Interplay between northern and southern sediment sources during Westphalian deposition in the Silverpit Basin, southern North Sea

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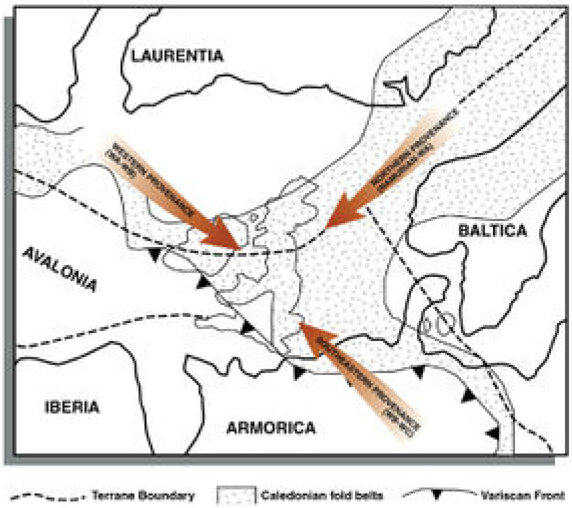

Figure 1 Regional palaeogeographical reconstruction, based on Hallsworth & Chisholm (2000).

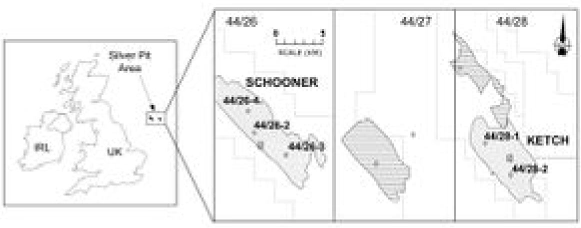

Figure 2 Location of the Schooner and Ketch fields, Silverpit Basin, the southern North Sea, showing wells discussed in this paper.

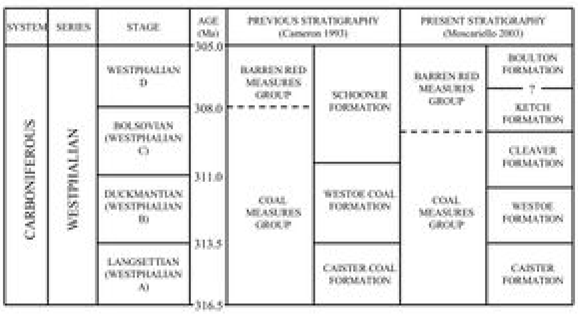

Figure 3 Westphalian stratigraphy of the

southern North Sea area.

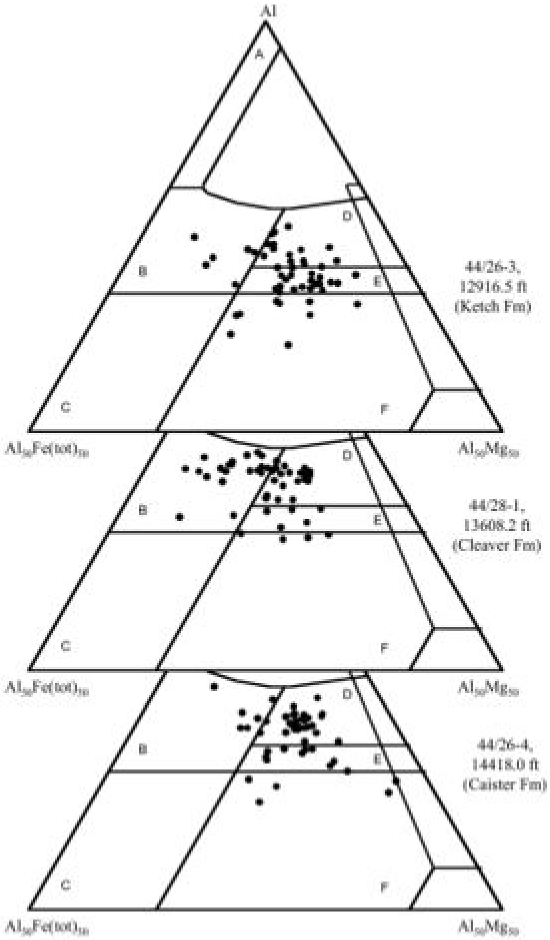

Figure 4 Compositions of representative tourmaline populations from the Westphalian of the southern North Sea, plotted on the ternary provenance-discriminant diagram devised by Henry & Guidotti (1985). Field A – Li-rich granitoids, pegmatites and aplites; field B – Li-poor granitoids, pegmatites and aplites; field C – hydrothermally altered granitic rocks; field D – metapelites and metapsammites (aluminous); field E – metapelites and metapsammites (Alpoor); field F – Fe3+-rich quartz-tourmaline rocks, calc-silicates and metapelites; field G – low-Ca ultramafics; field H – metacarbonates and metapyroxenites.

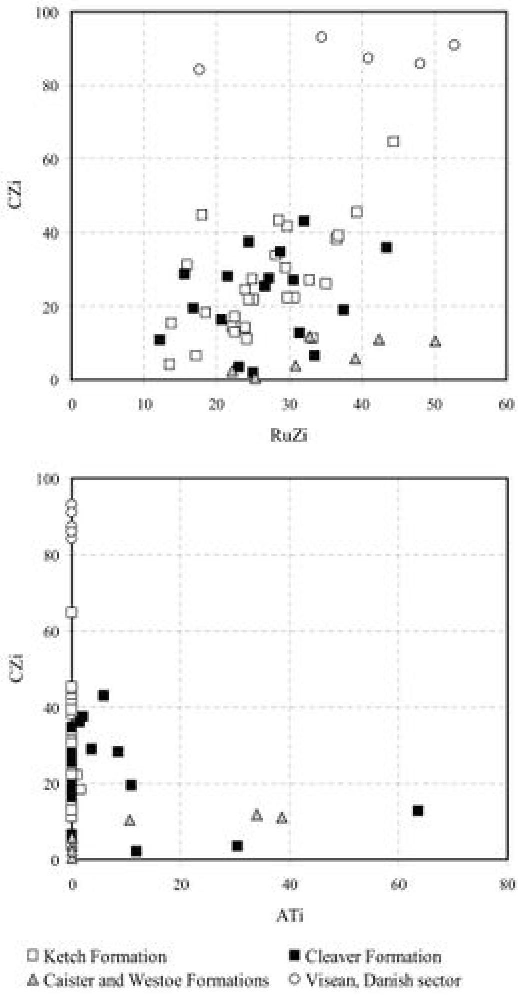

Figure 5 Westphalian sandstones from the Silverpit Basin plotted on CZi versus RuZi and ATi vs CZi diagrams.

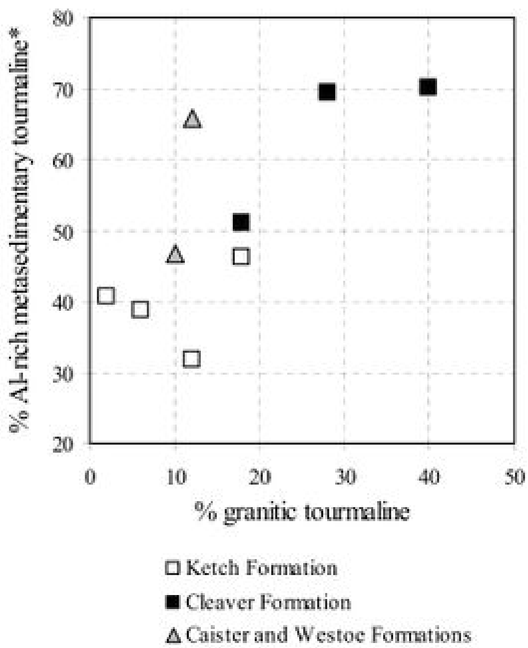

Figure 6 Crossplot showing the abundance of granitic and Al-rich metasedimentary tourmalines in Westphalian sandstones from the Silverpit Basin. An asterisk (*) denotes

proportion of Al-rich metasedimentary tourmalines was calculated by excluding the granitic component. Data used in the plot are shown in Table 3.

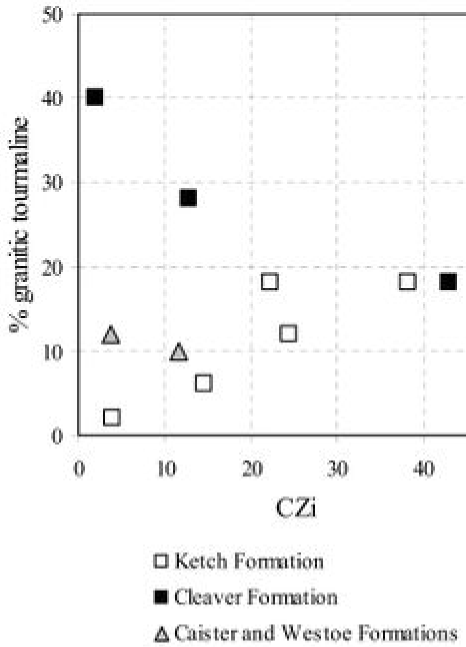

Figure 7 Abundance of granitic tourmalines, plotted against CZi, in Westphalian sandstones from the Silverpit Basin.

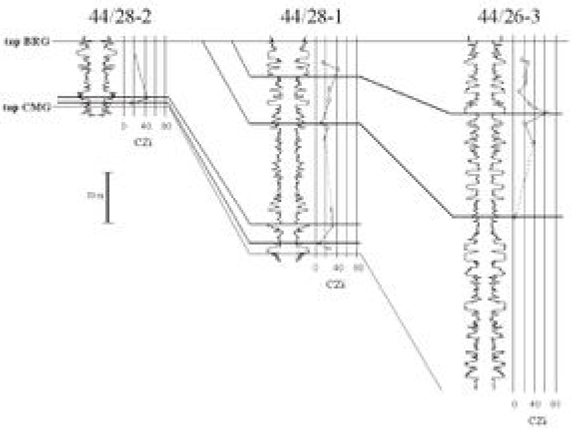

Figure 8 Correlation of gamma-ray logs (right-hand track reversed) of the Ketch Formation in Schooner field well 44/26-3 and Ketch field wells 44/28-1 and 44/28-2 on the basis of variations in CZi. BRG – Barren Red Group. CMG – Coal Measures Group.

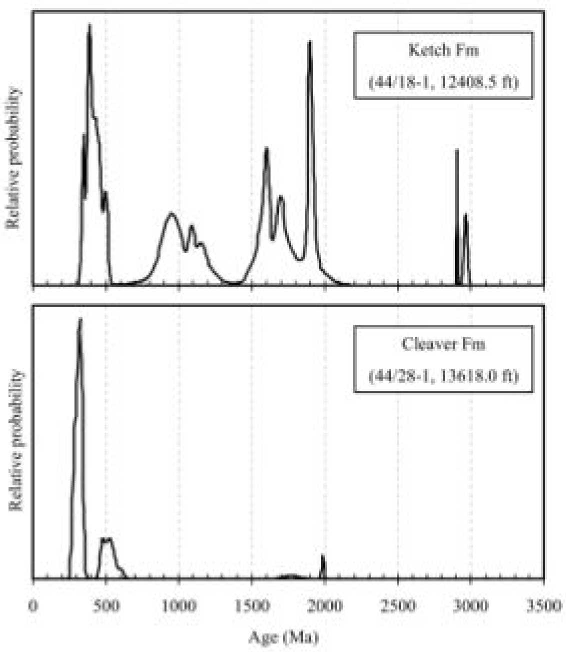

Figure 9 Relative probability diagrams showing zircon age spectra from the Ketch and Cleaver formations. Data from Morton et al. (2001).

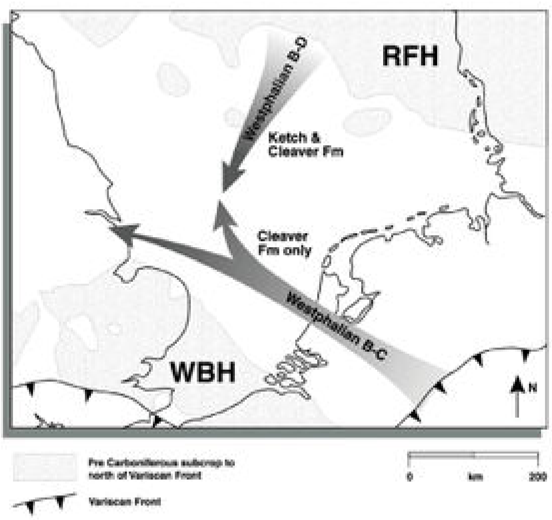

Figure 10 Proposed sediment supply routes in the southern North Sea during deposition of the Ketch and Cleaver formations. WBH – Wales–Brabant High. RFH – Rinkøbing–Fyn High.

Well	Depth (ft)	Formation	At	Ap	Ct	Cr	Gt	Mo	Ru	St	To	Zr	Total
44/26-3	12845.0	Ketch	0.5			14.3		0.5	14.7		5.9	64.1	370
	12854.0	Ketch	1.5			19.8		0.2	17.5		8.5	52.5	400
	12897.0	Ketch	0.5	0.2		13.2			20.7		18.4	47.0	430
	12916.5	Ketch	0.3			17.3			17.0		11.6	53.8	371
	12942.0	Ketch	0.6			6.4			26.8		12.4	53.8	500
	12980.9	Ketch	0.3			26.4			11.1		3.9	58.3	360
	12994.5	Ketch	0.2			27.6			16.5		16.9	38.8	515
	13009.0	Ketch	0.2			42.7			21.8		12.0	23.3	450
	13041.6	Ketch	0.7	0.2		14.4		0.2	17.4		15.1	52.0	430
	13096.5	Ketch	0.4			23.1			21.6		17.4	37.5	550
	13329.0	Ketch	0.6			3.3			12.7		2.7	80.7	300
44/26-4	13007.9	Cleaver	1.6			24.4			18.7		9.3	46.0	450
	13018.0	Cleaver				9.4	1.4		10.8		1.4	77.0	74
	14418.0	Caister	0.3			2.4		0.5	26.8		10.0	60.0	380
	14431.5	Caister	1.0			3.0		2.0	32.3		11.7	50.0	400
	14453.5	Caister				0.3		2.0	22.0		10.8	64.9	350
44/28-1	12551.2	Ketch	1.5			6.1	0.6	0.2	11.6		44.1	35.9	510
	12572.5	Ketch	0.2			32.5			17.1		7.3	42.9	468
	12589.3	Ketch	1.0			23.1			20.8		19.2	35.9	480
	12635.6	Ketch	2.4			11.2			17.9		30.6	37.9	330
	12671.0	Ketch	0.2			15.4			23.5		17.2	43.7	460
	12740.2	Ketch	3.1			7.8			20.0		6.6	62.5	320
	12753.1	Ketch	1.1			15.5			18.0		10.0	55.4	361
	12789.5	Ketch	3.2			12.1			17.1		8.5	59.1	340
	13013.0	Ketch	0.2			19.6			18.8	0.2	16.4	44.8	500
	13058.5	Ketch	0.2			22.2			17.2		16.8	43.6	459
	13116.0	Ketch	2.7			5.0			15.0		5.3	72.0	300
	13130.6	Ketch	0.8			17.8			19.1		9.9	52.4	382
	13608.2	Cleaver	0.5	6.2		0.7		0.5	11.6		45.7	34.8	420
	13630.1	Cleaver	1.0	10.2	0.2	1.7		0.5	14.7		22.9	48.8	410
44/28-2	12066.9	Ketch				14.1			21.5		14.4	50.0	404
	12195.0	Ketch				39.5			10.8		0.7	49.0	408
	12211.0	Ketch	0.9			12.7			11.2		4.8	70.4	330
	12235.9	Ketch	0.3			10.0			16.7		14.4	58.6	341
	12256.6	Ketch	0.3			10.0			19.4		3.3	67.0	300
	12273.8	Ketch				25.0		0.2	21.2		20.6	33.0	612
	12294.1	Cleaver	0.2	0.5		16.2			13.8		2.0	67.3	400
	12325.5	Cleaver				8.0	0.3		20.8		36.2	34.7	335
	12353.4	Cleaver		1.3		26.3		0.2	16.4		21.0	34.8	529
	12451.4	Cleaver				17.6			20.9		14.2	47.3	444
	12472.2	Cleaver	0.5	0.2		28.9			15.7		6.5	48.2	415
	12520.6	Cleaver	0.3	42.7		2.3			10.7		24.3	19.7	300
	12551.3	Cleaver	0.3			22.5			15.9		3.7	57.6	347
	14127.0	Westoe		4.7		7.0			25.8		9.7	52.8	400
	14232.0	Caister	0.4	9.9		4.9			29.0		16.4	39.4	507
	14274.5	Caister		5.2		3.4			24.4		43.9	23.1	442
	15015.0	Caister	12.5			1.0			11.0		39.0	36.5	400
44/28-3	11972.0	Cleaver	0.6	0.3		24.3			11.1		3.3	60.4	333
	11996.0	Cleaver	0.2			20.4			28.6		14.0	36.8	500
	12043.0	Cleaver	1.2			12.7			17.0		4.2	64.9	330
	12066.5	Cleaver	0.2			16.9			18.2		15.2	49.5	420
	12121.8	Cleaver	6.9			2.6	0.2		18.7		34.6	37.0	540
	12147.0	Cleaver	0.3			16.2			15.9		25.2	42.2	321

At – anatase, Ap – apatite, Ct – chloritoid, Cr – chrome spinel, Gt – garnet, Mo – monazite, Ru – rutile, St – staurolite, To – tourmaline, Zr – zircon

Table 1 Conventional heavy-mineral data from Carboniferous sandstones in the Schooner and Ketch fields. Data are expressed as frequency % of the non-opaque detrital component in the 63–125µm fraction.

Well	Depth (ft)	Formation	ATi	Count	GZi	Count	RuZi	Count	MZi	Count	CZi	Count
44/26-3	12845.0	Ketch	1.6	122	0.0	237	18.6	291	0.8	239	18.3	290
	12854.0	Ketch	0.0	100	0.0	210	25.0	280	0.5	211	27.3	289
	12897.0	Ketch	1.0	100	0.0	200	30.8	289	0.0	200	22.2	257
	12916.5	Ketch	0.0	100	0.0	200	24.0	263	0.0	200	24.4	264
	12942.0	Ketch	0.0	100	0.0	269	33.3	403	0.0	269	11.2	303
	12980.9	Ketch	0.0	27	0.0	210	16.0	250	0.0	210	31.1	305
	12994.5	Ketch	0.0	100	0.0	200	29.8	285	0.0	200	41.5	342
	13009.0	Ketch	0.0	100	0.0	200	44.5	308	0.0	200	64.6	297
	13041.6	Ketch	0.0	100	0.0	223	25.2	298	0.4	224	21.8	285
	13096.5	Ketch	0.0	100	0.0	206	36.6	325	0.0	206	38.1	333
	13329.0	Ketch	0.0	100	0.0	242	13.6	280	0.0	242	4.0	252
44/26-4	13007.9	Cleaver	0.0	52	0.0	207	28.9	291	0.0	207	34.7	317
	13018.0	Cleaver			1.7	58	12.3	65	0.0	57	10.9	64
	14418.0	Caister	0.0	100	0.0	228	30.9	330	0.9	230	3.8	237
	14431.5	Caister	0.0	66	0.0	200	39.2	229	3.8	208	5.7	212
	14453.5	Caister	0.0	74	0.0	227	25.3	304	3.0	234	0.4	228
44/28-1	12551.2	Ketch	0.0	225	1.5	203	24.0	263	0.5	201	14.2	233
	12572.5	Ketch	0.0	100	0.0	200	28.6	280	0.0	200	43.2	253
	12589.3	Ketch	0.0	92	0.0	172	36.8	272	0.0	172	39.2	283
	12635.6	Ketch	0.0	101	0.0	200	32.9	298	0.0	200	27.0	274
	12671.0	Ketch	0.0	100	0.0	200	35.1	308	0.0	200	26.2	271
	12740.2	Ketch			0.0	200	24.2	264	0.0	200	11.1	225
	12753.1	Ketch	0.0	100	0.0	200	24.5	265	0.0	200	21.9	256
	12789.5	Ketch	0.0	100	0.0	200	22.5	258	0.0	200	17.0	241
	13013.0	Ketch	0.0	100	0.0	224	29.6	318	0.0	224	30.4	322
	13058.5	Ketch	0.0	100	0.0	200	28.3	279	0.0	200	33.8	302
	13116.0	Ketch	0.0	58	0.0	216	17.2	261	0.0	216	6.5	231
	13130.6	Ketch	0.0	74	0.0	200	26.7	273	0.0	200	25.4	268
	13608.2	Cleaver	11.9	218	0.0	146	25.1	195	1.4	148	2.0	149
	13630.1	Cleaver	30.4	148	0.0	200	23.1	260	1.0	202	3.4	207
44/28-2	12066.9	Ketch	0.0	100	0.0	200	29.8	285	0.0	200	22.2	257
	12195.0	Ketch			0.0	200	18.0	244	0.0	200	44.6	361
	12211.0	Ketch	0.0	63	0.0	232	13.8	269	0.0	232	15.3	274
	12235.9	Ketch	0.0	100	0.0	200	22.2	257	0.0	200	14.5	234
	12256.6	Ketch	0.0	43	0.0	200	22.5	258	0.0	200	13.0	230
	12273.8	Ketch	0.0	130	0.0	200	39.4	330	0.5	201	45.3	353
	12294.1	Cleaver	10.9	46	0.0	269	16.9	324	0.0	269	19.5	334
	12325.5	Cleaver	0.0	121	0.9	117	37.6	186	0.0	116	18.9	143
	12353.4	Cleaver	5.9	118	0.0	184	32.1	271	0.5	185	43.0	323
	12451.4	Cleaver	0.0	100	0.0	210	30.7	303	0.0	210	27.1	288
	12472.2	Cleaver	2.1	48	0.0	200	24.5	265	0.0	200	37.5	320
	12520.6	Cleaver	63.7	201	0.0	102	31.5	149	0.0	102	12.8	117
	12551.3	Cleaver	8.6	35	0.0	200	21.6	255	0.0	200	28.1	278
	14127.0	Westoe	34.0	200	0.0	211	32.8	314	0.0	211	11.7	239
	14232.0	Caister	38.5	208	0.0	200	42.4	347	0.0	200	11.1	225
	14274.5	Caister	10.6	217	0.0	153	50.2	307	0.0	153	10.5	171
	15015.0	Caister	0.0	172	0.0	165	22.2	212	0.0	165	2.4	169
44/28-3	11972.0	Cleaver	3.7	27	0.0	200	15.6	237	0.0	200	28.8	281
	11996.0	Cleaver	1.4	72	0.0	192	43.5	340	0.0	192	36.0	300
	12043.0	Cleaver	0.0	26	0.0	214	20.7	270	0.0	214	16.4	256
	12066.5	Cleaver	0.0	79	0.0	208	26.8	284	0.0	208	25.4	279
	12121.8	Cleaver	0.0	200	0.5	201	33.6	301	0.0	200	6.5	214
	12147.0	Cleaver	0.0	81	0.0	136	27.3	187	0.0	136	27.6	188

ATi – apatite:tourmaline index, GZi – garnet:zircon index, RuZi – rutile:zircon index, MZi – monazite:zircon index, CZi – chrome spinel:zircon index

Table 2 Heavy-mineral ratio data from Carboniferous sandstones in the Schooner and Ketch fields.

Well	Depth (ft)	Formation	B%	D%	E%	F%
44/26-3	12916.5	Ketch	12	28	42	18
44/26-3	13096.5	Ketch	18	38	28	16
44/26-3	13329.0	Ketch	2	40	36	22
44/26-4	14418.0	Caister	12	58	20	10
44/28-1	13608.2	Cleaver	40	42	10	8
44/28-2	12066.9	Ketch	18	38	26	18
44/28-2	12235.9	Ketch	6	36	32	26
44/28-2	12353.4	Cleaver	18	42	30	10
44/28-2	12520.6	Cleaver	28	50	14	8
44/28-2	14127.0	Westoe	10	42	30	18

Table 3 Relative abundance of tourmalines falling into fields B (Li-poor granitoids, pegmatites and aplites), D (aluminous metapelites and metapsammites), E (Al-poor metapelites and metapsammites and F (Fe^{3+}-rich quartz-tourmaline rocks, calc-silicates and metapelites) on the provenance-discriminant diagram of Henry & Guidotti (1985). Typical tourmaline populations are shown in Figure 4.

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Contents

Interplay between northern and southern sediment sources during Westphalian deposition in the Silverpit Basin, southern North Sea

By Andrew Morton, Claire Hallsworth, Andrea Moscariello

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Summary

A heavy-mineral study – integrating conventional petrographic analysis, determination of provenance-sensitive mineral ratios, mineral chemistry and detrital zircon geochronology – has provided evidence for an evolution in provenance during Westphalian deposition in the Silverpit Basin of the southern North Sea. The Ketch Formation (mid-Bolsovian to ?Westphalian D) was derived from the northeast, the source area probably lying on the Rinkøbing–Fyn High. During deposition of the preceding Cleaver Formation (late Duckmantian to mid-Bolsovian), there was interfingering of detritus sourced from the Rinkøbing–Fyn High with sediment derived from the Variscan orogenic belt to the south. Sources of sediment in the Langsettian to Duckmantian Caister and Westoe samples are more difficult to specify because of a relative scarcity of data. However,

there is evidence that some sediment was introduced from a northern sourceland via the Pennine river system that dominated deposition in the Pennine Basin during Namurian times. Other sediment may have been introduced from the Wales–Brabant High or from the Variscan belt. The identification of southerly sourced sediment in the Silverpit Basin confirms earlier suggestions that Variscan-derived sediment was transported into the Pennine Basin by transport systems routed through the southern North Sea, and places palaeogeographic constraints on the location of these transport systems.

Introduction

Recent research, using a combination of quantitative heavy-mineral analysis, mineral–chemical analysis and detrital-zircon age, dating has significantly increased our understanding of the provenance of Namurian and Westphalian sandstones in the Pennine Basin, onshore Ux (Figure 1). It has long been recognized that most of the Namurian sandstones in the Pennine Basin are the products of a major fluviodeltaic system, termed the Pennine river system, that drained a sourceland to the north of the British

Isles (Gilligan 1920). Cliff et al. (1991), Hallsworth & Chisholm (2000), Hallsworth et al. (2000) and Evans et al. (2001) demonstrated that the source regions drained by the Pennine river system included Caledonian granites, mid-late Proterozoic metasediments (derived from a range of mid-Proterozoic basement rocks formed during the Svecofennian, Gothian and Sveconorwegian orogenies, and intervening phases of anorogenic magmatism) and Archaean basement rocks, and included high-grade (granulite facies) metasediments or charnockites. These mineralogical and isotopic data are inconsistent with derivation from northern Scotland, implying that the source lay to the north of the North Sea, as predicted by Gilligan (1920). Carboniferous sandstones from northern East Greenland share common mineralogical features with those of the Namurian in the Pennine Basin, suggesting that the source lay in the vicinity of East Greenland (Morton & Whitham 2002).

Heavy-mineral data have enabled identification of sandstones supplied by the Pennine river system in the subsequent Langsettian (Westphalian A), but these interfinger with, and are ultimately superseded by, sediment with a westerly provenance (Chisholm et al. 1996, Hallsworth & Chisholm 2000, Hallsworth et al. 2000). Supply from the west persisted until the late Duckmantian (Westphalian B). Therefore, provenance studies support sedimentological evidence indicating that most Langsettian–Duckmantian sediment in the Pennine Basin was fed from the west (Rippon 1996).

Sediment derived from the Variscan orogenic belt to the south reached the Pennine Basin in the late Duckmantian (Hallsworth & Chisholm 2000, Hallsworth et al. 2000, Evans et al. 2001), terminating supply from the west. Variscan-sourced sediment persists to the top of the Carboniferous sequence in Yorkshire (Bolsovian, Westphalian C). Palaeocurrent data indicate that input to the Pennine Basin during this period took place from the east, implying that transport routes were directed through the southern North Sea from an ultimate source in central Europe. Variscan-derived sediment also characterizes the Halesowen Formation (Westphalian D) in Staffordshire, at the southwest margin of the Pennine Basin. However, in this case, Hallsworth et al. (2000) suggested that the sediment might have been supplied from Armorica, in view of the evidence for breaching of the Wales–Brabant High by this time (Besly 1988).

The southern North Sea therefore occupies a key position in Westphalian palaeogeographical reconstructions, because an understanding of provenance of sandstones in this area is crucial in evaluating regional sediment-transport patterns. Here we present heavy-mineral data from Westphalian sandstones of the Schooner and Ketch fields (blocks 44/26 and 44/28), located in the Silverpit Basin, UK southern North Sea (Figure 2), and discuss their implications for local and regional sediment supply and their application in reservoir sandstone correlation.

The Westphalian succession in the Silverpit Basin has been subdivided by Moscariello (2003) into the Coal Measures Group and the Barren Red Measures Group. The Coal Measures Group contains three formations, Caister (Langsettian), Westoe (early to middle Duckmantian) and Cleaver (late Duckmantian to mid-Bolsovian). The Barren Red Measures Group includes two formations, the Ketch (mid-Bolsovian to ?Westphalian D) and the Boulton (Westphalian D). The relationship between this stratigraphical nomenclature and the previous nomenclature (Cameron 1993) is shown in Figure 3.

The heavy-mineral dataset discussed here (Table 1) and Table 2) comprises analyses of 53 core samples: 16 from the Schooner field (11 from well 44/26-3, 5 from well 44/26-4) and 37 from Ketch (14 from well 44/28-1, 17 from well 44/28-2, 6 from well 44/28-3). These samples cover the Ketch, Cleaver, Westoe and Caister formations (Langsettian to ?Westphalian D).

1. Review of southern North Sea Carboniferous provenance

For several reasons, including the lack of outcrop data and relatively limited research into sediment provenance, patterns of sediment supply to the southern North Sea during the Carboniferous are less well constrained than for the onshore Pennine Basin. The Pennine river system is believed to have supplied most of the sediment in the southern North Sea during the Namurian (Millstone Grit Group), with the possibility that southerly derived sandstones may fringe the northern margin of the Wales–Brabant High in southern parts of quadrants 47 and 48 (Leeder & Hardman 1990, Collinson et al. 1993). Fluviodeltaic sedimentation continued to be prevalent during deposition of the Langsettian to mid-Bolsovian Coal Measures Group (Leeder & Hardman 1990). In the Coal Measures Group there is significant decline in sand abundance from north to south, leading Besly (1998) and Collinson et al. (1993) to suggest that the majority of the detritus was fed from the north. There is also an overall decrease in sand deposition with time, implying that the northern source became progressively less important. It is noteworthy that the relative paucity of sand in the Westoe Formation corresponds to the acme of the westerly sourced systems in the Pennine Basin (Hallsworth & Chisholm 2000), to which the southern North Sea was relatively distal.

Table 1 Conventional heavy-mineral data from Carboniferous sandstones in the Schooner and Ketch fields. Data are expressed as frequency % of the non-opaque detrital component in the 63–125µm fraction.

Well	Depth (ft)	Formation	At	Ap	Ct	Cr	Gt	Mo	Ru	St	To	Zr	Total
44/26-3	12845.0	Ketch	0.5			14.3		0.5	14.7		5.9	64.1	370
	12854.0	Ketch	1.5			19.8		0.2	17.5		8.5	52.5	400
	12897.0	Ketch	0.5	0.2		13.2			20.7		18.4	47.0	430
	12916.5	Ketch	0.3			17.3			17.0		11.6	53.8	371
	12942.0	Ketch	0.6			6.4			26.8		12.4	53.8	500
	12980.9	Ketch	0.3			26.4			11.1		3.9	58.3	360
	12994.5	Ketch	0.2			27.6			16.5		16.9	38.8	515
	13009.0	Ketch	0.2			42.7			21.8		12.0	23.3	450
	13041.6	Ketch	0.7	0.2		14.4		0.2	17.4		15.1	52.0	430
	13096.5	Ketch	0.4			23.1			21.6		17.4	37.5	550
	13329.0	Ketch	0.6			3.3			12.7		2.7	80.7	300

44/26-4	13007.9	Cleaver	1.6			24.4			18.7		9.3	46.0	450
	13018.0	Cleaver				9.4	1.4		10.8		1.4	77.0	74
	14418.0	Caister	0.3			2.4		0.5	26.8		10.0	60.0	380
	14431.5	Caister	1.0			3.0		2.0	32.3		11.7	50.0	400
	14453.5	Caister				0.3		2.0	22.0		10.8	64.9	350
44/28-1	12551.2	Ketch	1.5			6.1	0.6	0.2	11.6		44.1	35.9	510
	12572.5	Ketch	0.2			32.5			17.1		7.3	42.9	468
	12589.3	Ketch	1.0			23.1			20.8		19.2	35.9	480
	12635.6	Ketch	2.4			11.2			17.9		30.6	37.9	330
	12671.0	Ketch	0.2			15.4			23.5		17.2	43.7	460
	12740.2	Ketch	3.1			7.8			20.0		6.6	62.5	320
	12753.1	Ketch	1.1			15.5			18.0		10.0	55.4	361
	12789.5	Ketch	3.2			12.1			17.1		8.5	59.1	340
	13013.0	Ketch	0.2			19.6			18.8	0.2	16.4	44.8	500
	13058.5	Ketch	0.2			22.2			17.2		16.8	43.6	459
	13116.0	Ketch	2.7			5.0			15.0		5.3	72.0	300
	13130.6	Ketch	0.8			17.8			19.1		9.9	52.4	382
	13608.2	Cleaver	0.5	6.2		0.7		0.5	11.6		45.7	34.8	420
	13630.1	Cleaver	1.0	10.2	0.2	1.7		0.5	14.7		22.9	48.8	410
44/28-2	12066.9	Ketch				14.1			21.5		14.4	50.0	404
	12195.0	Ketch				39.5			10.8		0.7	49.0	408
	12211.0	Ketch	0.9			12.7			11.2		4.8	70.4	330
	12235.9	Ketch	0.3			10.0			16.7		14.4	58.6	341
	12256.6	Ketch	0.3			10.0			19.4		3.3	67.0	300
	12273.8	Ketch				25.0		0.2	21.2		20.6	33.0	612
	12294.1	Cleaver	0.2	0.5		16.2			13.8		2.0	67.3	400
	12325.5	Cleaver				8.0	0.3		20.8		36.2	34.7	335
	12353.4	Cleaver		1.3		26.3		0.2	16.4		21.0	34.8	529
	12451.4	Cleaver				17.6			20.9		14.2	47.3	444
	12472.2	Cleaver	0.5	0.2		28.9			15.7		6.5	48.2	415
	12520.6	Cleaver	0.3	42.7		2.3			10.7		24.3	19.7	300
	12551.3	Cleaver	0.3			22.5			15.9		3.7	57.6	347
	14127.0	Westoe		4.7		7.0			25.8		9.7	52.8	400
	14232.0	Caister	0.4	9.9		4.9			29.0		16.4	39.4	507
	14274.5	Caister		5.2		3.4			24.4		43.9	23.1	442
	15015.0	Caister	12.5			1.0			11.0		39.0	36.5	400
44/28-3	11972.0	Cleaver	0.6	0.3		24.3			11.1		3.3	60.4	333
	11996.0	Cleaver	0.2			20.4			28.6		14.0	36.8	500
	12043.0	Cleaver	1.2			12.7			17.0		4.2	64.9	330
	12066.5	Cleaver	0.2			16.9			18.2		15.2	49.5	420
	12121.8	Cleaver	6.9			2.6	0.2		18.7		34.6	37.0	540
	12147.0	Cleaver	0.3			16.2			15.9		25.2	42.2	321

At – anatase, Ap – apatite, Ct – chloritoid, Cr – chrome spinel, Gt – garnet, Mo – monazite, Ru – rutile, St – staurolite, To – tourmaline, Zr – zircon

Table 2 **Heavy-mineral ratio data from Carboniferous sandstones in the Schooner and Ketch fields.**

Well	Depth (ft)	Formation	ATi	Count	GZi	Count	RuZi	Count	MZi	Count	CZi	Count
44/26-3	12845.0	Ketch	1.6	122	0.0	237	18.6	291	0.8	239	18.3	290
	12854.0	Ketch	0.0	100	0.0	210	25.0	280	0.5	211	27.3	289
	12897.0	Ketch	1.0	100	0.0	200	30.8	289	0.0	200	22.2	257
	12916.5	Ketch	0.0	100	0.0	200	24.0	263	0.0	200	24.4	264
	12942.0	Ketch	0.0	100	0.0	269	33.3	403	0.0	269	11.2	303
	12980.9	Ketch	0.0	27	0.0	210	16.0	250	0.0	210	31.1	305
	12994.5	Ketch	0.0	100	0.0	200	29.8	285	0.0	200	41.5	342
	13009.0	Ketch	0.0	100	0.0	200	44.5	308	0.0	200	64.6	297
	13041.6	Ketch	0.0	100	0.0	223	25.2	298	0.4	224	21.8	285
	13096.5	Ketch	0.0	100	0.0	206	36.6	325	0.0	206	38.1	333
	13329.0	Ketch	0.0	100	0.0	242	13.6	280	0.0	242	4.0	252
44/26-4	13007.9	Cleaver	0.0	52	0.0	207	28.9	291	0.0	207	34.7	317
	13018.0	Cleaver			1.7	58	12.3	65	0.0	57	10.9	64
	14418.0	Caister	0.0	100	0.0	228	30.9	330	0.9	230	3.8	237
	14431.5	Caister	0.0	66	0.0	200	39.2	229	3.8	208	5.7	212
	14453.5	Caister	0.0	74	0.0	227	25.3	304	3.0	234	0.4	228
44/28-1	12551.2	Ketch	0.0	225	1.5	203	24.0	263	0.5	201	14.2	233
	12572.5	Ketch	0.0	100	0.0	200	28.6	280	0.0	200	43.2	253
	12589.3	Ketch	0.0	92	0.0	172	36.8	272	0.0	172	39.2	283
	12635.6	Ketch	0.0	101	0.0	200	32.9	298	0.0	200	27.0	274
	12671.0	Ketch	0.0	100	0.0	200	35.1	308	0.0	200	26.2	271
	12740.2	Ketch			0.0	200	24.2	264	0.0	200	11.1	225
	12753.1	Ketch	0.0	100	0.0	200	24.5	265	0.0	200	21.9	256
	12789.5	Ketch	0.0	100	0.0	200	22.5	258	0.0	200	17.0	241
	13013.0	Ketch	0.0	100	0.0	224	29.6	318	0.0	224	30.4	322
	13058.5	Ketch	0.0	100	0.0	200	28.3	279	0.0	200	33.8	302
	13116.0	Ketch	0.0	58	0.0	216	17.2	261	0.0	216	6.5	231
	13130.6	Ketch	0.0	74	0.0	200	26.7	273	0.0	200	25.4	268
	13608.2	Cleaver	11.9	218	0.0	146	25.1	195	1.4	148	2.0	149
	13630.1	Cleaver	30.4	148	0.0	200	23.1	260	1.0	202	3.4	207
44/28-2	12066.9	Ketch	0.0	100	0.0	200	29.8	285	0.0	200	22.2	257
	12195.0	Ketch			0.0	200	18.0	244	0.0	200	44.6	361
	12211.0	Ketch	0.0	63	0.0	232	13.8	269	0.0	232	15.3	274
	12235.9	Ketch	0.0	100	0.0	200	22.2	257	0.0	200	14.5	234
	12256.6	Ketch	0.0	43	0.0	200	22.5	258	0.0	200	13.0	230
	12273.8	Ketch	0.0	130	0.0	200	39.4	330	0.5	201	45.3	353
	12294.1	Cleaver	10.9	46	0.0	269	16.9	324	0.0	269	19.5	334
	12325.5	Cleaver	0.0	121	0.9	117	37.6	186	0.0	116	18.9	143
	12353.4	Cleaver	5.9	118	0.0	184	32.1	271	0.5	185	43.0	323

	12451.4	Cleaver	0.0	100	0.0	210	30.7	303	0.0	210	27.1	288
	12472.2	Cleaver	2.1	48	0.0	200	24.5	265	0.0	200	37.5	320
	12520.6	Cleaver	63.7	201	0.0	102	31.5	149	0.0	102	12.8	117
	12551.3	Cleaver	8.6	35	0.0	200	21.6	255	0.0	200	28.1	278
	14127.0	Westoe	34.0	200	0.0	211	32.8	314	0.0	211	11.7	239
	14232.0	Caister	38.5	208	0.0	200	42.4	347	0.0	200	11.1	225
	14274.5	Caister	10.6	217	0.0	153	50.2	307	0.0	153	10.5	171
	15015.0	Caister	0.0	172	0.0	165	22.2	212	0.0	165	2.4	169
44/28-3	11972.0	Cleaver	3.7	27	0.0	200	15.6	237	0.0	200	28.8	281
	11996.0	Cleaver	1.4	72	0.0	192	43.5	340	0.0	192	36.0	300
	12043.0	Cleaver	0.0	26	0.0	214	20.7	270	0.0	214	16.4	256
	12066.5	Cleaver	0.0	79	0.0	208	26.8	284	0.0	208	25.4	279
	12121.8	Cleaver	0.0	200	0.5	201	33.6	301	0.0	200	6.5	214
	12147.0	Cleaver	0.0	81	0.0	136	27.3	187	0.0	136	27.6	188

ATi – apatite:tourmaline index, GZi – garnet:zircon index, RuZi – rutile:zircon index, MZi – monazite:zircon index, CZi – chrome spinel:zircon index

The provenance of sandstones in the succeeding Barren Red Measures Group (mid-Bolsovian to Westphalian D) is less certain. Two formations (Ketch and Boulton) are recognized in the Barren Red Measures Group of the southern North Sea (Moscariello 2003). Both are fluvial in origin, with the Ketch Formation consisting of reddened fluvial single- or multi-storey braided channel deposits (Besly et al. 1993) and the Boulton Formation comprising fluviolacustrine facies (Moscariello 2003). Collinson et al. (1993) suggested that the Ketch sandstones have compositions similar to those of the preceding Namurian and earlier Westphalian, implying that their ultimate source lay to the north. Leeder & Hardman (1990) proposed that Barren Red Group strata were derived locally by recycling of earlier Westphalian rocks during growth-fold development associated with the approaching Variscan front. Sm–Nd isotopic data from the Ketch Formation in the Schooner field (Moscariello 2003) are consistent with derivation from a combination of Palaeozoic igneous rocks and Proterozoic gneiss. Palaeocurrent data indicate that transport was from the northeast, suggesting a source on the Dogger Shelf (Moscariello 2003). The Boulton Formation (Westphalian D), which is not present in the Schooner and Ketch fields, is less feldspathic and more lithic than the Ketch Formation, and is ascribed to a southern, Variscan, source (Besly 1998).

2. Heavy-mineral studies

2.1 Sample preparation

Samples were gently disaggregated by pestle and mortar, avoiding grinding action. Following disaggregation, the samples were immersed in water and cleaned by ultrasonic probe to remove and disperse any clay that might have been adhering to grain surfaces. The samples were then wet sieved through the 125µm and 63µm sieves, and the resulting >125µm and 63–125µm fractions were dried in an oven at 80°C. The 63–125µm fraction was placed in bromoform with a measured specific gravity of 2.8. Heavy minerals were allowed to separate under gravity, with frequent stirring to ensure complete separation. The heavy-mineral residues were mounted under Canada balsam for optical study, using a polarizing microscope. Where possible, a split was retained for microprobe study.

Virtually all of the heavy-mineral residues were flooded with secondary carbonate (mostly dolomite). Consequently, the residues were subjected to acid digestion in warm acetic acid to remove the carbonate. Although it is preferable to avoid using any acid treatment because of the possible effect on detrital mineral phases (especially apatite), data could not have been obtained without this process. Dilute acetic acid was chosen because it has little effect on apatite or any other detrital heavy mineral. The process reduced the abundance of carbonate enough to enable the analysis to proceed, and the fact that apatite is preserved in several samples indicates that acetic acid did not cause apatite dissolution.

2.2 Conventional heavy-mineral data

Heavy-mineral proportions were estimated by counting 200 non-opaque detrital grains using the ribbon method described by Galehouse (1971). Identification was made on the basis of optical properties, as described for grain mounts by Mange & Maurer (1992). A qualitative assessment was also made of other components, such as diagenetic minerals, opaques and mica. The detrital heavy-mineral suites are restricted in diversity. Only ten species (anatase, apatite, chloritoid, chrome spinel, garnet, monazite, rutile, staurolite, tourmaline and zircon) are present, four of which (chloritoid, garnet, monazite and staurolite) are extremely scarce (Table 1). The restricted diversity is almost certainly attributable to advanced burial diagenesis, the samples being from depths in excess of 3650m (*c.* 12000 ft). Maximum burial could have been significantly greater prior to inversion during the Cimmerian or Alpine events, or both. Burial diagenesis removes unstable heavy minerals through circulation of high-temperature pore fluids (Morton & Hallsworth 1999). Garnet is the most stable of these minerals, with complete garnet dissolution taking place prior to burial depths of 3500m (*c.* 11500 ft) in central North Sea Jurassic sandstones (Morton & Hallsworth 1999). The scarcity of garnet and of all less stable phases (staurolite, kyanite, titanite, epidote, amphibole) is, therefore, likely to be a diagenetic effect and to have no bearing on provenance.

2.3 Provenance-sensitive heavy-mineral ratios

Basic heavy-mineral abundance data are not always useful guides to provenance, because of the impact of other processes that act during the sedimentary cycle (Morton & Hallsworth 1999). The most profound effects are caused by hydraulic segregation during transport and at the depositional site, and by burial diagenesis. However, provenance-sensitive information can be extracted from the residues by determining ratios of minerals with similar hydraulic and diagenetic behaviour. The ratios determined in this study are apatite:tourmaline, garnet:zircon, rutile:zircon, monazite:zircon and chrome spinel:zircon. These are denoted as index values (ATi, GZi, RuZi, MZi, CZi), following Morton & Hallsworth (1994), and were determined using the ribbon-counting method, ideally on the basis of a 200-grain count. However, it was not always possible to achieve the optimum 200-grain count because of the scarcity of some of the mineral phases.

Of the ratios determined in this study, useful provenance information is given by RuZi, MZi, CZi and ATi, but not by the GZi, which has been profoundly modified by garnet dissolution during deep burial. Furthermore, ATi also records the effects of weathering during the sedimentation cycle, since apatite is strongly affected by acidic groundwaters during periods of sub-aerial exposure. Low ATi values (as found, for example, throughout the Ketch Formation) are therefore likely to indicate prolonged weathering during transport, rather than diagnose a low-apatite sediment source.

2.4 Mineral–chemical data

Provenance-sensitive information can also be gathered by mineral–chemical studies, because analysis of a single mineral group minimizes hydraulic and diagenetic effects (Morton & Hallsworth 1994). In this study, tourmaline was selected for mineral chemistry, since it has a range of compositions more diverse than those of the other minerals present. Tourmaline grains were picked with a needle from the dry residues during optical examination under the polarizing microscope, in a manner analogous to the ribbon method of Galehouse (1971). The grains were placed on double-sided adhesive tape, coated with carbon, and analysed using a Link Systems AN 10/55S energy-dispersive X-ray analyzer attached to a Cambridge Instruments Microscan V electron microprobe. The count time was 30sec for each grain. The optimum analytical total for tourmaline is about 88 per cent, because of the presence of elements such as boron, lithium and hydrogen, which cannot be detected using energy-dispersive analysis. The quality of the tourmaline analyses was monitored to ensure the rejection of analytical totals that fell below 80 per cent because of grain-surface roughness or orientation.

Tourmaline compositions are plotted on the source discriminant ternary diagram of Henry & Guidotti (1985). As shown in Figure 4, there are significant differences in the proportions of granitic tourmalines (field B) compared with metasedimentary tourmalines (fields D, E and F), and also significant differences in abundance between tourmalines derived from Al-rich meta-sediments (field D) and those from Al-poor metasediments (fields E and F). The proportion of granitic tourmalines ranges from 2 per cent to 40 per cent, with Al-rich metasedimentary tourmalines forming 28–58 per cent and Al-poor metasedimentary tourmalines 18–60 per cent. The abundances of tourmalines falling in fields B, D, E and F are shown in Table 3.

3. Ketch Formation

The Ketch Formation has been extensively cored in three wells from the Schooner and Ketch fields (44/26-3, 44/28-1 and 44/28-2), enabling a thorough documentation of the heavy-mineral population. As discussed above, the population has limited diversity, primarily because of dissolution of unstable minerals (including garnet) during burial diagenesis. The sandstones also appear to have undergone extensive weathering on the floodplain, diagnosed by very low apatite abundances and ATi values. Monazite is scarce throughout, causing MZi values to be consistently low. By contrast, chrome spinel is common, and CZi values are generally high, some in excess of 60.

Well	Depth (ft)	Formation	B%	D%	E%	F%
44/26-3	12916.5	Ketch	12	28	42	18
44/26-3	13096.5	Ketch	18	38	28	16
44/26-3	13329.0	Ketch	2	40	36	22
44/26-4	14418.0	Caister	12	58	20	10
44/28-1	13608.2	Cleaver	40	42	10	8
44/28-2	12066.9	Ketch	18	38	26	18
44/28-2	12235.9	Ketch	6	36	32	26
44/28-2	12353.4	Cleaver	18	42	30	10
44/28-2	12520.6	Cleaver	28	50	14	8
44/28-2	14127.0	Westoe	10	42	30	18

The Ketch Formation data show a reasonably well defined linear pattern on a crossplot of CZi vs RuZi (Figure 5), with only two slightly aberrant points (one with relatively low RuZi and one with relatively low CZi). This pattern is consistent with a mixed two-component provenance, one with high CZi and high RuZi, and the other with low CZi and low RuZi. The distribution of the data points along the mixing trend suggests that the source region contained two distinct lithological components (one characterized by high CZi and RuZi, the other by low CZi and low RuZi), and that the variations in Ketch mineralogy are the result of variable input from these two components.

Ketch Formation tourmaline populations are dominated by Al-poor metasedimentary types (fields E and F), which comprise 44–60 per cent of the assemblages (Table 3). Al-rich meta-sedimentary types (field D) form 28–40 per cent, and granitic tourmalines (field B) are comparatively minor (6–18%). On a crossplot of abundance of granitic versus Al-rich metasedimentary tourmalines (Figure 6), the Ketch Formation samples form a single group, with relatively low abundances of granitic and Al-rich metasedimentary tourmalines. The crossplot of CZi versus abundance of granitic tourmalines (Figure 7) shows that the Ketch Formation samples with highest CZi also have the greatest abundance of granitic tourmaline. This provides added sophistication to the provenance-mixing model for the Ketch Formation, indicating that the high-CZi, high-RuZi end member also supplied more granitic tourmalines compared with the low-CZi, low-RuZi end-member.

Since the Ketch Formation has no age-diagnostic fossils, alternative methods of correlation are therefore required for this interval. Chemostratigraphic data have proved useful for the onshore and offshore Westphalian (Pearce et al. 1999). The marked variations in heavy-mineral assemblages, in particular CZi and RuZi, in the Ketch Formation sequences provide an alternative non-biostratigraphic basis for reservoir sandstone correlation in the area. The mineralogically based correlation of the Ketch Formation in the three wells is shown in Figure 8.

4. Cleaver Formation

Most of the Cleaver Formation samples conform with the same mixing trend as that shown by the Ketch Formation (Figure 5), and a similar two-component provenance is envisaged. However, several samples fall away from the linear trend on the CZi–RuZi crossplot. These include both Cleaver Formation samples from 44/28-1, two of the Cleaver samples in 44/28-2, and one of the Cleaver samples in 44/28-3. This group of five samples have somewhat lower CZi than the other Cleaver Formation samples, suggesting the possible involvement of a different source terrain. Furthermore, although ATi values are low for most Cleaver samples, three of the group that deviate from the main Ketch and Cleaver mixing trend have relatively high values (Figure 5). This provides further evidence for a difference in origin for these sandstones, suggesting that they may have undergone less prolonged floodplain weathering.

Tourmalines from 44/28-2 (12353.4 ft; one of the Cleaver samples that lie on the typical Ketch and Cleaver mixing trend on the CZi–RuZi crossplot) have relatively low abundances of granitic tourmalines and Al-rich metasedimentary tourmalines (Table 3, Figure 6), similar to the tourmalines from the Ketch Formation. However, tourmalines from two other Cleaver Formation samples (44/28-1, 13608.2 ft; 44/28-2, 12520.6 ft) are distinctly different. Granitic tourmalines are abundant in them (*c.* 30–40% of the assemblage), and the metasedimentary component is dominated by Al-rich tourmaline types (Table 3, Figure 6). These two samples were identified as aberrant on the basis of their CZi, RuZi and ATi values, and the tourmaline geochemistry therefore confirms that they have a distinctly different provenance to both the Ketch and the majority of the Cleaver Formation samples.

5. Westoe and Caister formations

Core coverage of the Westoe and Caister formations is poor, and consequently the data presented here do not represent comprehensive provenance information at these levels. All of the Caister and Westoe samples fall away from the main linear mixing trend shown by the Ketch Formation and the majority of the Cleaver samples, having relatively low CZi (0.4–11.7) in conjunction with a wide range of RuZi values up to *c.* 50. The Caister Formation in 44/26-4 differs from the Caister and Westoe samples in 44/28-2 by having lower RuZi and CZi, together with significantly higher MZi (up to 3.8). The variations in mineralogy imply that the Caister and Westoe samples were supplied by several source components. The lack of extensive core coverage of the Caister and Westoe in the wells studied to date precludes further interpretation of the observed differences within these formations. However, the difference between the Caister and Westoe, compared with the Ketch and most of the Cleaver, indicates a significant change in provenance during the Westphalian, with the Ketch (and most of the Cleaver) being supplied by a different transport system tapping a different combination of source lithologies.

Tourmalines in a high-MZi Caister Formation sample (44/26-4, 14418.0 ft) have low abundances of granitic types (*c.* 10%), and are dominated by the Al-rich metasedimentary component (Figure 6), and are therefore different from those found in the Cleaver and Ketch formations. The tourmaline data, therefore, confirm that the Caister Formation sandstones in 44/26-4 were not supplied by the systems that sourced the Cleaver or Ketch sandstones. Westoe Formation tourmalines fall close to the Ketch and main Cleaver group on the tourmaline crossplots (Figure 6). This suggests that the Westoe sandstone provenance is more akin to that of the Ketch and Cleaver than the mineral ratios suggest. Since only one Westoe sandstone sample is included in the dataset, it is probably premature to make any firm conclusions on the provenance of the formation at this stage.

6. Provenance

The heavy-mineral study of Westphalian sandstones in the Schooner and Ketch fields has identified significant heterogeneity in provenance. The Ketch Formation and most of the Cleaver Formation samples form a coherent group (group 1), with a small subset of the Cleaver samples having markedly different characteristics (group 2). The Caister and Westoe samples form a third separate grouping (group 3), although there is evidence for heterogeneity within the group.

6.1 Group 1 provenance

Group 1 comprises all the Ketch samples and most of those from the Cleaver. Although they form a single coherent group, there is a well defined linear trend on crossplots of CZi–RuZi and CZi versus percentage granitic tourmaline. This indicates the source of the group 1 sandstones consisted of two distinct lithologies, one with high CZi, high RuZi and relatively common granitic tourmalines, and the other with low CZi, low RuZi and tourmalines dominated by Al-poor metasedimentary types. Variable supply from these two lithological types caused the observed variations.

The presence of a high-CZi end member indicates a major contribution from ultramafic rocks, because chrome spinel is exclusively found in such lithologies. Ophiolite complexes are the most likely source of the chrome spinel, because layered ultramafic intrusions are relatively rare and none are present in the immediate vicinity of the southern North Sea. By contrast, ophiolites are common within the Caledonides, especially in southern Norway (Stephens et al. 1985, Rankin et al. 1988). Early Carboniferous sandstones in the Danish sector of the southern North Sea, to the northeast of the Silverpit area, have extremely high CZi values (Spathopoulos et al. 2000). These Early Carboniferous sandstones fall at the extreme end of the high-CZi, high-RuZi mixing trend displayed by group 1 sandstones (see Figure 5). Consequently, it can be inferred that one of the provenance components supplying the Ketch and Cleaver was the same as the one that sourced the Early Carboniferous in the Danish sector. The Early Carboniferous is most likely to have been derived from the adjacent Rinkøbing–Fyn High, which, on the basis of heavy-mineral data, must have included ultramafic (probably ophiolitic) material. Alternatively, the high-CZi, high-RuZi end member could have been recycled Early Carboniferous of the type found in the Danish sector. The origin of the low-CZi, low-RuZi component is more speculative. Tourmaline data indicate that it was dominated by Al-poor metasedimentary rocks, but it is not clear from the present data whether they represent direct derivation from metamorphic basement or recycling from earlier sediment. A source in the vicinity of the Rinkøbing–Fyn High is consistent with the southwest-directed palaeocurrent directions for the Ketch Formation in the Schooner field, and with the Sm–Nd isotopic data that suggested derivation from a combination of Palaeozoic igneous rocks and Proterozoic gneiss (Moscariello 2003). Zircons in a Ketch Formation sandstone from well 44/18-1, to the north of the Schooner and Ketch fields (Morton et al. 2001), include Caledonian (390–460 Ma), Sveconorwegian (900–1200 Ma), Gothian and Kongsbergian (1570–1750 Ma), Svecofennian (1850–1950 Ma) and minor Archaean elements (Figure 9). This combination of zircon ages indicates an ultimate provenance in the Laurentian-Baltican shield to the north.

6.2 Group 2 provenance

Group 2 comprises a subset of Cleaver Formation sandstones with characteristics significantly different from those of group 1. Group 2 includes 44/28-1 (13608.2 ft), 44/28-1 (13630.1 ft), 44/28-2 (12325.5 ft), 44/28-2 (12520.6 ft) and 44/28-3 (12121.8 ft). These samples all have relatively low CZi and moderate RuZi, causing them to fall below the linear mixing trend shown by the group 1 sandstones. Three Cleaver Formation samples that combine low CZi with anomalously high ATi values fall in this group. Mineral–chemical studies show that samples with group 2 characteristics contain much more granitic tourmaline, and that the metasedimentary tourmalines are dominated by Al-rich types.

The provenance of group 2 therefore appears to be unrelated to that of group 1, although there is overlap in some parameters, notably CZi, which ranges up to 20 in group 2. The tourmaline data indicate a terrain with widespread granites and Al-rich metasediments, and the presence of chrome spinel indicates some ultramafic material. The detrital zircon age spectrum of a group 2 sample from 44/28-1 (Morton et al. 2001) has a distinct cluster at approximately 326 Ma (Variscan), a well defined group between 460 Ma and 600 Ma (Cadomian), and two older grains between 1770 and 1986 Ma. These three elements can only be matched with a Variscan provenance, and indicate that the source of group 2 sandstones lay to the south, with the SaxoThuringian zone of Germany being considered the most likely.

6.3 Group 3 provenance

Group 3 comprises the Caister and Westoe samples of 44/26-4 and 44/28-2. This group is clearly different from group 1 on the mineral-ratio crossplots, all having relatively low CZi, and therefore has a different provenance. However, the samples show a range of mineralogical compositions (RuZi, ATi and MZi) that suggest that group 3 may itself have a heterogeneous provenance. The sandstones in 44/26-4 have relatively high MZi, suggesting they may be related to the major Pennine delta that supplied monazite-rich sediment to the Pennine Basin during the Namurian and Langsettian. Tourmaline data from 44/26-4 indicate a source dominated by Al-rich metasediments and poor in granites, but no tourmaline data are available from the Pennine Basin for comparison at this stage. The Caister Formation in 44/28-2 includes sandstones with high RuZi and relatively high ATi, together with low MZi, and therefore differs from the Caister in 44/26-4. One possible source for the lowMZi Caister Formation sandstones might be the Wales–Brabant High, which is known to have sourced sandstones northwards into the Pennine Basin (Trewin & Holdsworth 1973). Similar sandstones in the Widmerpool Gulf show low MZi and a range of CZi (Hallsworth et al. 2000). Another possibility is that these sandstones were also shed from a Variscan source to the south. Further zircon age dating is required to evaluate the provenance of the Caister Formation sandstones.

7. Impact on sediment supply to the Pennine Basin

Sediment derived from the Variscan orogenic belt to the south reached the Pennine Basin in the late Duckmantian and persisted at least into the Bolsovian, which is the highest horizon sampled in the Carboniferous sequence in Yorkshire (Hallsworth & Chisholm 2000, Hallsworth et al. 2000). Palaeocurrent data indicate that the Variscan-sourced detritus was fed from the east, implying that transport routes were directed through the southern North Sea from an ultimate source in central Europe. The identification of southerly derived Variscan-sourced Cleaver Formation sandstones in the Ketch field therefore supports the suggestion of Hallsworth & Chisholm (2000) and Hallsworth et al. (2000) for sediment supply via the southern North Sea area. Most of the Variscan-derived Yorkshire samples have relatively high MZi (typically 5–10), but some have lower values akin to those in the Cleaver Formation. The Variscan source was therefore heterogeneous with respect to monazite. It is unclear at this stage whether the differences in MZi are related to temporal variations within a single fluvial system, or to interplay between two or more fluvial systems draining the heterogeneous source.

In view of the presence of detritus sourced from the Rinkøbing–Fyn High or adjacent areas in the Cleaver and Ketch formations, it is evident that the main supply route of Variscansourced detritus must have passed to the south of the Silverpit Basin area (Figure 10). Interfingering of northern and southern sources occurred during Cleaver Formation deposition in the Ketch area, but northern sources dominated deposition in the Silverpit Basin during Ketch Formation times (mid-Bolsovian to ?Westphalian D). It is difficult to ascertain at this stage whether southerly supplied transport systems continued to influence the southern North Sea during this depositional phase, because the record of Carboniferous sedimentation in the Pennine Basin of Yorkshire terminates within the Bolsovian. However, the Halesowen Formation (Westphalian D) provides a record of supply from the south to the onshore UK, and the Boulton Formation (Westphalian D) in the southern North Sea may also reflect the re-establishment of southerly derived sediment transport pathways into the southern North Sea (Besly 1998).

8. Conclusions

Although heavy-mineral assemblages in Westphalian sandstones of the Silverpit Basin (southern North Sea) have been modified by burial diagenetic processes, provenance information has been successfully acquired using a combination of provenance-sensitive mineral-ratio determination and mineral chemistry (concentrating on the ultrastable mineral tourmaline). The heavy minerals provide evidence for major changes in provenance during Westphalian deposition in the Schooner and Ketch field areas in the Silverpit Basin. Three distinct mineralogical groupings have been recognized, all of which represent input from different source regions:* Group 1, which comprises all Ketch Formation (midBolsovian to ?Westphalian D) and most Cleaver Formation (late Duckmantian to mid-Bolsovian) samples, represents detritus derived from a region with two distinct lithological types, one characterized by high CZi and high RuZi, and the other by low CZi and low RuZi. ATi values are very low throughout, indicating extensive floodplain weathering. Mineral chemistry shows that most tourmalines in both end-members were ultimately derived from an Al-poor metasedimentary terrain, although granitic tourmalines are more common in the high-CZi, high-RuZi component. A source on the Rinkøbing–Fyn High, where ophiolites are inferred to be widespread, is considered likely. This is consistent with the southwest-directed palaeocurrents seen in the Ketch Formation of the Schooner field. A source within the Laurentian– Baltican Shield (to the north) is also required by zircon age data from Ketch Formation sandstones in well 44/18-1. Variations in supply from the two main lithological components present in the source area, identified on the basis of variations in CZi and RuZi, provide a basis for correlation of the Ketch Formation reservoir sandstones.

- Group 2, which comprises a subset of the Cleaver Formation, was derived from a region containing widespread granites and Al-rich metasediments. Ophiolitic material was present, but was a smaller component of the source terrain than for group 1. ATi values are variable, with some samples containing common apatite. This indicates a difference in sediment-transport history and confirms that group 2 had an origin different from group 1. Zircon geochronology indicates a source within the Variscan terrain to the south, probably the Saxo-Thuringian zone of Germany.
- Group 3, which comprises the Caister and Westoe samples (Langsettian to mid-Duckmantian), is relatively heterogeneous and probably had more than one source. The group is distinguished from group 1 in having relatively low CZi values throughout, and it differs from groups 1 and 2 on the basis of tourmaline compositions. Relatively high MZi in the Caister Formation of 44/26-4 suggests a possible link with the Pennine river system, which transported monazite-rich sediment to the Pennine Basin during the Namurian and Westphalian A. It is possible that the low-MZi Caister and Westoe sediments may have been shed from the Wales–Brabant High, although a source in the Variscan terrain to the south cannot be ruled out. The relatively few samples, scarcity of tourmaline geochemical data and absence of zircon geochronology all preclude a greater definition of Caister sand provenance at this stage.

Detritus sourced from the Rinkøbing–Fyn High or adjacent areas reached the Silverpit Basin during deposition of the Cleaver and Ketch formations. Interfingering of northern (Rinkøbing–Fyn High) and southern (Variscan) sources occurred during Cleaver Formation deposition (late Duckmantian to mid-Bolsovian), but the northern source dominated deposition during Ketch Formation times (mid-Bolsovian to ?Westphalian D). It is evident, therefore, that the main supply route of Variscan-sourced detritus to the Pennine Basin must have passed to the south of the Silverpit Basin area (Figure 10). It is difficult to ascertain at this stage whether southerly supplied transport systems continued to influence the southern North Sea from the mid-Bolsovian, because the record of Carboniferous sedimentation in the Pennine Basin of Yorkshire terminates around this time. However, the Westphalian D Halesowen Formation (onshore UK) was also derived from the Variscan orogenic belt, and the Boulton Formation (Westphalian D) in the southern North Sea may also reflect the re-establishment of southerly derived sediment transport pathways into the southern North Sea (Besly 1998).

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References

Besly, B. M. 1988. Palaeogeographic implications of late Westphalian to early Permian red-beds, central England. In *Sedimentation in a synorogenic basin complex: the Upper Carboniferous of northwest Europe*, B. M. Besly & G. Kelling (eds), 200–221. Glasgow: Blackie. ——1998. Carboniferous. In *Petroleum geology of the North Sea: basic concepts and recent advances*, K. W. Glennie (ed.), 104–136. Oxford: Blackwell Science.

Besly, B. M., S. D. Burley, P. Turner 1993. The late Carboniferous “Barren Red Bed” play of the Silver Pit area, southern North Sea. In *Petroleum geology of northwest Europe: proceedings of the 4th conference*, J. R. Parker (ed.), 727–40. London: Geological Society. Cameron, T. D. J. 1993. Carboniferous and Devonian of the southern North Sea. In *Lithostratigraphic nomenclature of the UK North Sea* (vol. 5), R. W. O’B. Knox & W. G. Cordey (eds), 1–93. Keyworth, Nottingham: British

Geological Survey.

Chisholm, J. I., C. N. Waters, C. R. Hallsworth, N. Turner, G. E. Strong, N. S. Jones 1996. Provenance of Lower Coal Measures around Bradford, West Yorkshire. *Yorkshire Geological Society, Proceedings* 51, 153–66.

Cliff, R. A., S. A. Drewery, M. R. Leeder 1991. Sourcelands for the Carboniferous Pennine river system: constraints from sedimentary evidence and U/Pb geochronology using zircon and monazite. In *Developments in sedimentary provenance studies* A. C. Morton, S. P. Todd, P. D. W. Haughton (eds), 137–59. Special Publication 57, Geological Society, London.

Collinson, J. D., C. M., Jones, G. A., Blackbourn, B. M., Besly, G. M. Archard, A. H. McMahon 1993. Carboniferous depositional systems of the Southern North Sea. In *Petroleum geology of northwest Europe: proceedings of the 4th conference*, J. R. Parker (ed.), 677–87. London: Geological Society.

Evans, J. A., J. I. Chisholm, M. J. Leng 2001. How U/Pb detrital monazite ages contribute to the interpretation of the Pennine Basin infill. *Geological Society of London, Journal* 158, 741–4.

Galehouse, J. S. 1971. Point-counting. In *Procedures in sedimentary petrology*, R. E. Carver (ed.), 385–407. New York: John Wiley. Gilligan, A. 1920. The petrography of the Millstone Grit of Yorkshire. *Geological Society of London, Quarterly Journal* 75, 251–94. Hallsworth, C. R. & J. I. Chisholm 2000. Stratigraphic evolution of provenance characteristics in Westphalian sandstones of the Yorkshire coalfield. *Yorkshire Geological Society, Proceedings* 53, 43– 72.

Hallsworth, C. R., A. C., Morton, J. C. Claoué-Long, C. M. Fanning 2000. Carboniferous sand provenance in the Pennine Basin, UK: constraints from heavy mineral and SHRIMP zircon age data. *Sedimentary Geology* 137, 147–85.

Henry, D. J. & C. V. Guidotti 1985. Tourmaline as a petrogenetic indicator mineral: an example from the staurolite-grade metapelites of NW Maine. *American Mineralogist* 70, 1–15.

Leeder, M. R. & M. Hardman 1990. Carboniferous geology of the Southern North Sea Basin and controls on hydrocarbon prospectivity. In *Tectonic events responsible for Britain's oil and gas reserves*, R. F. P. Hardman & J. Brooks (eds), 87–105. Special Publication 55, Geological Society, London.

Mange, M. A. & H. F. W. Maurer 1992. *Heavy minerals in colour*. London: Chapman & Hall.

Morton, A. C. & C. R. Hallsworth 1994. Identifying provenance-specific features of detrital heavy-mineral assemblages in sandstones. *Sedimentary Geology* 90, 241–56.

Morton, A. C. 1999. Processes controlling the composition of heavy-mineral assemblages in sandstones. *Sedimentary Geology* 124, 3–29. Morton, A. C., C. R. Hallsworth, J. C. Claoué-Long 2001. Zircon age and heavy-mineral constraints on provenance of North Sea Carboniferous sandstones. *Marine and Petroleum Geology* 18, 319–37. Morton, A. C. & A. G. Whitham 2002. The Millstone Grit of northern England: a response to tectonic evolution of a northern sourceland. *Yorkshire Geological Society, Proceedings* 54, 47–56.

Moscariello, A. 2003. The Schooner field, Blocks 44/26a, 43/30a, UK North Sea. In *United Kingdom oil and gasfields, commemorative millennium volume*, J. G. Gluyas & H. M. Hichens (eds), 811–24. Memoir 20, Geological Society, London.

Pearce, T. J., B. M. Besly, D. S. Wray, D. K. Wright 1999. Chemostratigraphy: a method to improve interwell correlation in barren sequences – a case study using onshore Duckmantian/Stephanian sequences (West Midlands, UK). *Sedimentary Geology* 124, 197– 220.

Rankin, D. W., H. Furnes, A. C. Bishop, B. Cabanis, D. J. Milton, S. J. O'Brien, R. S. Thorpe 1988. Plutonism and volcanism related to the pre-Arenig evolution of the Caledonide–Appalachian orogen. In *The Caledonian–Appalachian orogen*, A. L. Harris & D. J. Fettes (eds), 149–83. Special Publication 38, Geological Society, London.

Rippon, J. H. 1996. Sandbody orientation, palaeoslope analysis and basin-fill implications in the Westphalian A–C of Great Britain. *Geological Society of London, Journal* 153, 881–900.

Spathopoulos, F., P. A. Doubleday, C. R. Hallsworth 2000. Structural and depositional controls on the distribution of the Upper Jurassic Fulmar Formation in the Fife and Angus fields area, quadrants 31 and 39, UK central North Sea. *Marine and Petroleum Geology* 17, 1053–1082.

Stephens, M. B., H. Furnes, B. Robins, B. A. Sturt 1985. Igneous activity within the Scandinavian Caledonides. In *The Caledonide orogen – Scandinavia and related areas*, D. G. Gee & B. A. Sturt (eds), 623–56. New York: John Wiley.

Trewin, N. J. & B. K. Holdsworth 1973. Sedimentation in the lower Namurian rocks of the north Staffordshire Basin. *Yorkshire Geological Society, Proceedings* 39, 371–408.