. Jenkyns & Senior (1977, 1991) described neptunian sills and dykes of Toarcian, *falciferum–thouarsense* Zone age in the footwall of the Eypemouth Fault on the Dorset Coast

[SY 448 909]. Here the fissure fills are principally developed as cross- and parallel-laminated pale pink- to buff-coloured micrites (Junction Bed) which commonly occur within the underlying green to reddish brown iron-oolitic conglomeratic crinoidal biosparites (Marlstone). The sills cause significant thickening of the Toarcian Junction Bed fissure complex in the immediate vicinity of the fault. Similar 'fissure facies', of similar age, are also recorded from close to the Eypemouth Fault at Bothenhampton [SY 478 916]. Fissures containing cream-coloured, finely laminated micrite of *garantiana* Zone, *acris* Subzone age occur along the line of the same fault inland at Shipton Gorge [SY 501 913]. Identical fissure facies, of Bajocian, *garantiana* Zone age, are found in Toarcian Bridport Sands close to the Bride Fault at Burton Beach [SY 489 887] (Jenkyns & Senior, 1991). Undated fissure facies, similar in type to the Bajocian examples, have also been recorded in a temporary exposure of Toarcian Yeovil Sands next to the Coker Fault [SS 507 135] (Prudden, pers. comm. 1996). The Mere Fault at Cadbury Castle [ST 626 252], just south of the Mendips, is similarly associated with Bajocian fissures in the Toarcian Yeovil Sands (Jenkyns & Senior, 1991).

4.c. Sub-surface fissures in the Wessex Basin–Mendip area

Many boreholes that penetrate Palaeozoic rocks in the Wessex Basin area show evidence for fissures filled with Mesozoic sediment. The IGS Bruton Borehole [ST 690 328] penetrated, at a depth of 95 m within the Carboniferous Limestone, fissures filled with red/brown argillaceous and arenaceous sediments (Holloway & Chadwick, 1984). The fissured Carboniferous Limestone underlies a thin Mercia Mudstone Group section and the fissures presumably contain this type of Triassic sediment. This borehole is thought to lie on a high in the Carboniferous Limestone north of a southward-dipping normal fault (Holloway & Chadwick, 1984) and so lies in a similar palaeogeographical position to the Mendip fissures. The IGS deep borehole at Knap Farm, Cannington [ST 248 401], just northeast of the Quantocks, passes through, at depths greater than 550 m within a sequence of Carboniferous Limestone, fissures filled with red/green silty mudstones of possible Triassic age (Whittaker & Scrivener, 1982). Below a Mercia Mudstone Group sequence, the Clifton Down Group in a borehole at Banwell [ST 398 592] contains several levels of Triassic material contained in 'infillings' and 'wedges' below a depth of 20.2 m (Green & Welch, 1965). A National Rivers Authority borehole at Merehead (Fig. 3) just south of the Cranmore Fault [ST 692 436] reached, at a depth of 63 m, Carboniferous Limestone cut by thin fissures containing mudstone. Fissured Carboniferous Limestone is also reported from beneath a 35 m sequence of Mercia Mudstone Group, Penarth

Group and Downside Stone in a borehole at Darshill (Fig. 1), near Shepton Mallet (Green & Welch, 1965). North of the Mendips at Filton on the outskirts of Bristol [ST 601 795], red marl, associated with calcite and gypsum, is found in fissures in jointed Carboniferous Limestone, immediately below its unconformable contact with the Triassic, at a depth of 51.4 m (Whittard & Smith, 1942). Further to the northwest, at Beachley [ST 554 907] in the Severn Estuary, Lower Limestone Shales with joints filled with Triassic marl constitute the stratigraphically highest material recovered at a depth of 6.6 m (Whittard, 1947).

To summarize, these records from outcrop studies and boreholes suggest that fissuring and intrusion of Mesozoic material into Palaeozoic and Mesozoic lithified sediment of the Wessex Basin–Mendip area was a ubiquitous phenomenon. In fact, in almost all places where Carboniferous Limestone is encountered there is some evidence of fissuring and filling by Triassic–Jurassic sediment. The Carboniferous Limestone and associated sedimentary dykes of the Mendips hence offer a view of the nature of the Hercynian basement of the Wessex Basin and perhaps much of southern England, at least as far north as the Midlands where fissures are also described (Fraser, 1994).

4.d. Geological evidence for sedimentary fissures in south Glamorgan, Wales

The geology of South Glamorgan is rather similar to that of the Mendips, with Carboniferous Limestone unconformably overlain by Triassic (including Rhaetian) and Lower Jurassic sediments. Sediment-filled fissures cutting through the Carboniferous Limestone, locally associated with faults, have been described by many authors (e.g. Kühne, 1949; Thomas, 1952; Robinson, 1957; Wilson *et al*. 1990); most of the fissure-fills are Triassic red sandstones and they have yielded rich faunas of terrestrial vertebrates (e.g. Fraser, 1994). Evans & Kermak (1994) suggest that some vertebrate-bearing fissures are earliest Jurassic in age. These occurrences indicate that Mesozoic extension and fissuring also affected South Wales.

5. Mapping of the Mendip fissure systems

In order to understand the timing and extent of Mesozoic extension in southern Britain, detailed mapping of the fissure systems was carried out using all available exposures in the eastern Mendips. Because exposure is almost exclusively limited to active and disused quarries, Cloford Quarry and the Coleman's Quarry Complex (including Cree's Quarry, North Quarry and Bartlett's Quarry) were studied in most detail. Maps of Cloford Quarry and the Coleman's Quarry Complex, illustrating the location of the fissures, their thickness and their contained fill-types, are given in Figures 7 and 8. The active quarrying taking place in the
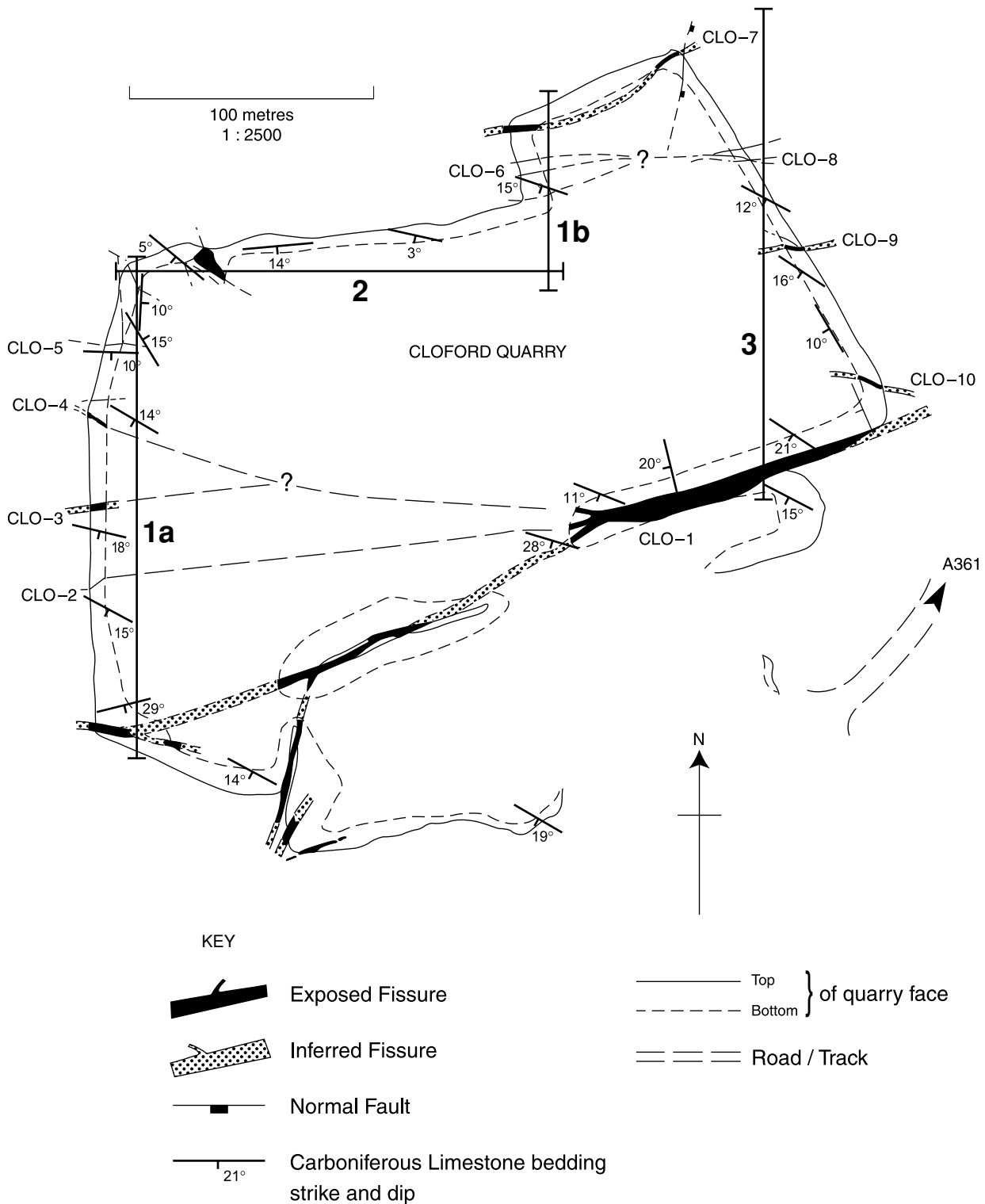
Figure 7. Map of Cloford Quarry, showing distribution of fissures, many of which are disrupted by calcite veins. CLO-1 is a large (average width 4.5 m) multi-generational fissure, one of the largest in the Mendips, which is more or less contiguous with the Leighton Fault; it contains all major Triassic and Jurassic fills but is not associated with an offset of the unconformity between the Carboniferous Limestone and the overlying Inferior Oolite. CLO-2 (~ 30 cm wide) contains Fill-types 1 and 2.2; CLO-3 (~ 1.4 m wide) contains Fill-types 1, 2.2, 3 and 5; CLO-4 (~ 1.5 m wide) contains Fill-types 1, 2.2 and 4; CLO-5 (~ 40 cm wide) contains Fill-types-1, 2.1 and 5; CLO-6, part of an E–W-trending negative flower structure (~ 45 cm wide) contains Fill-types 1, 2.2 and 4; CLO-7 (~ 1.75 m wide) contains Fill-types 1, 2.2, 3 and 4. CLO-8 comprises a large zone of fissures extending over ~ 1.5 m and includes Fill-types 1, 2.2 and 4; CLO-9 (~ 2 m wide) contains Fill-types 1 and 2.2; CLO-10 (~ 75 cm wide) contains Fill-type 2.2. Lines of section used for strain analysis also shown.
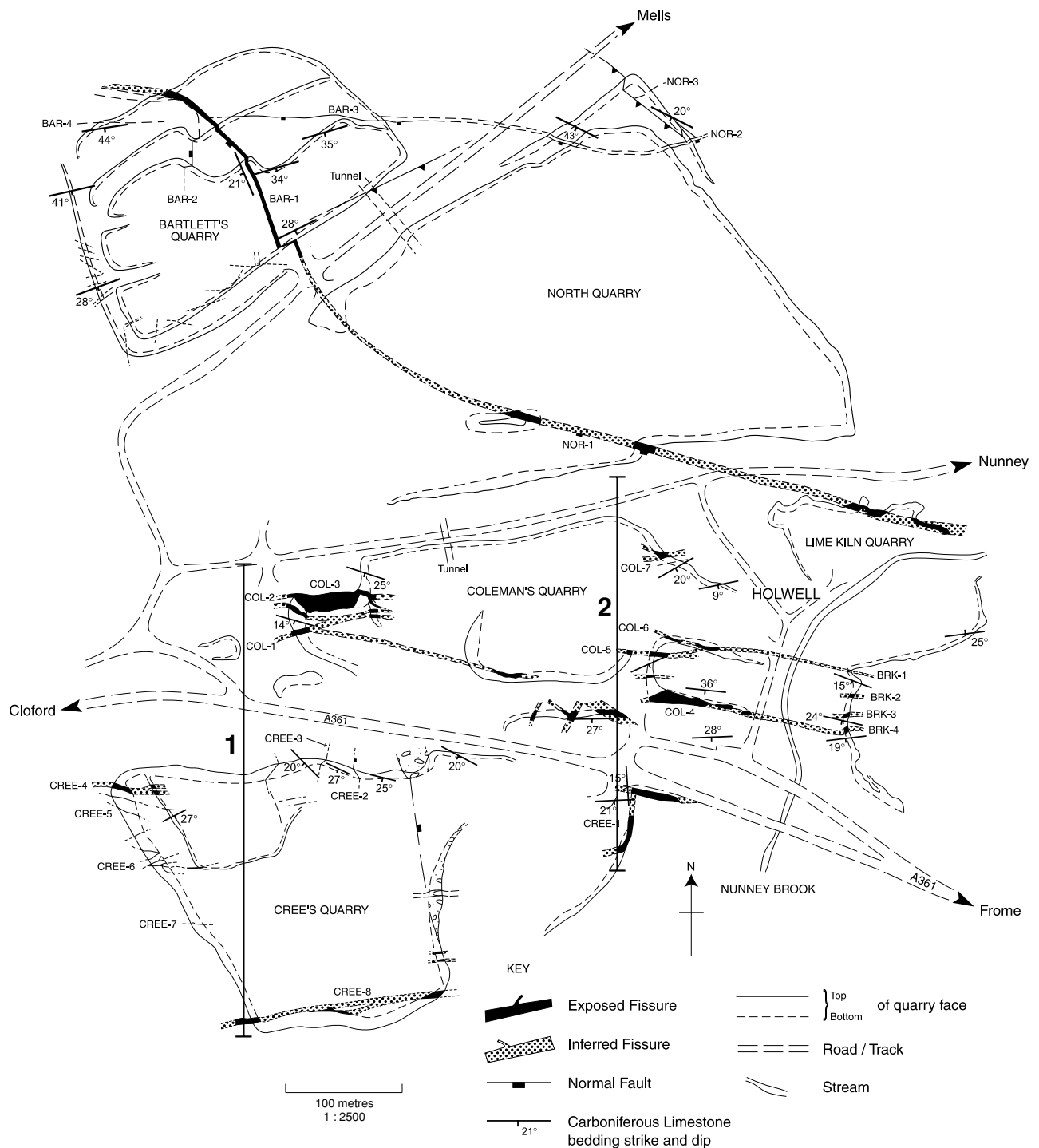
Figure 8. Map of the Coleman's Quarry complex, including Cree's Quarry, North Quarry, Bartlett's Quarry and Lime Kiln Quarry. CREE-1 (~ 80 cm wide) contains Fill-types 2.2 and 4; CREE-2 (~ 1 m wide) contains Fill-types 1, in a fault breccia of Carboniferous Limestone, and 2.1; CREE-3 (~ 2 m wide) contains Fill-types 1 and 2.2; CREE-4 (~ 1.9 m wide) contains Fill-types 1, 2.2 and angular clasts of 4 in 5; CREE-5 (~ 1.3 m wide) contains Fill-types 1, 2.2 and 3. CREE-6 comprises a zone of fissures some 2.5 m wide containing Fill-types 2.2 and 5; CREE-7 (~ 1 m wide), containing Fill-type 5, follows a thin fissure containing Fill-type 1; CREE-8 (~ 2 m wide), contains Fill-types 1, 2.1, 2.2 and 5. COL-1 (> 5 m wide) contains Fill-types 1, 2.2, the black clay described under 'Fill-types: minor lithologies', Fill-type 5 and calcite veins; COL-2 (~ 2 m wide) contains spectacular calcite veins, Fill-types 1 and 2.2 and traces of the dark grey sparry limestone described under 'Fill-types: minor lithologies'; COL-3 (~ 2.8 m wide) is largely constituted by calcite veins, associated with Fill-types 1 and 2.2; COL-4 (1.5–2 m wide) is largely constituted by a coating of Fill-type 1 and Fill-type 2.2; COL-5 (~ 4 m wide) mostly consists of Fill-type 2.2 with clasts of Fill-type 1, Fill-types 1, 2.1, 4 and calcite veins; COL-6 (~ 1.7 m wide) contains traces of Fill-types 1 and 2.2 but is largely constituted by Fill-types 2.1, 4 and 5, the latter associated with calcite veins. NOR-1 (2–3 m wide, locally more), where exposed in Lime Kiln Quarry contains fill-types 1 to 5 arranged in vertical sheets incorporating clasts of older fills: fills 2.2 and 2.2 are the most important and there are traces of the grey limestone

Holwell region causes the shape and dimensions of the quarry and exposure of the fissure systems to change rapidly.

6. Sedimentology and stratigraphy of the fill-types in the Mendip fissures

The complex set of sediments that form the Mendip fissures, commonly in composite multi-generational fills, can be separated into groups based on lithology and age. Biostratigraphy, as well as lithostratigraphical correlation between sedimentary dykes and assumed coeval facies found in the normal sedimentary succession, allows dating of some fills. In addition, correlation is also made possible by the application of strontium-isotope stratigraphy. The presence of belemnites in many Mendip fissure-fills, which otherwise lack biostratigraphically useful fossils, allows application of this technique, using the detailed sea-water strontium-isotope curve for the Jurassic of Jones, Jenkyns & Hesselbo (1994) and Jones *et al.* (1994) as a reference. The $^{87}Sr/^{86}Sr$ ratio of Mendips belemnites with Fe < 150 ppm (that is, assumed to be unaffected by diagenesis; discussion in Jones, Jenkyns & Hesselbo, 1994) were correlated with a spline curve fitted to the strontium-isotope curve using Isoplot 2.11 (Ludwig, 1990). The 'age' from this correlation is given in terms of ammonite subzones from the base of the Jurassic. The zonal scheme is based on Cope *et al.* (1980*a,b*) with modifications by Ivimey-Cook & Donovan (1983), with the rationale behind the stratigraphical scheme used fully described in Jones, Jenkyns & Hesselbo (1994).

Examples of the correlation are given in Figure 9. Several samples (e.g. CREE-1) have a single intercept with a steep portion of the spline curve, allowing an accurate estimate of age. Many samples, however, intersect the curve at two or three points (e.g. part of the fill from CLO-3) and must be further differentiated on the basis of field relationships, lithological correlation and any available biostratigraphy. Error estimates for single-intercept samples, however, are on the order of plus/minus half an ammonite subzone.

7. Lithology and stratigraphy of fissure fills in the Mendips

7.a. Fill-type 1: red siltstones and marls

The most well-known group of fill-types found in Mendip fissures is probably the red siltstones and marls that have yielded so many examples of early mammals and therapsid reptiles (e.g. Robinson, 1957; Tarlo, 1962; Halstead & Nicoll, 1971; Marshall & Whiteside, 1980; Fraser, 1985; Simms, 1994). Simms & Ruffell (1989, 1990) have attributed the formation of these cave systems in the Carboniferous Limestone to a period of high runoff produced by a monsoonal climate during middle and late Carnian times. However, the undoubted occurrence of Triassic caves and associated karstic features has commonly overshadowed the tectonic origin of many Triassic fissures.

The fill-types present in the Triassic caves and tectonic fissures vary from red and green marls of typical Mercia Mudstone Group facies, through red sandstones and siltstones, to conglomerates characteristic of the Dolomitic Conglomerate, typical continental facies

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described under 'Fill-types: minor lithologies'; in North Quarry it similarly contains multiple generations of sediment fill (dominantly Fill-types 1, 4 and the grey limestone described under 'Fill-types: minor lithologies' and calcite veins): this fissure downthrows the unconformity surface between the Carboniferous Limestone and the Inferior Oolite by 2 m to the south. NOR-2 (∼ 2 m wide, similar to NOR-1) also offsets the unconformity. NOR-3 (∼ 1.2 m wide) largely comprises Fill-type 1 with some later calcite veins and traces of the grey limestone described under 'Fill-types: minor lithologies' that again cross the unconformity. BAR-1 (> 3 m wide) is mapped as a continuation of NOR-1 and contains Fill-types 1 (red siltstone with centimetre-scale angular Carboniferous Limestone fragments), 2.1, 2.2 and 4, plus some later calcite veins and traces of the characteristic accompanying grey limestone); its trace forms a noticeable ridge on the unconformity surface. BAR-2 (∼ 1 m wide) is a N–S splay from BAR-1 and contains similar fill-types. BAR-3 contains Fill-types 1, 2.2 and 4 (∼ 1.5 m wide) and is associated with a large (∼ 4 m across) fault-bounded rhombohedral mass of grey limestone and calcite veins (Fill-type: minor lithologies) below a step on the unconformity surface. BAR-4 may be a westerly continuation of BAR-3; it is constituted by 1.2 m of Fill-type 4 incorporating fragments of older Fill-types 1 to 3. The BRK fissures crop out in the Holwell Brook Section and are figured by Moore (1867, p. 484); they probably link with the fissures in the eastern part of Coleman's Quarry, but the intervening ground is not exposed. Fissure BRK-1 trends NW–SE and contains ∼ 50 cm of Fill-type 2.2 along the lines of an existing, thin fissure of Fill-type 1. There are also some very thin (< 5 cm) associated fissures containing Fill-type 3. BRK-2 displays a complex internal structure in that a total width of 4.38 m can be subdivided into 10 cm of Fill-type 1 coating the walls of the Carboniferous Limestone on both sides of the fissure, 45 cm of Fill-type 2.2 (yielding *Calcirhyncia calcaria*), 1.10 m of Fill-type 3, 1.04 m of Fill-type 4, 65 cm of Fill-type 5 and 1.04 m of later (?Bajocian) calcite veins. In this fissure the various fills occur in more than one position, separated by other lithologies. BRK-3 is filled with Fill-types 1 and 2.2, the latter partly in laminated facies and calcite veins, and has a total width of 4 m. BRK-4, some 3 m wide, contains the best example in the whole study area of the horizontally laminated facies of Fill-type 2.2a. Lines of section in Coleman's Quarry used for strain analysis also shown. This map records the outline of the quarry in the 1990s.
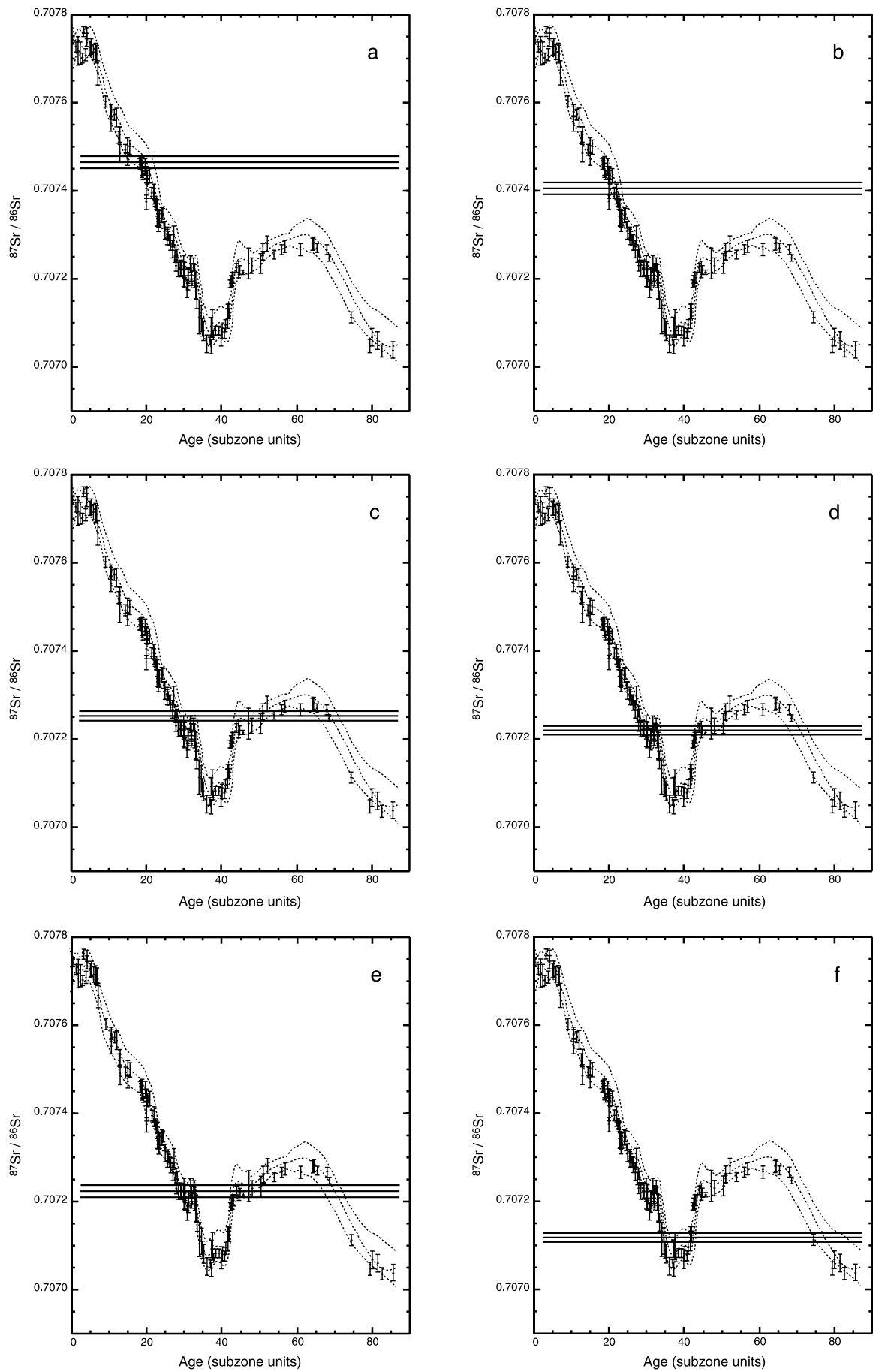
Figure 9. For legend see facing page.

probably including fluviatile and lacustrine sediments (e.g. Tucker & Benton, 1982). In thin-section, the silts and sands can be seen to consist of detrital quartz and a large amount of calcite crystal silt, with scattered grains of quartzite and volcanics. All grains are heavily coated with haematite that gives this fill-type its distinctive red colour (Fig. 10). Direct dating of this fill-type is difficult because of its continental nature and the consequent lack of biostratigraphical data. Marshall & Whiteside (1980) dated (from Tytherington Quarry north of Bristol [ST 660 890]) a fossiliferous Triassic fissure deposit of red and green marls associated with conglomerates as Rhaetian (*Rhaetipollis germanicus* Zone), using its palynomorph assemblage. This age correlates with the Westbury Formation or possibly the lower Cotham Member of the Lilstock Formation, which implies that Rhaetian sediments are diachronous, including both marine and continental facies. The vertebrate fauna of the Mendip fissures was attributed to the 'late Upper Triassic' by Robinson (1957), although her exact age assignments have been challenged (Fraser, 1994). No faunal elements were found in this fill-type during this study. The Mercia Mudstone Group in the Mendip area ranges in age from Ladinian to Norian with little or no subdivision. Taken overall, the interval Ladinian–Rhaetian gives the best estimate for the range in age of Fill-type 1 in tectonic fissures and caves.

7.b. Fill-type 2: varicoloured clastic limestones and breccias

The appearance of these fill-types varies a great deal, depending on their oxidation/weathering state, but they are all dominantly bioclastic in nature and contain a variable admixture of quartz and other terrigenous grains. Two end-members can be distinguished.

Type 2.1: Grey, clastic limestones constitute this facies and typically contain exquisitely preserved vertebrate remains, in which the internal structure of tooth and scale fragments can be seen. In some fissures, cross-cutting relationships show that these grey clastic limestones are older than the orange/brown components of the more common Fill-type 2.2. The large amount of well-preserved phosphatic material in the grey, clastic limestones is generally suggestive of a Rhaetian to early Hettangian age for Fill-type 2.1. Such facies could correspond to the Rhaetian Wedmore Stone of Green & Welch (1965), a shelly biosparite containing quartz fragments, found in the normal stratigraphical succession.

Type 2.2: In most exposures these sediments are orange-brown, although they are pale grey/green on freshly exposed surfaces. The predominant fill-type is a clastic-textured, orange/brown biomicrite containing abundant comminuted brachiopod material. Ostracods and foraminifera (*Nodosaria*, *Triloculina*) are also present in most samples, and echinoid spines, small thin-shelled bivalves, bryozoans, pentacrinid debris and rare ooids also occur. This fill-type contains a high proportion of siliclastic material that can make up 20 % of the rock (Fig. 10). Well-rounded quartz and lithic pebbles can be seen in most localities and, in thin-section, clasts include medium quartz sand, fresh feldspars, 'hackle-texture' polycrystalline quartz, vein-quartz fragments, highly weathered volcanic rocks, angular micrite chips and orange sparite clasts. A finer-grained fill is developed in those fissures, commonly

Figure 9. Examples of strontium-isotope values determined on belemnites from fissure-fills plotted against the reference curve of Jones, Jenkyns & Hesselbo (1994) and Jones *et al.* (1994). Sample preparation, normalization procedures (all samples normalized to a value of the Eimer & Amend standard of $^{87}Sr/^{86}Sr = 0.708000$, equivalent to a value of 0.710226 for the NIST SRM-987) and the subzonal scheme on the *x*-axis are as given in Jones, Jenkyns & Hesselbo (1994) and Jones *et al.* (1994). The $^{87}Sr/^{86}Sr$ ratio of each belemnite with Fe < 150 ppm (that is, containing negligible diagenetic ferroan calcite) has been correlated with a spline curve fitted to the reference curve using Isoplot 2.11 (Ludwig, 1990). (a) Strontium-isotope correlation of a belemnite from Fill-type 3 (grey biomicrite) in CLO-3, Cloford Quarry (Fig. 7); the single intercept ($^{87}Sr/^{86}Sr = 0.707456 \pm 0.000013$) is at a subzone age of 19.71, suggesting a Sinemurian age, *raricostatum* Zone, probably *raricostatoides* Subzone. (b) Strontium-isotope correlation of a belemnite from Fill-type 4 (pink crinoidal limestone) in CLO-1, Cloford Quarry (Fig. 7); the single intercept ($^{87}Sr/^{86}Sr = 0.707404 \pm 0.000013$) is at a subzone age of 22.08, suggesting a Pliensbachian age, *jamesoni* Zone, probably *taylori* Subzone. (c) Strontium-isotope correlation of a belemnite from Fill-type 'Minor Lithologies: dark grey sparry limestone' from NOR-1, North Quarry (Fig. 8), a fissure that displaces the sub-Inferior Oolite unconformity and contains Bajocian brachiopods; the multiple intercepts ($^{87}Sr/^{86}Sr = 0.707258 \pm 0.000011$) occur at subzone ages 27.9 (Pliensbachian, *ibex* Zone, probably *valdani* Subzone), 49.1 (Toarcian, *thouarsense* Zone, probably *fallaciosum* Subzone) and 67.8 (Bajocian, *sauzei* Zone). (d) Strontium-isotope correlation of a belemnite from Fill-type 'Minor Lithologies: dark grey sparry limestone' from NOR-3, North Quarry (Fig. 8), a fissure that also displaces the sub-Inferior Oolite unconformity; the multiple intercepts ($^{87}Sr/^{86}Sr = 0.707226 \pm 0.000010$) occur at subzone ages 31.7 (Pliensbachian, *davoei* Zone, probably *figulinum* Subzone), 42.5 (Toarcian, *falciferum* Zone, probably *falciferum* Subzone) and 69.9 (Bajocian, *humphriesianum* Zone, probably *humphriesianum* Subzone). (e) Strontium-isotope correlation of a belemnite from Fill-type 'Minor Lithologies: sticky black clay' from COL-1, Coleman's Quarry (Fig. 8); the multiple intercepts ($^{87}Sr/^{86}Sr = 0.707230 \pm 0.000013$) occur at subzone ages 29.95 (Pliensbachian, *davoei* Zone, probably *maculatum* Subzone), 31.59 (*davoei* Zone, probably *figulinum* Subzone), 32.34 (Pliensbachian, *margaritatus* Zone, probably *stokesi* Subzone), 42.78 (Toarcian, *falciferum* Zone, probably *falciferum* Subzone) and 69.727 (Bajocian, *humphriesianum* Zone, probably *humphriesianum* Subzone). *Davoei* Zone and *falciferum* Zone ages are deemed most likely. (f) Strontium-isotope correlation of a belemnite from Fill-type 5 (pale blue/green marly micrites) from CLO-3, Cloford Quarry (Fig. 7); the multiple intercepts ($^{87}Sr/^{86}Sr = 0.707123 \pm 0.000010$) occur at subzone ages 34.07 (Pliensbachian, *margaritatus* Zone, probably *gibbosus* Subzone), 41.36 (Toarcian, *falciferum* Zone, *exaratum* Subzone) and 76.05 (Bajocian *garantiana* Zone, *tetragona* Subzone). A *margaritatus* Zone age is deemed most likely.
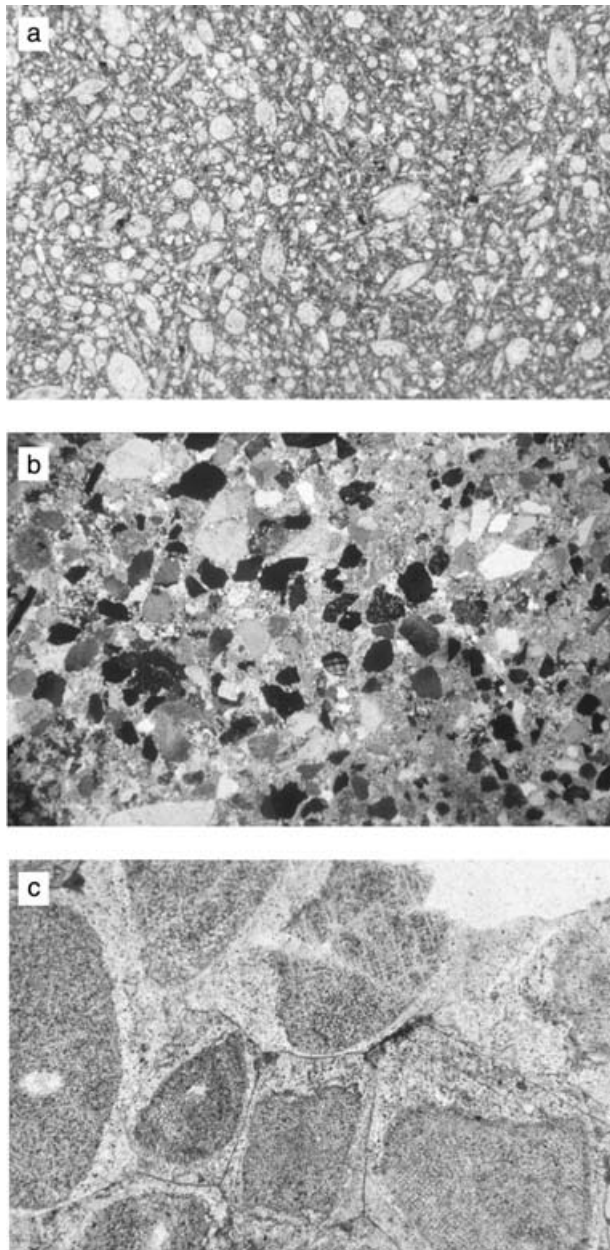
Figure 10. Microfacies of common fill-types. (a) Fill-type 1, comprising detrital quartz in a matrix of calcite silt and haematite-rich clay, from CLO-8, Cloford Quarry (Fig. 7). Plane-polarized light. Width of photomicrograph = 3 mm. (b) Fill-type 2.2, comprising quartz, microcline and plagioclase, volcanic fragments and phosphatic skeletal fragments set in a matrix of biomicrite containing comminuted brachiopod remains, foraminifera and ostracods, from NOR-1 in Lime Kiln Quarry (Fig. 8). Crossed nicols. Width of photomicrograph = 6 mm. (c) Fill-type 4 (pink crinoidal calcarenite), comprising crinoid ossicles with haematite-stained rims surrounded by syntaxial calcite cements, from fissure CLO-7 in Cloford Quarry (Fig. 7). Crossed nicols. Width of photomicrograph = 3 mm.

narrow, with restricted access to the unconformity and in small pockets or tension gashes within previous fills; the typical contained sediment is a horizontally laminated, pale buff/yellow micrite which is pale green when fresh. Fissure BRK-4 in the Holwell Brook section (Fig. 8) shows an excellent example of this lithology with micro-faulted and folded laminae. The microfacies typically contains abundant cortoids and medium quartz sand together with phosphatic grains, echinoid spines and rare ooids. Locally, Fill-type 2.2 contains centimetre-scale angular clasts of earlier fills and/or Carboniferous limestone.

These facies have been described by previous authors from several localities in the Mendips, both from fissures and from normal stratigraphical position. Moore (1867) and Robinson (1957) suggested a late Hettangian, *angulata* Zone age for a fissure containing a grey 'comminuted shell limestone' at Gurney Slade (Fig. 1) based on its brachiopod (*Calcirhyncia calcaria*), bivalve and gastropod fauna. Copestake (1982) recorded an early Sinemurian (*bucklandi–semicostatum* Zone) fauna of foraminifera and ostracods from a 'brown siltstone' in a fissure at Cloford Quarry and a 'grey siltstone' from Cree's Quarry, Holwell. These localities correspond to mapped fissures CLO-4 in Cloford and CREE-8 in Cree's Quarry (Figs 7, 8). Copp (*in* Duff, McKirdy & Harley, 1985) listed *Oxytoma inequivalvis* and *Calcirhyncia calcaria* from a fissure (CREE-1) containing orange limestone breccia in Cree's Quarry, again suggesting an earliest Sinemurian, possibly *bucklandi* Zone age. A freshly fallen section of the large fissure in the small 'Lime Kiln Quarry' at Holwell exposed pale green, sandy limestones that weather orange/brown and yielded *Calcirhyncia calcaria*. The fissure BRK-2, in the Holwell Brook Section (Fig. 8), contains a laminated facies of grey/green clastic limestone from which *Calcirhyncia calcaria* was obtained. These limited biostratigraphical data all indicate an age in the late Hettangian–early Sinemurian interval for this series of orange/brown–grey/green bioclastic limestones and breccias. Ager (1962), in his monograph on British Liassic rhynchonellid brachiopods, comments specifically that '*Calcirhyncia calcaria* is most abundant in the *angulata* and *bucklandi* zones, where it is virtually the only rhynchonellid present. Locally it persists into the *semicostatum* Zone.'

During the Hettangian–Sinemurian, the Downside Stone (a bioclastic limestone, locally containing quartzose conglomeratic material) was deposited in the Shepton Mallet and Wells areas to the west (Fig. 1) and this would appear to be the source material for these fills. Many previous authors (e.g. Moore, 1867; Green & Welch, 1965) have described 'Downside Stone' in Mendip fissures that are no longer visible.

7.c. Fill-type 3: grey fine-grained limestones (biomicrites)

This fill-type is often extremely difficult to recognize in the field because its appearance is strikingly similar to that of the Carboniferous Limestone. It

contains abundant punctate brachiopods, echinoid debris, crinoid ossicles and ostracods, with scattered belemnites and gastropods. Foraminifera, typically with a dark brown infill, are common and include *Nodosaria*, *Quinquiloculina* and *Triloculina*. These limestones contain a considerable amount of clastic material such as fragments of Fill-type 2.2, including orange sparite, and crinoidal biosparite. Angular Carboniferous Limestone fragments derived from the fissure walls are common in some localities. Medium sand-grade quartz grains with monocrystalline and 'hackle-texture' polycrystalline textures can be found in all fills and form 1–10% of the rock. In some areas, this fill-type is conglomeratic, containing well-rounded quartz pebbles. A fine-grained, laminated sub-facies can be found in some fissures; these presumably had restricted access to the area of sediment supply and were filled slowly as sediment trickled through the system of submarine cracks. Fill-type 3 is commonly found in association with the crinoidal limestones of Fill-type 4 and in some fissures contacts are gradational between the two, suggesting some degree of mixing of semi-lithified sediment during emplacement of the fills. The matrix of micrite is commonly altered to fine neomorphic spar, particularly where it is in contact with Fill-type 4.

Correlation of the ^{87}Sr/^{86}Sr ratio of a belemnite from Fill-type 3 in fissure CLO-3 in Cloford Quarry with the ^{87}Sr/^{86}Sr ratio curve of Jones, Jenkyns & Hesselbo (1994) and Jones *et al*. (1994) indicates a likely *raricostatum* Zone, *raricostatoides* Subzone age for this fill-type (Fig. 9). At this time on the Radstock Shelf, the Raricostatum Clay, typically a few centimetres to tens of centimetres thick, was deposited, and this thins rapidly towards the Mendips. If the fissure-fill material correlates with the Raricostatum Clay, then more obviously carbonate-rich facies were transiently developed over the Mendips. Tutcher & Trueman (1925) postulated a time of uplift along the 'Mendip Axis' immediately prior to the deposition of the Raricostatum Clay, so the underlying material may have been eroded post-depositionally. On the Dorset coast, this time interval corresponds to the top of the Black Ven Marls and the Hummocky limestone (Fig. 4), the latter associated with a stratigraphical gap (e.g. Hesselbo & Jenkyns, 1995).

7.d. Fill-type 4: crinoidal calcarenites (biosparites)

The most distinctive fill-types found in the fissure system are crinoidal biosparites that vary in colour from red to pink, through white to grey. These rocks consist of moderately sorted crinoid ossicles of coarse sand grade, scattered foraminifera with dark micrite infills and rare phosphatic material, all set in a syntaxial sparry cement. Other clasts include rare monocrystalline fine-sand-grade quartz, quartz pebbles, glauconitic siltstone

chips and grey sparry limestone clasts enclosing fragments of orange/brown limestone. Fragments of previous fissure fills and/or Carboniferous Limestone are quite common, especially close to contacts with the wall-rock. The pink colour is the product of haematite staining of the crinoid ossicles prior to growth of the syntaxial cement. Some ossicles have a thin micrite rim and the pores within the ossicles are locally filled with dark micrite. The ossicles in the white crinoidal limestones are free from haematite staining and possess a syntaxial isopachous bladed cement surrounded by a later drusy spar (Fig. 10). The grey muddy crinoidal limestones are transitional with Fill-type 3 and have a matrix of grey micrite around ossicles and an isopachous, bladed cement. Macrofossils are rare, but scattered brachiopods (*Cirpa* sp.) and belemnites are found in some fissures.

These limestones have been described previously, both in fissures and in normal stratigraphical position. Moore (1867) suggested an age around the Sinemurian–Pliensbachian boundary. Jenkyns & Senior (1991), on the basis of the brachiopod fauna, suggested a Pliensbachian, possibly *spinatum* Zone age. Copp (*in* Duff, McKirdy & Harley, 1985) suggested a *raricostatum–jamesoni* Zone age based on the brachiopod and ammonite fauna from fissures in Holwell and Cloford quarries. Correlation of the ^{87}Sr/^{86}Sr ratio of belemnites from two crinoidal limestones with the ^{87}Sr/^{86}Sr curve of Jones, Jenkyns & Hesselbo (1994) gives a best-fit age of *jamesoni* Zone, *taylori* Subzone for the pink crinoidal limestones (Fig. 9) and *jamesoni* Zone, *taylori–polymorphus* Subzone for the white crinoidal limestones. All the evidence indicates that deposition of Fill-type 4 took place in the late *raricostatum* and *jamesoni* zones (latest Sinemurian–earliest Pliensbachian).

This age assignment corresponds to the time of deposition of the Raricostatum Clay, Armatum Bed and Jamesoni Limestone to the north of the Mendips on the Radstock Shelf (Green & Welch, 1965). The Armatum Bed contains a significant amount of crinoid material and varies from 'a shelly or crinoidal limestone' to 'a sandy crinoidal marl' (Tutcher & Trueman, 1925). The Jamesoni Limestone also contains a high proportion of crinoidal material that is commonly iron-stained. In the Wessex Basin, the upper *raricostatum* and lower *jamesoni* zones are represented by the Belemnite Marls which locally contain crinoidal remains (Hesselbo & Jenkyns, 1995).

7.e. Fill-type 5: pale blue/green marly limestones (micrites)

This fill-type is a biomicrite, very similar in appearance to Fill-type 3, but distinguishable in the field by its lack of carbonate or other other clasts and its pale blue/green, clay-rich aspect. It is generally massive, although a laminated facies is found in some fissures.

Cross-cutting relationships show that this fill-type is younger than Fill-type 4, that is, most probably syn- or post-*jamesoni* Zone in age. ^{87}Sr/^{86}Sr ratios of contained belemnites give three possible chemostratigraphical ages: (1) *margaritatus* Zone, *gibbosus* Subzone (Pliensbachian); (2) *falciferum* Zone, *exaratum* Subzone (Toarcian); (3) *garantiana* Zone, *tetragona* Subzone (Bajocian).

The Bajocian age is unlikely, due to the fact that the sub-Upper Inferior Oolite unconformity transects this fill in all fissures and reliably dated Bajocian fills are of markedly different facies and typically associated with calcite veining. The *falciferum* Zone age corresponds to the stratigraphically condensed iron-impregnated fine-grained biomicrites of the Cephalopod Bed or Junction Bed found in adjacent areas (Wilson *et al*. 1958; Green & Welch, 1965; Hallam, 1967; Donovan & Kellaway, 1984; Jenkyns & Senior, 1991). Indeed, the microfacies of this fissure fill resemble the Junction Bed and fissures of this age are known from the Dorset coast (Jenkyns & Senior, 1977, 1991). However, if the blue-green colour is any way diagnostic, it is notable that reworked, iron-coated pebbles of greenish limestone have been recorded in (?)*tenuicostatum* Zone sediments on Dundry Hill (Fig. 1; Donovan & Kellaway, 1984). Green and greenish-blue, thinly laminated limestones, containing a (?)*spinatum* Zone fauna, were also recorded from a Holwell fissure by Moore (1867), who described blue marls and Marlstone, which contained *Ammonites* (*Pleuroceras*) *spinatum*, directly overlying the Coal Measures in a coal shaft at Holwell Farm, near Mells (Fig. 1; [ST 712 501]). Copp (*in* Duff, McKirdy & Harley, 1985) reported pale, marly limestones of ?*spinatum* Zone age in fissures near Merehead and Dean (Fig. 3). This age corresponds to that of the Marlstone Rock Bed in the Mendip area (Fig. 5).

Although inconclusive, the balance of evidence points to a late Pliensbachian, *margaritatus–spinatum* Zone age for Fill-type 5, that is, just younger than the black clays described in the following section.

7.f. Fill-types: minor lithologies

In addition to the five main groups of fill-types, two other facies occur much less commonly. Fissure COL-1 in Coleman's Quarry (Fig. 8) includes a sticky, black to grey clay, containing laminated mud chips and centimetre-scale framboidal pyrite nodules that weather to a reddish brown colour. The clay contains a large number of contorted calcite veins. Minor occurrences of similar black clays, in 13 fissures, are spread throughout the study area. This fill-type has yielded abundant belemnites, allowing application of ^{87}Sr/^{86}Sr ratio stratigraphy. The ^{87}Sr/^{86}Sr ratio of the belemnites from this fill-type is such that multiple intercepts occur when correlated with the curve of

Jones, Jenkyns & Hesselbo (1994) and Jones *et al*. (1994) (Fig. 9). The possible ages, based on the belemnites analysed are: (1) *davoei–margaritatus* zones, *maculatum–subnodosus* subzones (Pliensbachian); (2) *falciferum* Zone, *exaratum–falciferum* subzones (Toarcian); (3) *humphriesianum–subfurcatum* zones, *humphriesianum–polygyralis* subzones (Bajocian).

As discussed below, fissures containing Bajocian fills generally cross-cut the unconformity, whereas these clay fills are invariably transected by the unconformity. As discussed for Fill-type 5, the facies of Bajocian and Toarcian sediments in normal stratigraphical position in the surrounding area and in neptunian sills and dykes in the Wessex Basin (Jenkyns & Senior, 1991) are very different from this fill-type. Organic-rich black shales of *falciferum* Zone age are known, however, from the relatively expanded succession in the Winterborne Kingston Trough in the Wessex Basin (Jenkyns & Clayton, 1997), were also revealed in a temporary exposure at Chapel Cross, east of Sparkford, Somerset [ST 6313 2628] (Prudden, pers. comm. 2002) about 1 km north of the Mere Fault and are known from the English Midlands and areas to the north (Howarth *in* Cope *et al*. 1980*a*; Jenkyns *et al*. 2002). However, such organic-rich facies are generally absent where typical Junction Bed is developed, as it is locally in the Mendips and on the Dorset coast.

The *davoei* Zone is characterized by clay deposits around the Mendips (Fig. 5), with sediments of this age overlying the Spargrove Limestone in the Shepton Mallet area. On the Radstock Shelf, the Striatum and Capricornum Clays, of the same age, also contain 'ironstone nodules', and pyrite is particularly common in rocks of the *ibex–davoei* zones (Donovan & Kellaway, 1984). Thus, it seems most likely that the grey/black clays found in the Mendip fissures are of *davoei–margaritatus* Zone age (mid-Pliensbachian), although a *falciferum* Zone age cannot be ruled out.

Five fissures in the Holwell area contain a dark grey, sparry limestone with some crinoid debris, belemnites and brachiopods. Fissure NOR-1 has yielded abundant specimens of *Acanthothyris spinosa*, which suggest a Bajocian, *garantiana* Zone (possibly *acris* Subzone) age, as postulated by Jenkyns & Senior (1991). This age corresponds to the base of the Upper Inferior Oolite and is consistent with the fact that fissures containing this fill-type are unique in that they offset the sub-Upper Inferior Oolite unconformity. In other localities, this fill-type is found along the central part of blocky, white calcite veins that locally pass up into the Upper Inferior Oolite. Fissures of this age are found adjacent to faults in other parts of the Wessex Basin (Jenkyns & Senior, 1991). The ^{87}Sr/^{86}Sr ratio from belemnites from this fill-type in North Quarry, Holwell (Fig. 8) are consistent with a Bajocian age because one of three multiple intercepts correlates with a *sauzei–humphriesianum* Zone age (Fig. 9).

7.g. Calcite veins

Calcite veins, which are associated with many fissures, were mapped in two main groups. The first is filled with blocky, white calcite and dog-tooth spar and is associated with Bajocian sediments at many localities. Veins of this type cut all pre-Bajocian sediment fills and are the only structures that consistently cross the sub-Upper Inferior Oolite unconformity (Alabaster, 1976). The blocky white calcite veins show the same two strong trends (E–W, NNW–SSE) as the sediment-filled fissures, with a large degree of spread between them. The dog-tooth spar veins, which were not completely filled with calcite and may reflect larger opening increments, are predominantly of E–W orientation. The second group of veins is filled with pink calcite and is associated with the Mendip lead/zinc mineralization (e.g. Haggerty *et al.* 1996). These veins strike predominantly N–S, with some following an E–W trend, in a similar pattern to that followed by the barytes veins in the area.

Isotopic data ($\delta^{18}O = \sim -8\,\permil$; $\delta^{13}C = \sim -6\,\permil$) from the calcites associated with Fill-type 1 are consistent with the interpretation that they represent subaerial speleothem deposits; younger fills are associated with calcites whose isotopic ratios suggest precipitation from seawater. Some multiple calcite veins show a clear difference in isotopic and trace-element signatures, reflecting a change from meteoric (Triassic) through hydrothermal to marine (Rhaetian–Bajocian) cements in successive generations of precipitate (Wogelius *et al.* 1997).

8. Opening mechanisms for the Mendip fissures

Although Mesozoic karstic cavities, with a clear solutional geometry, do occur in the Mendip area, the evidence from the eastern Mendips demonstrates a tectonic origin for the vast majority of fissures, as suggested by Robinson (1957), Copp (*in* Duff, McKirdy & Harley, 1985) and Jenkyns & Senior (1991). The contacts of the sedimentary dykes with the Carboniferous Limestone show no signs of solution or weathering prior to filling; there is no evidence of siliceous fossils, crinoids or corals etched out in positive relief. On the contrary, the clean fracture surface of the margins is a striking feature of most fissures and can be readily observed in thin-section; parallel walls can be matched up exactly across the fill. The parallelism of the margins is maintained even when the fissure itself has a sinuous profile. Where fissures can be seen in the Triassic Dolomitic Conglomerate (e.g. Cree's Quarry), they cut straight through boulders and matrix alike. Some fissures are offset along Carboniferous Limestone bedding planes and locally split into smaller brethren, with the same total width. This transfer of motion across a bedding plane can lead to bedding-parallel steps on the walls of larger fissures where the amount of dilation is greater than the size of the transfer. Minor fissures and small branches of larger fissures have angular, tapering geometries or even form tension-gash sets, as seen in Cloford Quarry. Some fissure-fills contain angular fragments of wall-rock that can be matched to the adjacent margin. For such fragments to be suspended in sediment requires that they were spalled from the margins as the fissure was formed and filled.

All fissure localities are associated with kinematic indicators, of one sort or another, on the following: fissure walls, the margins of previous fills, Carboniferous Limestone bedding surfaces and minor faults. Calcite-fibre lineations are very widespread, along with oblique stylolites and asperity wear-grooves. In fissures with more than one generation of sedimentary fill, the different units are generally arranged as vertical, tabular bodies within the fissure (e.g. CLO-9, Fig. 7). Later fills may cut across earlier ones, may follow the area of contact between previous fills or may follow the fissure margin. This geometry is inconsistent with sedimentation into a pre-existing karstic cavity. Recent cave development along the lines of the fissures shows an irregular shape with little relationship to the previous fills (CLO-3, Fig. 7). Some fissures show evidence for deformation of early fills during the emplacement of younger sediments in the fissure. In addition, angular fragments of wall-rock and previous fills are a common component of the intruded material.

9. Filling mechanisms of Mendip fissures

9.a. Rapid injection of unlithified sediment

The majority of Mendip fissures are interpreted as having been filled by rapid injection of soft sediment. Most fills are massive, and any fabric that is developed, such as the alignment of clasts, is parallel to the fissure walls. The presence of large, angular clasts of wall-rock suspended in the fill also points to a rapid influx of unlithified sediment. Copp's (*in* Duff, McKirdy & Harley, 1985) view that most fissures young symmetrically inwards towards a central 'suture', suggesting the telescoping of a pre-existing horizontal stratigraphy down into the fissures, as modelled by Jenkins (1925), is not confirmed by this study. Although some early fills are split by a later generation of material, many fissure-fills follow the margins of earlier intrusions and may even change relative position along the length of the fissure.

If fissure formation were a catastrophic process, linked to seismic activity on the major normal faults, then the formation of a transient void in the Carboniferous Limestone beneath a cover of unlithified sediment would produce a sudden drop in pressure in the fissure. This effect would suck sediment very rapidly down from the seafloor into the fissure system.

The sudden drop in pressure would also produce angular fragments of wall-rock, as pore-fluid pressures would still be at their pre-fracturing level and hydraulic fracturing would burst the country rock apart (Phillips, 1972). It is also possible that tectonic fissures were open to the sea floor for a short time before being rapidly filled by a migrating isolated sand wave. Such crinoidal sand bodies were commonly developed in the Jurassic, particularly above unconformities (Jenkyns, 1971) and are relevant to the formation of Fill-type 4. There is no evidence for colonization of the walls of the fissures by serpulids or bivalves prior to filling, despite the abundance of *Trypanites* and *Lithophaga* on the Inferior Oolite (Bajocian) unconformity itself (Cole & Palmer, 1999).

Unlike many discussions on sediment-filled fissure systems, there is no problem concerning the direction of sediment transport into the fissures. Overall, the transport must have been downwards from the unconformity, although some lateral transport of sediment is required to fill those portions of the fissures along strike that did not connect straight up to the unconformity. The rapid filling of a sharp-sided fissure indicates that the age of the intruded sediment dates the formation of the fissure system, as suggested by Hugh Miller in his *Sketch-book of Popular Geology* well over 100 years ago when describing Jurassic sediment-filled fissures in the Moray Firth area. He stated that the country rock ' . . . already existing in its present consolidated state, opened into yawning rents and fissures . . . as the earth opened . . . during the great earthquake, — and that the loose sand and calcareous matter which formed the sea bottom at the time, borne downwards by the rushing water, suddenly filled up these rents, ere the yielding matrix had time to lose any of its steepness of side or sharpness of edge, which it could not have failed to have done had the process been a slow one' (Miller, 1859, p. 308).

Sediment injection associated with submarine faulting has long been considered the dominant process generating Jurassic neptunian dykes in the Alpine-Mediterranean region (Wiedenmayer, 1963; Castellarin, 1965, 1970; Wendt, 1965, 1971; Bernoulli & Jenkyns, 1974; Lehner, 1991; Winterer, Metzler & Sarti, 1991; Winterer & Sarti, 1994; Martire *et al*. 2000; Luczynski, 2001; Mallarino, 2002). As in the Mendips, one of the most common fills in the Tethyan region is white to grey to pink crinoidal limestone (Jenkyns, 1971).

9.b. Sedimentation *in situ*

Many narrow fissures and some larger fissures show evidence for relatively slow sedimentation in the cavity, as noted by Moore (1867). Such evidence includes laminated sediments that prograde from one end of a void to the other to produce a convex-up cavity fill. Horizontally laminated micrite also locally fills narrow fractures in previous fills and in the Carboniferous

Limestone. This type of sediment has been described from sediment-filled fissures in the Jurassic of Italy, Spain and Poland (e.g. Wendt, 1971; Winterer, Metzler & Sarti, 1991; Winterer & Sarti, 1994; Luczynski, 2001) and indicates significant lateral water currents in the fissure system as well as influx of material from above. Erosive bases to some laminae also indicate relatively vigorous current activity. The margins of such fissures are still sharp and show no signs of solution or colonization, which again suggests that the age of the fill corresponds closely with the age of the fissure.

10. Structural setting of the fissures

Although most fissures are seen in isolation, some localities illustrate the links between fissures and other structures in the Carboniferous Limestone. At several Mendip localities, fissures can be seen as part of transtensional, negative flower structures. At Cloford (Fig. 7), a flower structure, showing oblique lineations on its margins, contains a 45 cm wide fissure (CLO-6) with several generations of sedimentary fill. A common feature of fissure exposures is the apparent importance of the orientation of bedding in the Carboniferous Limestone to fissure geometry. Bedding planes provide a slip surface in the Carboniferous Limestone, as well as a pathway for sediment to fill otherwise isolated fissures; this can lead to the formation of isolated, rhomboidal, sediment-filled fissures whose internal geometry may reveal successive stages of incremental opening. Where the Carboniferous Limestone is more steeply inclined, some small fissures maintain this relationship with bedding, as seen in Barn Close Quarry (Fig. 3) on the north limb of the Beacon Hill Pericline. Spectacular calcite veins in Halecombe Quarry (Fig. 3) show that this transfer of slip can occur across tens of metres of section, as well as across single beds of Carboniferous Limestone. Where the transfer of bedding-plane slip is large compared to the amount of slip, the geometry is best described as the transfer of fissure extension along bedding planes. Fissure CLO-2 in Cloford Quarry (Fig. 7) demonstrates the geometry produced when the fissure extension is transferred by an amount comparable to the extension. If the amount of extension is greater than the length of the transfer along a bedding plane, then the transfer is preserved as a bedding step on the wall of the fissure. Stepping of fissures along bedding planes was also noted by Moore (1867, p. 488).

Some fissures can be related directly to normal faults in the Carboniferous Limestone, either as sediment fills along the fault plane (e.g. CREE-2; BAR-1; Figs 7, 8), secondary (Riedel) fractures off the fault-plane or tension fractures in the extended hanging wall. The Griffith fracture criterion predicts that, as normal faults approach the surface, their dip will increase

to become vertical at the earth's surface (Anderson, 1951). At shallow crustal levels, extension can be taken up by tension fractures that sole out onto a normal fault-plane at depth. Fissure formation as the surface expression of normal faulting can be seen in Bartlett's Quarry (BAR-3; Fig. 8). In North Quarry, a vertical displacement of several metres across a vertical fissure (NOR-2; Fig. 8) probably represents the vertical component of the displacement of a normal fault that at deeper levels dips at less than 90°, as discussed in Walsh & Watterson (1988). In the north-west corner of Cloford Quarry (Fig. 7), Mesozoic sediments are found along a normal fault plane as well as in fissures in the disrupted hanging wall. Less commonly, fissures descend from fault planes into the footwall.

11. Fissure geometry

For the purpose of analysis, the fissures are treated as planar structures, a valid approximation in the vast majority of cases. A total of 481 fissures was measured in the Mendip area, including calcite veins. The majority of fissures are steeply dipping (80–90°). A few faults and bedding planes, with shallower dips, mainly towards the southwest, contain Triassic–Jurassic sediment, but no fissures have dips shallower than 26°. Unlike the Wessex Basin fissures, neptunian sills are conspicuously absent.

In terms of fissure orientation, two trends are dominant in the data (Fig. 11): E–W and NNW–SSE. This diagram shows that the NNW–SSE trend is as important as the E–W trend, at least in terms of number of fissures. The dominance of the E–W set is, however, evident in the plots in which stereograms for particular fills within the fissures are illustrated. The NNW–SSE fissures are dominantly single-generation phenomena with only one dilation episode, whereas the E–W fissures contain multiple fills due to reactivation of the individual fractures. The average number of extension episodes per fissure comes to 1.96, that is, on average, each fissure in the Mendip area opened twice during its history, with some opening only once and others opening several times.

The variation in the orientation of the active fissures through time can be illustrated by plotting the orientation of fissures containing different ages of fill. Almost half the fissures recorded in the Mendip area (222) contained some Triassic sediment, although this was commonly no more than a thin trace on the walls of later fissures, indicating the reactivation of narrow Triassic fractures. Two trends are dominant: E–W and NNW–SSE (Fig. 11). Thin haematite veins (seven examples measured), which represent fractures permeated by iron-rich water from the Triassic land-surface, cluster about a WNW–ESE trend. The 54 examples of fissures containing grey, clastic limestones

of probable Rhaetian age (Fill-type 2.1) show a strong preferred orientation in the NNW–SSE trend (Fig. 11). Fissures (145 examples measured) containing the orange limestones and breccias of Fill-type 2.2 (Hettangian–Sinemurian boundary age) show the same trends as those containing Fill-type 1, but the E–W trend is much more pronounced (Fig. 11). These data indicate that a swing in the orientation of active fissuring took place at the end of the Triassic, with the E–W trend becoming dominant.

Fissures containing laminated buff 'fissure-facies' micrites (the fine-grained variant of Fill-type 2.2) locally cut the orange limestones and breccias of the more typical Fill-type 2.2 and are of comparable age or slightly younger. Not surprisingly, the 72 examples measured form a similar pattern to the orange/brown components of Fill-type 2.2, with a dominant E–W trend and associated NNW–SSE trend. Fissures containing Fill-type 3 (33 examples measured) show a spread in orientation from E–W through NW–SE. Because this fill-type is not readily identified in the field due to its superficial resemblance to Carboniferous Limestone or the less clastic portions of Fill-types 2, it is possible that these results reflect an incomplete or biased data set.

There are no such problems, however, with the distinctive crinoidal limestones of Fill-type 4. The 56 fissures found containing this fill-type show a strong E–W trend with a subsidiary N–S orientation (Fig. 11). Green/grey limestones and clays of probable *margaritatus* Zone age (Fill-type 5) are found in 52 fissures that are principally oriented ENE–WNW, with a significant number of NNW–SSE trend. *Davoei* Zone grey–black clays (Fill-type: minor lithologies) are found in 13 fissures with a predominantly E–W orientation, with four examples of NNW–SSE trend. A few fissures contain dark grey limestones of Bajocian age; the six examples measured vary in orientation with the E–W examples being dominant in terms of width.

The relative importance of the various trends through time can be illustrated by plotting the total thickness of fissures containing a particular fill-type against dip-direction. Figure 12 shows the frequency curves for five fill-types plotted against dip-direction. All five frequency curves show similar maxima on the E–W and NNW–SSE trends which were evident from the stereograms (Fig. 11), but the thickness curves in Figure 13 are quite different. The curve for Fill-type 1 (red siltstones and marls) contains two maxima centred on 190° and 260° and is very similar to the frequency curve. This implies that Triassic fissures of all orientations were open to a similar degree. The clastic limestone fissures of Fill-type 2.1 are concentrated in a broad band between N–S through NW–SE to E–W, with the E–W fissures dominant in terms of thickness. The thickness curve for the orange limestones and breccias of Fill-type 2.2 shows that
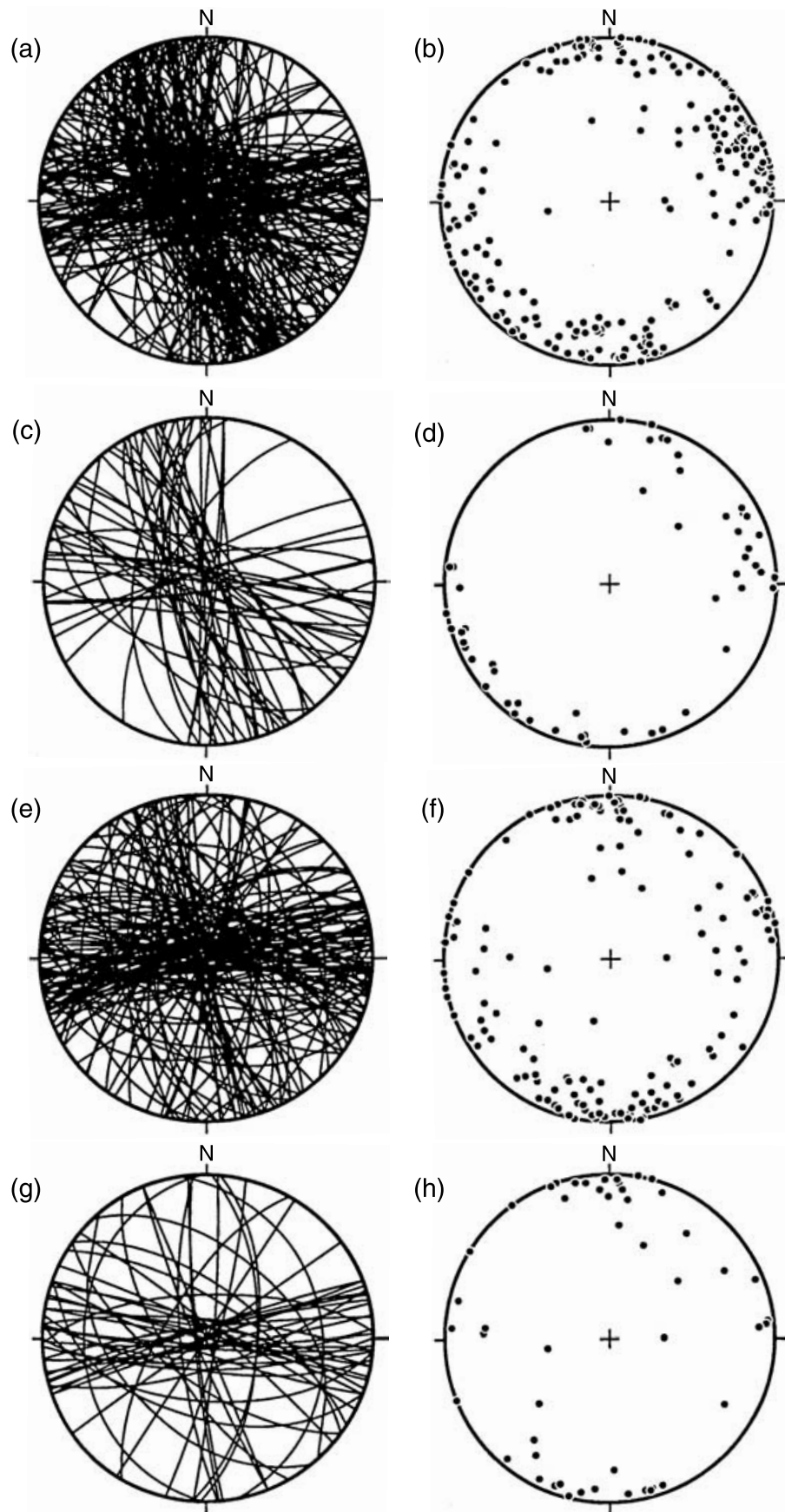
Figure 11. For legend see facing page.

extension was taken up by fissures in two narrow ranges of dip-direction and the dilation is concentrated in the E–W-trending fissures, dipping towards 180° or 0/360°. The dominance of these fissures is not apparent in the frequency curve, which is similar to that for Fill-type 1. This concentration of extension on the E–W-trending fissures is continued in the Fill-type 4 (crinoidal limestones) thickness curve, with broader zones of high total thickness centred on 180° and 0/360°. The concentration of extension on the E–W fissures is also demonstrated by Fill-type 5 (pale blue-green marly micrites), with very little dilation of the NNW–SSE fissures.

12. Theoretical considerations of fissure formation

The Griffith fracture criterion predicts that vertical tension fractures at the surface will pass vertically into oblique tensional fractures and finally into inclined shear planes, that is, normal faults, at some critical depth. This depth depends on the tensile strength of the host rock, the differential stress, the pore-fluid pressure and host-rock density. Previous field studies (e.g. Forslund & Gudmundsson, 1992) have suggested that this depth is of the order of a few hundred metres. Exposures in the Mendip area show vertical fissuring at depths of over 80 m below the unconformity and very few exposures show the base of fissures, with most descending below the floor of the quarry. The IGS deep borehole at Knap Farm, Cannington [ST 2479 4011], just northeast of the Quantocks, passes through a sequence of Carboniferous Limestone which contains fissures filled with Triassic red/green marls and silty mudstones at depths greater than 550 m (Whittaker & Scrivener, 1982). In order to test the hypothesis that these and the Mendip examples could be tension fractures, the theoretical considerations are discussed below. The Griffith fracture criterion relates the shear stress on the failure plane, τ_f^2, and the normal stress on the failure plane, σ_n, to the uniaxial tensile strength of the material, T:

$$\tau_f^2 - 4T\sigma_n - 4T^2 = 0 \tag{1}$$

Anderson (1951) showed that two of the principal stresses are contained in the Earth's surface, with the other perpendicular to it, as a result of the fact that the shear stress on the surface is zero. During extension it follows that the maximum principal stress is vertical, close to the Earth's surface. The value of the maximum principal stress, σ_1, is simply related to the depth, D, the bulk density of the country rock, ρ_L, and gravitational acceleration, g, as shown below:

$$D = \frac{\sigma_1}{\rho_L g} \tag{2}$$

The greatest depth for the formation of vertical tension fractures in dry rocks is found from the value of the maximum principal stress of the largest circle that will intersect the failure envelope on the abscissa at a tensile minimum principal stress of $-T$, whilst remaining within the stability field at all other points. It can be shown that this situation requires a differential stress of $4T$, or less, for the formation of vertical tension fractures (Secor, 1965), which gives a maximum depth, D_{max}, for vertical tension fractures in dry rock as:

$$D_{max} = \frac{3T}{\rho_L g} \tag{3}$$

The bulk density of Carboniferous Limestone is approximately 2700 kgm^{-3} (Holloway & Chadwick, 1984) and the tensile strength of crystalline limestones is approximately 7 MPa (Jaeger & Cook, 1976), which gives a maximum depth for vertical tensile fractures of ≈ 780 m. In saturated rocks, the concept of effective stress is used to include the effects of pore-fluid pressure, P_f, on the fracture mechanics. The effective normal stress on a surface, σ_n^*, is given by:

$$\sigma_n^* = \sigma_n - P_f \tag{4}$$

If fluid is free to move through the body of rock, then P_f at a given depth will equal the hydrostatic pressure produced by the overlying column of fluid of density ρ_f:

$$P_f = \rho_f g D \tag{5}$$

In some cases, involving permeability seals, P_f can rise above hydrostatic pressure and even approach lithostatic pressure, P_L. The situation in which vertical tension fractures can form in saturated rocks is the same as that in dry rocks, but for the use of effective normal

Figure 11. Structural data from Mendip fissures. (a) Lower-hemisphere, equal-area stereogram of fissures containing Fill-type 1 (Ladinian–Rhaetian). (b) Lower-hemisphere, equal-area stereogram of poles to fissures containing Fill-type 1. Note the dominant E–W and NNW–SSE fissure trends. (c) Lower-hemisphere, equal-area stereogram of fissures containing Fill-type 2.1 (Rhaetian–early Hettangian). (d) Lower-hemisphere, equal-area stereogram of poles to fissures containing Fill-type 2.1. Note the dominant NNW–SSE fissure trend. (e) Lower-hemisphere, equal-area stereogram of fissures containing Fill-type 2.2 (late Hettangian–early Sinemurian). (f) Lower-hemisphere, equal-area stereogram of poles to fissures containing Fill-type 2.2. Note the dominant E–W trend, suggesting that a change took place in the orientation of fissuring between the Late Triassic and Early Jurassic. (g) Lower-hemisphere, equal-area stereogram of fissures containing Fill-type 4 (late Sinemurian–early Pliensbachian). (h) Lower-hemisphere, equal-area stereogram of poles to fissures containing Fill-type 4. Note the strong E–W and subsidiary N–S trends.
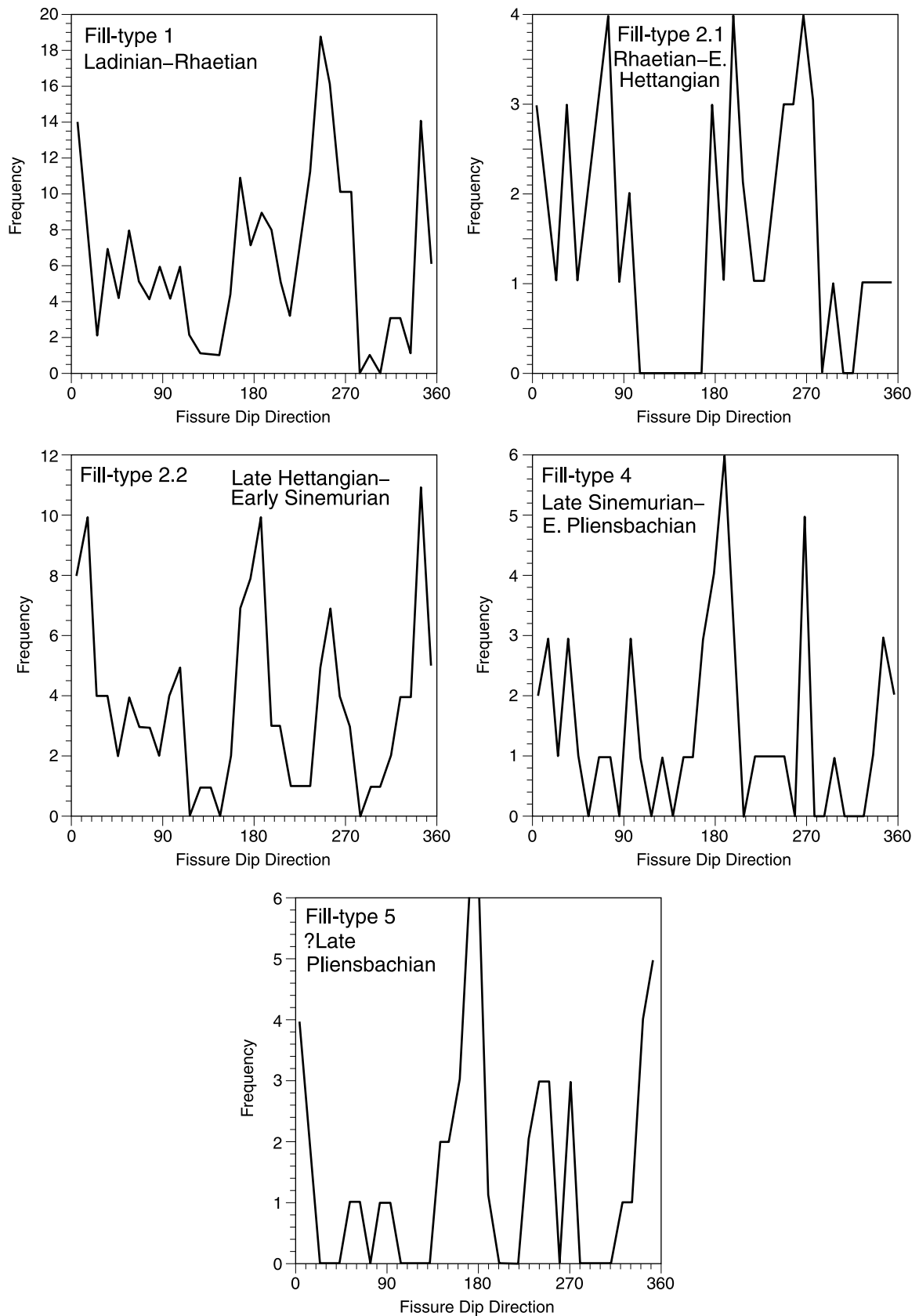
Figure 12. Plots of fissure dip direction (°) versus frequency for various fill-types. All five frequency curves show maxima on the E–W and NNW–SSE trends.
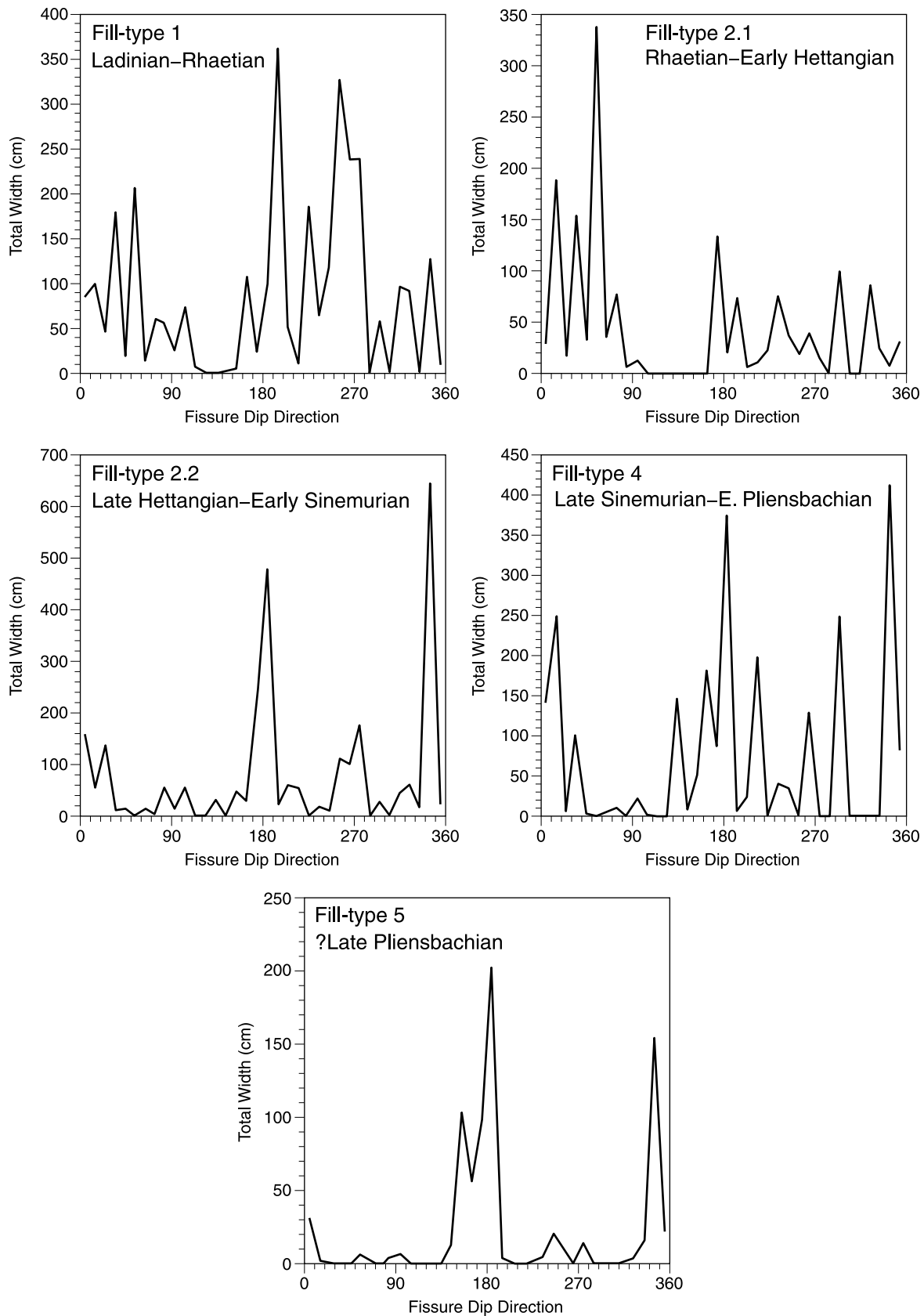
Figure 13.   Plots of fissure dip direction (°) versus total fill width for various fill types. Note the difference between this figure and Figure 12. Note also the progressive concentration of extension from the Late Triassic (Fill-type 2.1) into the Early Jurassic (Fill-type 2.2) onto the E–W-trending fissures that record N–S extension.

stress, that is, if $(\sigma_3 - \rho_f) = (-T)$ and the differential stress is less than $4T$. An important effect of pore-fluid pressure is to increase the maximum depth of formation of vertical tension fractures. Adapting equation (3) to account for fluid pressure gives:

$$D_{max} = \frac{3T}{(\rho_L - \rho_f)g} \qquad (6)$$

In Carboniferous Limestone with water-filled pore space this gives a maximum depth for the formation of vertical tension fractures of 1.2 km. If, however, the fissures were rapidly filled with unlithified sediment as they formed, the column of fluidized sediment in the fissure might have increased pore-fluid pressures at the base of the fissure in an analogous way to the effect of drilling mud in wells. The bulk densities of unlithified sediments are typically in the range 1.5–2.3×10^3 kgm^{-3}, which predicts a maximum depth of vertical tension fracture formation, with the aid of a sediment column load, of 1.78–5.35 kilometres. Over longer time scales, the water in the sediment could migrate to the surface allowing P_f to fall back to hydrostatic pressure. The fractures thus produced, at depths greater than predicted by equation (6) for water alone, would be held open by the infilling sediment and so become preserved in the geological record. At differential stresses between $4T$ and $8T/\sqrt{2}$, oblique tensile fractures can form with dips between 90° and 67.5°, with increasing components of shear across the fractures at lower dips. This range of differential stresses corresponds to depth ranges of 0.78–1.28 km in dry Carboniferous Limestone and 1.24–2.03 km with water-filled pore space.

The special case when the differential stress equals $8T/\sqrt{2}$ corresponds to the formation of shear fractures with zero effective normal stress, at the transition with compressive shear failure. Thus, at depths greater than 1.28 km in dry Carboniferous Limestone and 2.03 km in water-saturated Carboniferous Limestone, fractures will form as compressive shear fractures, that is, normal faults, with no dilation across the fracture. This limits the depth of formation of any open fractures to less than ≈ 2 km for water-saturated Carboniferous Limestone. The variation in the style of deformation with depth in water-saturated Carboniferous Limestone is summarized in Figure 14.

The above theoretical discussion predicts a range of dips of between 90° and $\sim 67°$ for open fractures at different depths. The observed frequency distribution of fissure-dips in the Mendip data set shows a distinct cut-off at $\sim 65°$ (Fig. 15), supporting the conclusion that the fissures have a tectonic origin. The calculated maximum depths for vertical tension fractures are of the same order as the total thickness of the Carboniferous Limestone Series in the Mendip area (900–1100 m). Thus, it is likely that sub-vertical tectonic tension fractures penetrate through the entire thickness of the
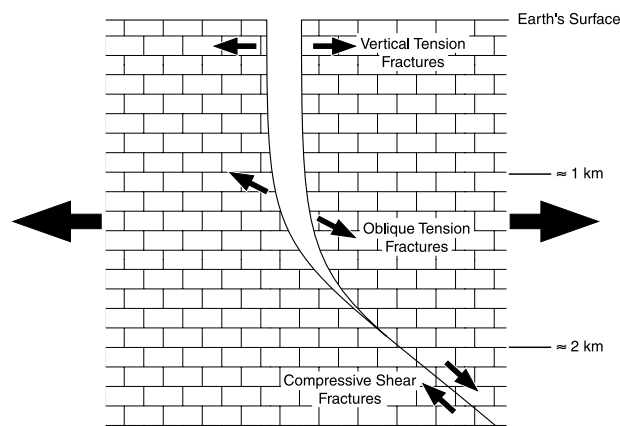

Figure 14. Schematic cross-section illustrating the variation in fracture style with depth in water-saturated Carboniferous Limestone, using the Griffith fracture criterion. With a Carboniferous Limestone bulk density of 2700 kg m^{-3} and a tensile strength of 7 MPa, the transition between vertical and oblique extension fractures occurs at ~ 1 km depth and the latter pass into compressive shear fractures at ~ 2 km depth.
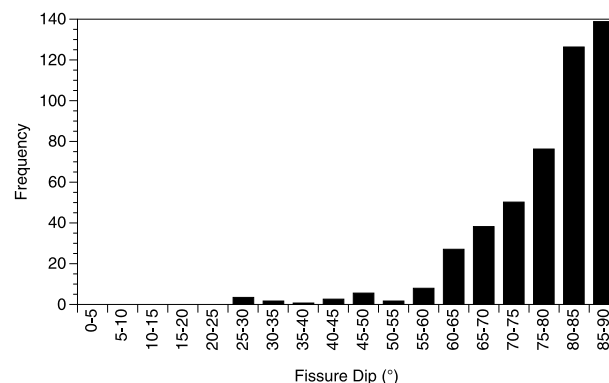

Figure 15. Frequency histogram of observed fissure dips in the eastern Mendips. Note the cut-off at around 65°, which corresponds closely with the minimum dip for dilatant fractures predicted by the Griffith fracture criterion.

Carboniferous Limestone Series and possibly sole out in the underlying Lower Limestone Shales.

13. How much extension was produced by fissure formation?

The amount of extension produced by the formation of extensional fissures within the Carboniferous Limestone was calculated along traverses across well-exposed areas. Three sections were constructed across Cloford Quarry and two across the Coleman's Quarry complex (Figs 7, 8). The nature of the exposure is such that only one E–W section of sufficient length (north face of Cloford Quarry) is well enough exposed to allow the calculation of extension factors in this direction. For each section, the extension produced by the formation of fissures containing Fill-type 1 was calculated, using

Table 1. Amount of extension produced by fissures containing main fill-types

Section		Cloford 1a,b N–S	Cloford 2 E–W	Cloford 3 N–S	Holwell 1 N–S	Holwell 2 N–S
L_0 (m)		260.44	173.22	189.72	383.43	347.50
Fill-type 1	(cm/%)	48/0.19	24/0.14	11/0.05	65/0.17	90/0.26
Fill-type 2.1	(cm/%)	95/0.36	3/0.02	27/0.14	0/0	173/0.50
Fill-type 2.2	(cm/%)	204/0.78	41/0.24	441/2.32	658/1.71	446/1.27
Fill-type 3	(cm/%)	56/0.21	8/0.05	66/0.34	82/0.21	65/0.18
Fill-type 4	(cm/%)	243/0.92	6/0.03	340/1.74	150/0.38	317/0.89
Fill-type 5	(cm/%)	84/0.31	0/0	14/0.07	345/0.88	50/0.14
Calcite etc.	(cm/%)	225/0.84	24/0.12	127/0.64	662/1.67	409/1.14
Total	(cm/%)	955/3.67	106/0.61	1026/5.41	1962/5.12	1550/4.46

the amount of Carboniferous Limestone as an original length (L_0). The resulting section length was used as the starting length for the next calculation for Fill-type 2.1 and so on. Because very little three-dimensional or plan-view exposure was available to investigate the exact dilation direction, the fissures were assumed to have opened in a horizontal direction, perpendicular to strike, a reasonable assumption for vertical tension fractures. For each fissure, the component of this extension vector parallel to the section was added to the total. The total amounts of extension for each fill-type, expressed in centimetres and as a percentage, are presented in Table 1. These results, assuming they are representative for the region, show that during Late Triassic–Early Jurassic times, the southern margin of the Carboniferous Limestone, in the southern limb of the Beacon Hill Pericline, moved south by at least 10–20 m, relative to the periclinal axis. The total amounts of extension produced by fissure formation from the Late Triassic to Bajocian range from 3.67 to 5.41 % in a N–S direction and 0.61 % in an E–W direction. Estimates of mean N–S and E–W strain and strain rates, assuming fissure formation was spread over the stratigraphic range of a particular fill-type and that an ammonite zone represents approximately 1 My, are presented in Tables 2 and 3. The figures for strain rate are clearly minima. Note that N–S strain rates increased to a maximum in the early Pliensbachian with the intrusion of Fill-type 4. By contrast, E–W strain rates reached a maximum during the late Sinemurian with the intrusion of Fill-type 3.

To summarize, fissuring produced a mean N–S strain of ~4.7 % and an E–W strain of ~0.6 %. Strain rates increased to a peak around Sinemurian–Pliensbachian boundary time, during the formation of fissures that were filled by the crinoidal calcarenites of Fill-type 4. Modelling of palaeostress magnitudes in the Mesozoic of the Bristol Channel Basin similarly identifies the Pliensbachian as an interval of major rifting (Nemcock & Gayer, 1996). The calculated strains are very significant when compared to estimates of the extension factors for the formation of the Wessex Basin, based on back-stripping of Mesozoic sections. Such estimates

Table 2. Estimates of mean N–S strain during each fissuring episode

Fill-type	Stratigraphic range (Myr)	Mean strain (N–S)	Mean strain rate ($\times 10^{-17}$ s^{-1})
1	$\ll 25$	0.0017	$\gg 0.2$
2.1	≈ 1	0.0025	8.0
2.2	5	0.0152	9.7
3	0.5	0.0024	15.2
4	1.25	0.0098	25.0
5	0.8	0.0035	13.8

Table 3. Estimates of mean E–W strain during each fissuring episode

Fill-type	Stratigraphic range (Myr)	Mean strain (E–W)	Mean strain rate ($\times 10^{-17}$ s^{-1})
1	$\ll 25$	0.0014	$\gg 0.18$
2.1	1.25	0.0002	0.50
2.2	5	0.0024	1.53
3	0.5	0.0005	3.17
4	1.5	0.0003	0.76
5	0.5	0.0	0.0

range from 1.05 ($= 5$ % extension) for the Early Jurassic extensional phase in the Pewsey Sub-basin, south of the Mendips (Chadwick, 1986) to 1.11 ($= 11$ % extension) for the average Mesozoic crustal extension factor across the whole Wessex Basin (Karner, Lake & Dewey, 1987). The extension accommodated by the fissure system on the northern margin of the Wessex Basin is, therefore, of comparable magnitude to the entire Jurassic extensional phase and at least half of the total Mesozoic extension in the Wessex Basin.

14. Implications for estimates of regional extension

A frequently arising problem in the study of extensional terrains is the apparent discrepancy between the amount of extension calculated from basement subsidence and that calculated by the summation of observed fault displacements (e.g. Wood & Barton, 1983; Ziegler, 1983). Extension factors calculated from

back-stripping sections are up to four times greater than those estimated from direct observation of faults (Hellinger, Sclater & Giltnert, 1988). Possible explanations of the discrepancy include: (1) the summation of fault heaves is not an accurate measure of fault-related extension (e.g. Barnett *et al.* 1987; White, 1987; Sclater & Célérier, 1989); (2) a significant amount of displacement occurs on faults below the limit of seismic resolution (e.g. Walsh, Watterson & Yielding, 1991; Walsh & Watterson, 1992); (3) stretching is depth-dependent (e.g. Hellinger & Sclater, 1983; Badley *et al.* 1988); (4) ductile deformation accommodates a significant amount of extension (e.g. Angelier & Colletta, 1983; Walsh & Watterson, 1991).

Errors in the estimates of extension from the summation of fault heaves can be significant (Sclater & Célérier, 1989), especially when extension occurs on listric faults whose hanging walls deform by inclined simple shear (White, Jackson & McKenzie, 1986). The basic process of equating initial length to final length minus total heave, even with simple domino-faulting, can lead to an error of up to 13% for fault rotations of up to 30° (Sclater & Célérier, 1989). A 20% uncertainty in the seismic velocities used during depth conversion of seismic sections also introduces a small error of around 5% in the extension measured from steep ($> 30°$) faults (Sclater & Célérier, 1989). It is, however, hard to imagine that these sources of error can account for the wide discrepancies observed (Ziegler, 1983).

The fractal nature of faulting can be used to predict the amount of extension accommodated on faults with offsets below the level of seismic resolution. Walsh, Watterson & Yielding (1991) showed that, assuming a typical vertical seismic resolution of 100 m, for a population of faults with a scaling exponent, S, of 0.8, only 60% of the total fault displacement is above the resolution threshold. Thus, an interpretation of seismic data is likely to underestimate significantly the amount of extension that is accommodated on faults.

Karner, Lake & Dewey (1987) showed that extension was unequally distributed between the upper crust and the rest of the lithosphere during the Mesozoic development of the Wessex Basin. With a crustal extension factor (δ) of 1.11 and lithospheric extension factor (ß) of 1.05, ductile stretching of the lower crust and sub-crustal lithosphere must have occurred over an area approximately twice that affected by brittle extension of the upper crust. If ß and δ are treated separately in subsidence analysis then there is no need for local, upper-crustal, seismically resolvable extension factors to balance the overall lithospheric extension factor.

The results of this study are relevant to the notion that ductile deformation (more properly, 'pervasive' or 'continuous' deformation in this context) accommodates a significant amount of extension, if 'ductile' is taken to mean any deformation that occurs on discontinuities that cannot be resolved on the scale of observation. The formation of vertical sediment-filled fissures within the footwall of a major basin-bounding fault (the Leighton Fault; Fig. 2) produced an extensional strain of 5%. Such vertical features, filled with limestone in a limestone host-rock, with widths much less than the Fresnel-zone radius of any seismic survey and producing little or no vertical offset of the host-rock, would be invisible on seismic sections. What is more, the introduction of sediment from above the basement blocks violates the usual assumption of constant volume, and so any restorations of the pre-extension configuration of the basement, based on constant area or length of beds, would be in error. Any assessment of extension that fails to take account of this extension within the fault blocks will underestimate the true extension factor (δ), due to an overestimate of the original length of the section (Fig. 16).

The theoretical consideration of fissure formation and the widespread occurrence of sediment-filled fissures in the basement of the Wessex Basin suggest that a significant amount of extension could be accommodated by this mechanism, at least in the upper 2 km of the basement blocks. Such a mechanism is one means by which fault blocks could deform internally to correspond to the 'soft-domino' fault model of Walsh & Watterson (1991).

With increasing extension ($\delta \approx 1.5$–2.5), fault blocks rotate to angles of 25–30° and originally vertical tension fractures (e.g. sediment-filled fissures) can be reactivated as second-order normal faults (Angelier & Colletta, 1983), which turn the original 'dominoes' into 'packs of cards'. At higher values of extension the deformation can be accommodated by these second-order faults, entirely within the original fault-bounded blocks. If the spacing and offset of the second-order faults are below seismic resolution, then the internal deformation will result in an apparent flattening and thinning of beds reconstructed on seismic-reflection profiles (Angelier & Colletta, 1983). The deformation accommodated by slip on the second-order faults will occur in addition to the dilation produced if the tension fractures have a finite width, as in the case of sediment-filled fissures described above. This additional extension was not considered by Angelier & Colletta (1983), who treated the original tension fractures as closed joints.

Thus, there are two mechanisms by which sediment-filled fissures can produce internal deformation within fault-bounded blocks: (1) dilation by formation of the fissures at low extension factors ($\delta < 1.5$–2) and (2) reactivation of these fractures as normal faults at values of δ (> 1.5–2). Because much of the acoustic basement beneath the Mesozoic basins around the UK consists of Carboniferous sediment, the possible significance of hidden, internal extension of 'rigid' fault-blocks, due to the formation of sediment-filled fissures, should be taken into consideration.
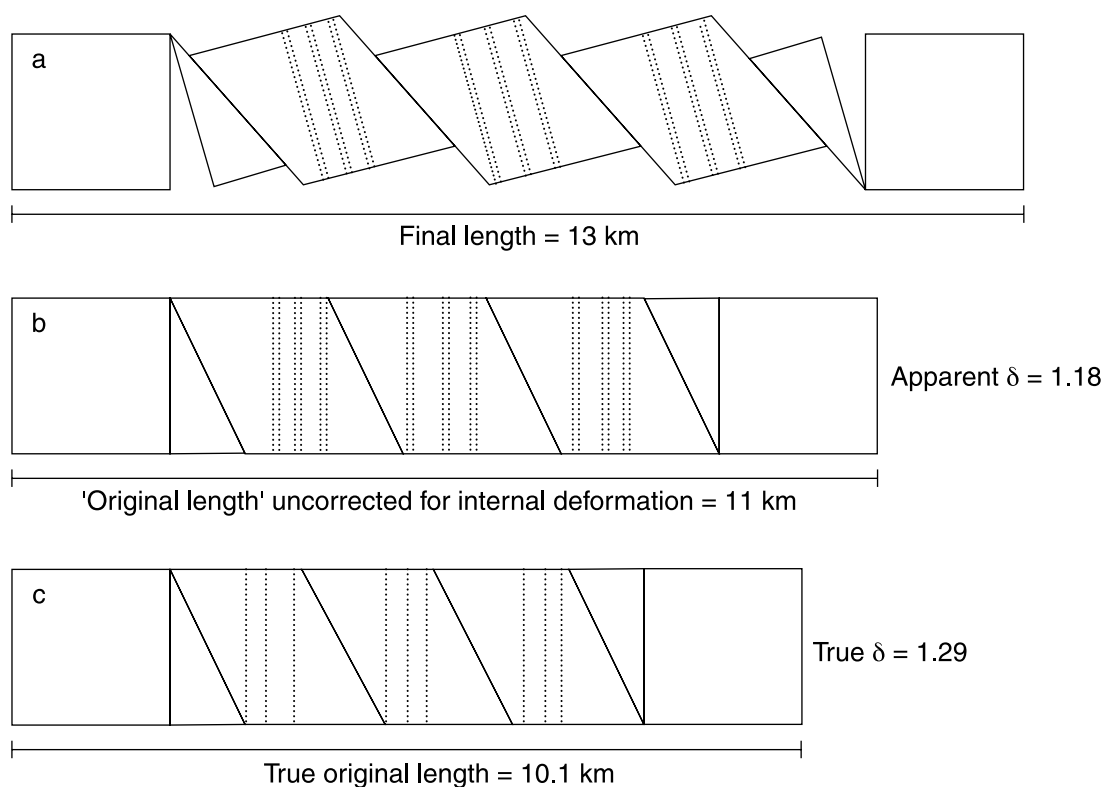
Figure 16. Schematic cross-section illustrating the effect of internal deformation of fault-bound blocks on the estimate of regional extension factors. (a) This section represents a seismic section through an extended region. Basement blocks have been extended by domino-style faulting (visible on seismic section) and, internally, by the formation of sediment-filled fissures (hatched, not visible on a seismic section). (b) The standard procedure of restoring the fault movements gives an apparent original section length of 11 km and, consequently, an estimate for δ of 1.18. This procedure can be refined to account for faulting below the level of seismic resolution by modelling the sub-seismic fault population as a fractal system, using the scaling exponent, S, derived from the rest of the data (Walsh, Watterson & Yielding, 1991). However, a significant amount of extension is still represented by the sediment-filled fissures. (c) Accounting for the internal deformation of the fault blocks, due to formation of sediment-filled fissures, gives the true original section length of 10.1 km and a revised estimate of δ of 1.29.

15. Correlation of episodes of fissure formation in the Mendips and Wessex Basin with periods of onlap/relative sea-level rise in the Early Jurassic

Certain episodes of fissure formation in the Mendips and the Wessex Basin correlate strongly with sharp rises in the Early Jurassic relative sea-level curves of Hallam (1981, 1988, 2001) and Hesselbo & Jenkyns (1998). These curves are largely based on palaeobathymetric interpretation of facies changes in Lower Jurassic sediments from western Europe, particularly Britain, and increases in the depositional extent of these epicontinental facies relative to underlying strata or onlap onto Hercynian basement. The oldest Jurassic fissuring episode, associated with Fill-type 2.2 (clastic limestones and breccias), is poorly constrained in time, but broadly correlates with an assumed general sea-level rise through the late Hettangian–early Sinemurian. The restricted area of transgressive Hettangian deposits, and the magnitude of the apparent relative sea-level rise, have led to previous suggestions of a predominantly tectonic origin

for this transgression (e.g. Hallam & Sellwood, 1976; Donovan, Horton & Ivimey-Cook, 1979; Hallam, 1984). The early *raricostatum* Zone was a time of marked onlap onto the northwest flank of the London Platform (Donovan, Horton & Ivimey-Cook, 1979), with rocks of this age overstepping rocks of *turneri–oxynotum* Zone age to rest on the basement. This transgressive event is recorded throughout much of Europe (Hallam, 1981). The transgression at the base of the Pliensbachian (*jamesoni* Zone) is well documented in the North Atlantic region and follows a probable minor shallowing event in the late *raricostatum* Zone (Sellwood, 1972; Hallam, 1981; Parkinson & Hines, 1995; Hesselbo & Jenkyns, 1998). Fissure formation during the early *jamesoni* Zone (Fill-type 4: crinoidal biosparites), and *falciferum* Zone (well represented by pink to buff biomicrites in the Wessex Basin, possibly in parts of the Mendips: Copp *in* Duff, McKirdy & Harley, 1985; Jenkyns & Senior, 1991) also corresponds to an interval of assumed rapid relative sea-level rise. Studies of regional facies distributions equally suggest a rise in relative sea level during the late Bajocian (Hallam,

1988), corresponding closely in time with fissuring and filling in the Mendips.

The correlation of fissuring episodes and onlap of sediments is even more marked in the Mendip area, where events can be correlated with greater spatial and temporal precision. There is strong correlation between age of the Mendip fissures and sediment packages on the southern margin of the Radstock Shelf, as illustrated by the sections in Donovan & Kellaway (1984). Fill-type 2.2 broadly corresponds with a Hettangian–lower Sinemurian package of sediment. For later fissuring episodes, where the stratigraphical positions of the fill-types are well constrained, the fissuring episodes can be seen to coincide with the time of deposition of the base of sediment packages that are separated by biostratigraphical gaps. Fill-type 3 correlates exactly (to ammonite subzonal level) with the age of the base of an upper Sinemurian package, which lies above a widespread biostratigraphical gap (*denotatus–densinodulum* subzones). The most dramatic onlap occurred in the early *jamesoni* Zone when the highly transgressive Jamesoni Limestone overstepped all earlier Mesozoic rocks locally to rest directly on Carboniferous Limestone. Again, the base of this limestone corresponds exactly in age with the formation of fissures containing Fill-type 4. Fill-type 5 likely corresponds with the Dyrham Silts of the *margaritatus* Zone age, which occur above a biostratigraphical gap that includes the upper *davoei* Zone. Similarly, the Upper Inferior Oolite (*garantiana* Zone), present in fissures in both the Mendips and Wessex Basin, rests with spectacular unconformity on the Carboniferous Limestone in the region of the Beacon Hill Pericline (Fig. 2; Arkell, 1933; Green & Welch, 1965).

One important consideration is whether the correlation between fissuring episodes and onlap of sediments is due to the fissures only being filled when sediment was available to fill them, that is, during episodes of onlap. There is no evidence, however, for fissures remaining open for any length of time prior to their being filled with sediment. As discussed above, this suggests that the age of the fill-type essentially gives the time of formation of the fissures. It is also notable that the largest extents of onlap, in the Hettangian–Sinemurian and the Pliensbachian, *jamesoni* Zone, correspond in time with the largest amounts of extension in the eastern Mendips, as recorded by fissures containing Fill-types 2.2 and 4.

There are many proposed mechanisms for changes in relative sea level at different scales involving eustasy, tectonic subsidence and sedimentation (e.g. Hallam, 1981, 1988; Watts & Thorne, 1984; Haq, Hardenbol & Vail, 1988; Vail *et al.* 1991; Dewey & Pitman, 1998). The identification of pulses of tectonic activity with very fine temporal resolution (e.g. from sediment-filled fissures) provides one method of identifying a potential tectonic signal in the relative sea-level

changes interpreted from the stratigraphical record. This study represents a further refinement of the temporal resolution of Karner, Lake & Dewey's (1987) polyphase, finite re-rifting model for the Mesozoic evolution of the Wessex Basin. Taken as a whole, the formation of the main marine Mendip fissures covered a period from the Rhaetian to the Bajocian ($\sim$45 My: Gradstein *et al.* 1994; Pálfy, Smith & Mortensen, 2000), which coincides with one rifting episode in the western Wessex Basin in the model of Karner, Lake & Dewey (1987). The episodes of fissure formation in the eastern Mendips demonstrate that this rifting episode was itself subdivided into a number of pulses. It is these pulses of tectonic activity, on a scale of ammonite subzones/zones (10^5–10^6 yr), that provide direct evidence for a possible high-frequency tectonic component in recently published relative sea-level curves derived from the Wessex Basin (e.g. Hallam, 1981, 1988; Haq, Hardenbol & Vail, 1988; Hesselbo & Jenkyns, 1998).

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