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Resolution of the age structure of the detrital zircon populations of two Lower Cretaceous sandstones from the Weald of England by fission track dating

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Abstract – Modes in the frequency of distribution of fission track ages obtained from detrital zircon grains may prove characteristic of individual sandstone bodies, supporting the identification of the sources from which a particular flow of sedimentary detritus was derived and thus allowing new inferences to be made concerning palaeogeography. A computer program has been written and used to identify modes in the zircon fission track age distribution within two Lower Cretaceous sandstone samples from the Weald of southern England. Pronounced modes appear in one rock around 119 Ma, 160 Ma, 243 Ma and 309 Ma and in the other around 141 Ma, 175 Ma, 257 to 277 Ma and 394 to 453 Ma. The geological implications of these quite dissimilar zircon age spectra are discussed. It is concluded that they support the palaeogeographical models of Allen (1981) and indicate that the provenance of the first sample, from the Top Ashdown Sandstone member at Dallington in East Sussex, was almost entirely southerly, while that of the second, from the Netherside Sand member at Northchapel in West Sussex, was more varied, but predominantly westerly and northerly.

1. Introduction

The external detector fission track dating method can be used to date individual zircon crystals extracted from a sediment. Statistical evaluation of the individual zircon ages obtained from a detrital population may suggest connection with possible source areas and, thus, assist in palaeogeographic reconstruction. In this study the approach has been applied to zircons separated from samples of two Lower Cretaceous (Wealden) sandstones from Sussex in southern England, kindly made available by P. Allen of Reading University. Analysis of the measured zircon ages, with their estimated statistical errors, makes it possible to determine the probability of occurrence of crystals possessing ages within given intervals.

In his latest provincial model for the Wealden of southern England, Allen (1981) envisages a broad, shallow sedimentary basin bordered by tectonically active, block-faulted, source massifs. Internal tectonism of the same kind may have divided the basin into sub-basins at times. Upfaulting of the bordering massifs generated sandy outwash plains; downfaulting, with concomitant lessening of the relief contrast, led to the development of muddy lake–lagoon–bay environments. The clastic detritus was very largely derived from the erosion of outcrops of old sediments (with some volcanic horizons) underlying thick soils or directly exposed in deep river valleys within the massifs. The principal source areas of the Wealden sediments are thought to have been (i) Londinia to the north, exposing mostly Lower Palaeozoic, Old Red Sandstone, Lower Carboniferous and Upper Jurassic rocks, (ii) Armorica to the south, exposing Precambrian as well as extensive outcrops of Permo-Triassic and Jurassic rocks and (iii) Cornubia to the west, exposing a sequence of Carboniferous, Permo-Triassic and Upper Jurassic rocks. Further to the northwest, both Lower and Upper Palaeozoic rocks were exposed in Hibernia. At times, incursions of the Boreal Sea along the northwestern margin of Londinia may have brought into the Weald sediment ultimately derived from northern Britain and the northern North Sea area. Contemporaneous Lower Cretaceous volcanism is known to have occurred in the Channel Approaches and in the North Sea (Dixon, Fitton & Frost, 1981) and there may have been other nearby centres.

2. Experimental procedure

Zircons were separated from two crushed samples of Wealden sandstone using conventional panning, heavy liquid and magnetic techniques. Sample BK 1762 (5 kg) came from the Top Ashdown Sandstone member of the Ashdown Beds Formation, outcropping in a shaw east of Hoad's Wood, 1.2 km southwest of the parish church of Dallington in East Sussex (TQ 648185). The rock is lower Wealden, presumably early Valanginian, in age. The analysed material is part of a bulk sample (AWJ 54, locality 14 of Allen, 1947) collected and described by Allen (1949, 1959, 1981). A ferruginous sandstone of medium grade carrying reworked glauconite, it does not differ significantly from the description given by Allen in 1949.

Sample BK 1761 (2 kg) came from the Netherside

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Sand member of the Weald Clay Group 0.36 km east of Upper Diddesfold Farm, Northchapel, West Sussex (SU 945298). This horizon is upper Wealden, presumably Hauterivian or Barremian in age. The sampled rock is, again, a ferruginous sandstone of medium grade originally collected by Allen. Detrital tourmaline from this sandstone has been dated previously by the argon-40/argon-39 technique (see below and Allen, 1975, p. 430, sample no. S 8052).

The separated zircon crystals were mounted in FEP Teflon, polished and etched in KOH/NaOH eutectic melt at 230 °C for sufficient time to fully reveal the spontaneous fission tracks, usually between five and ten hours (Gleadow, Hurford & Quaife, 1976). The zircon mounts were then irradiated, each in close contact with a muscovite detector, in the thermal neutron facility J1 of the Herald reactor at Aldermaston, UK, following the procedures of Hurford & Gleadow (1977). The neutron fluence was monitored by cobalt activation wires, by the inclusion of the NBS dosimeter glass SRM 612, and on the first occasion by including a zircon age standard. After irradiation the external mica detectors were etched in 48% HF at 20 °C for 30 min, to fully reveal the neutron-induced tracks.

For a given crystal, tracks were counted over identical areas of the crystal and its mica detector, using a magnification of 1563 times, under oil immersion. Tracks were counted using a calibrated eyepiece graticule, selecting only zircons with well-etched faces parallel to the *c* crystallographic axis and possessing low bulk etch rates, the criteria being the visual appearance of the track and the presence of sharply etched polishing scratches with widths less than 1.5 μm. Gleadow & Lovering (1977) have demonstrated that for such crystals a geometry factor of 0.5 is valid for the ratio of track density on an external detector (2π) to the track density on an internal surface (4π). The spontaneous-to-induced track count ratio (N_s/N_i) was then available for each crystal, allowing its age to be estimated using the zeta calibration approach (Hurford & Green, 1981). Hurford & Green (1983) describe the repeated evaluation over seven years of a ζ factor for dosimeter glass SRM 612 using four zircons of known age. A grand weighted mean ζ_{612} value of 339 ± 10 (2σ) was derived and has been used in this study.

A probability distribution of the real age about an estimated age requires the use of a notional standard deviation (the 'conventional error' of Green, 1981) which is estimated from the radioactivity counts:

$$\text{s. d.} = T\sqrt{\left(\frac{1}{N_s}+\frac{1}{N_i}+\frac{1}{N_d}\right)}$$

where N_s, N_i and N_d are respectively the spontaneous, induced and SRM 612 detector counts and T is the estimated age. A computer was programmed to establish a normal distribution of probability density against age for each zircon, using an expression of the form

$$C = \frac{1}{\sqrt{(2\pi)}\sigma}\exp^{-}[(T-x)^2/2\sigma^2]$$

where σ is the notional s.d., calculated as above. The individual probability distributions were summed to form a weighted histogram for the whole zircon population, showing the probable frequency of occurrence of crystals within given age intervals. The form of such histograms is illustrated in Figures 1*a*, etc., to be discussed below.

3. Results

Ninety zircons were counted from sample BK 1762 and 44 from BK 1761, with the results set out in Tables 1 and 2. Figures 1 and 2 show the total histograms obtained from the computer analysis. Figures 1*a* and 2*a* represent the summation of the individual probability distributions for each zircon over the total number of zircons in the sample, applying the notional s.d. to each as described above. In Figures 1*b* and 2*b* the discrimination has been enhanced by halving each of the s.d.s. Figures 2*c* and 2*d* are repeats of Figure 2*a* and 2*b* but omitting ten crystals (marked 'e' in Table 2) which were slightly below the quality of etching which we would normally select for counting (as described above). The modes identified in the analyses, with the relative heights of their maxima, are set out in Table 3.

For BK 1762 Figure 1*a* indicates a concentration of ages around and below 163 Ma (late mid-Jurassic). The increased resolution of Figure 1*b* suggests a pronounced mode around 160 Ma and lesser modes around 119 Ma (mid Lower Cretaceous), 243 Ma (late Permian/early Triassic) and 309 Ma (late Carboniferous). There are also indications of older material, some perhaps going beyond 700 Ma (see Table 1, e.g. HS 14, HS 47, ZJ 21, ZL 13).

For BK 1761 Figure 2*a* indicates ages concentrated around 179 Ma (early mid Jurassic) and 253 Ma (Permian). The greater resolution of Figure 2*b* suggests that the main mode is a little lower (173 Ma) and the next most pronounced around and above 257 Ma, with another around 141 Ma (late Jurassic/earliest Cretaceous). There is also evidence of older material, between 393 and 475 Ma (Devonian to Ordovician) and some older than 500 Ma (see Table 2, e.g. AA 10, EE 6).

Figures 2*c* and 2*d* show the effect of omitting the ten slightly sub-quality crystals (which had been included in an effort to achieve an adequate sample in a rock with few good-quality zircons). The modes indicated by the increased resolution of Figure 2*d* are at 141 Ma, 175 Ma, 277 Ma (Lower Permian) and 398–453 Ma. Except that the 257 Ma mode now appears rather higher (277 Ma), the results from the two sizes of sample are substantially in agreement. The

Table 1. Results of fission track dating of detrital zircon grains extracted from a sample (BK 1762) of the Top Ashdown Sand

Crystal	N_s	N_i	Irradiation	$\rho_d/10^5$* (t cm^{-2})	Age (Ma)	s.d. (Ma)
HS 1	266	65	FTD 84	3.313 (2520)	226	32
HS 2	139	48	FTD 84	3.313 (2520)	161	27
HS 3	348	52	FTD 84	3.313 (2520)	365	55
HS 4	191	57	FTD 84	3.313 (2520)	185	28
HS 5	118	45	FTD 84	3.313 (2520)	146	26
HS 6	282	39	FTD 84	3.313 (2520)	394	68
HS 7	139	55	FTD 84	3.313 (2520)	140	23
HS 8	48	14	FTD 84	3.313 (2520)	190	58
HS 9	231	19	FTD 84	3.313 (2520)	649	155
HS 10	165	31	FTD 84	3.313 (2520)	292	57
HS 11	187	39	FTD 84	3.313 (2520)	264	47
HS 12	131	65	FTD 84	3.313 (2520)	112	17
HS 13	136	14	FTD 84	3.313 (2520)	524	147
HS 14	213	15	FTD 84	3.313 (2520)	752	201
HS 15	217	116	FTD 84	3.313 (2520)	104	12
HS 16	69	37	FTD 84	3.313 (2520)	104	21
HS 18	135	36	FTD 84	3.313 (2520)	207	39
HS 19	199	115	FTD 84	3.313 (2520)	96	11
HS 20	210	49	FTD 84	3.313 (2520)	236	38
HS 21	52	19	FTD 84	3.313 (2520)	152	41
HS 22	125	24	FTD 84	3.313 (2520)	286	64
HS 23	345	75	FTD 84	3.313 (2520)	253	33
HS 24	197	37	FTD 84	3.313 (2520)	292	53
HS 25	423	57	FTD 84	3.313 (2520)	404	58
HS 26	253	33	FTD 84	3.313 (2520)	417	78
HS 27	125	20	FTD 84	3.313 (2520)	342	83
HS 28	119	36	FTD 84	3.313 (2520)	183	35
HS 29	114	38	FTD 84	3.313 (2520)	166	31
HS 30	210	20	FTD 84	3.313 (2520)	564	132
HS 31	319	26	FTD 84	3.313 (2520)	655	134
HS 32	316	60	FTD 84	3.313 (2520)	289	41
HS 33	150	45	FTD 84	3.313 (2520)	184	32
HS 34	202	47	FTD 84	3.313 (2520)	237	39
HS 35	283	32	FTD 84	3.313 (2520)	478	90
HS 36	113	33	FTD 84	3.313 (2520)	189	38
HS 37	262	57	FTD 84	3.313 (2520)	253	37
HS 38	368	67	FTD 84	3.313 (2520)	301	40
HS 39	195	51	FTD 76	3.186 (2440)	203	32
HS 40	230	20	FTD 76	3.186 (2440)	593	139
HS 41	269	45	FTD 76	3.186 (2440)	315	51
HS 42	250	75	FTD 76	3.186 (2440)	178	24
HS 43	247	39	FTD 76	3.186 (2440)	333	58
HS 44	283	88	FTD 76	3.186 (2440)	171	21
HS 45	358	33	FTD 76	3.186 (2440)	561	103
HS 46	260	82	FTD 76	3.186 (2440)	169	22
HS 47	254	22	FTD 88	4.207 (2154)	775	173
HS 48	139	72	FTD 88	4.207 (2154)	136	20
HS 49	306	58	FTD 88	4.207 (2154)	366	53
HS 50	104	48	FTD 88	4.207 (2154)	153	27
HS 51	146	66	FTD 88	4.207 (2154)	156	23
HS 52	278	122	FTD 88	4.207 (2154)	160	18
HS 53	78	29	FTD 88	4.207 (2154)	189	41
HS 54	174	38	FTD 88	4.207 (2154)	318	57
HS 56	231	48	FTD 88	4.207 (2154)	334	54
HS 57	119	58	FTD 88	4.207 (2154)	145	23
HS 58	176	84	FTD 88	4.207 (2154)	148	20
HS 59	127	81	FTD 88	4.207 (2154)	111	16
HS 60	258	149	FTD 88	4.207 (2154)	122	13
ZA 3	113	22	FTD 111	5.17† (700)	435	103
ZA 7	191	66	FTD 111	5.17† (700)	249	37
ZA 10	116	19	FTD 111	5.17† (700)	514	129
ZA 11	88	42	FTD 111	5.17† (700)	181	35
ZA 14	188	41	FTD 111	5.17† (700)	390	69
ZB 4	191	175	FTD 111	5.17† (700)	95	11
ZB 6	238	86	FTD 111	5.17† (700)	238	31
ZB 7	83	30	FTD 111	5.17† (700)	238	51
ZB 16	169	71	FTD 111	5.17† (700)	205	30
ZB 19	191	140	FTD 111	5.17† (700)	118	14
ZB 29	437	114	FTD 111	5.17† (700)	327	37
ZD 13	194	16	FTD 104	3.20 (662)	626	165
ZE 1	137	38	FTD 104	3.20 (662)	193	36
ZE 7	156	38	FTD 104	3.20 (662)	219	40

Table 1. (cont.)

Crystal	N_s	N_i	Irradiation	$\rho_d/10^5$* (t cm^{-2})	Age (Ma)	s.d. (Ma)
ZE 8	313	111	FTD 104	3.20 (662)	151	18
ZE 10	103	34	FTD 104	3.20 (662)	162	33
ZE 14	211	71	FTD 104	3.20 (662)	159	23
ZI 2	556	110	FTD 104	3.20 (662)	268	30
ZI 16	106	53	FTD 104	3.20 (662)	108	19
ZJ 1	184	87	FTD 111	5.17† (700)	183	25
ZJ 13	528	186	FTD 111	5.17† (700)	244	23
ZJ 21	195	20	FTD 111	5.17† (700)	802	191
ZJ 26	84	20	FTD 111	5.17† (700)	358	90
ZJ 27	102	33	FTD 111	5.17† (700)	265	54
ZJ 44	85	66	FTD 111	5.17† (700)	112	19
ZL 4	145	20	FTD 111	5.17† (700)	605	146
ZL 10	160	111	FTD 111	5.17† (700)	125	16
ZL 12	168	30	FTD 111	5.17† (700)	473	95
ZL 13	232	21	FTD 111	5.17† (700)	902	203
ZL 14	125	50	FTD 111	5.17† (700)	215	37
ZL 16	84	22	FTD 111	5.17† (700)	326	79
ZL 28	152	101	FTD 111	5.17† (700)	131	17

* ρ_d is the detector track density from the glass standard dosimeter (tracks per cm^2). No. of tracks counted shown in brackets.

† Inferred notional value obtained by including zircons HS 23–28 in the irradiation as a standard and comparing with ρ_d for SRM 612 in irradiation FTD 84.

Table 2. Results of fission track dating of detrital zircon grains extracted from a sample (BK 1761) of the Netherside Sand

Crystal	N_s	N_i	Irradiation	$\rho_d/10^5$* (t cm^{-2})	Age (Ma)	s.d. (Ma)
AA 1	138	41	FTD 111	5.17† (700)	288	52
AA 2	446	86	FTD 111	5.17† (700)	439	54
AA 3	169	71	FTD 111	5.17† (700)	205	30
AA 4	144	25	FTD 111	5.17† (700)	486	107
AA 5	104	34	FTD 111	5.17† (700)	263	53
AA 6	179	53	FTD 111	5.17† (700)	289	47
AA 9	274	85	FTD 111	5.17† (700)	276	36
AA 10	154	22	FTD 111	5.17† (700)	586	135
AA 16	404	70	FTD 111	5.17† (700)	487	66
AA 17	168	31	FTD 111	5.17† (700)	458	91
AA 18	222	60	FTD 111	5.17† (700)	316	48e
AA 20	114	81	FTD 111	5.17† (700)	122	18e
BB 6	300	67	FTD 111	5.17† (700)	381	53
BB 16	218	61	FTD 111	5.17† (700)	301	45
BB 21	266	58	FTD 111	5.17† (700)	390	58
BB 25	266	133	FTD 111	5.17† (700)	173	19
CC 1	270	107	FTD 110	6.70 (1394)	280	33
CC 4	116	40	FTD 110	6.70 (1394)	321	60
CC 24	383	169	FTD 110	6.70 (1394)	252	24
CC 25	309	173	FTD 110	6.70 (1394)	200	20
DD 2	228	102	FTD 110	6.70 (1394)	249	30
DD 7	81	40	FTD 110	6.70 (1394)	226	44e
DD 8	67	52	FTD 110	6.70 (1394)	145	27
DD 9	94	34	FTD 110	6.70 (1394)	307	62e
DD 11	85	21	FTD 110	6.70 (1394)	444	109
DD 12	96	40	FTD 110	6.70 (1394)	267	51e
DD 13	214	45	FTD 110	6.70 (1394)	519	86
EE 2	239	155	FTD 110	6.70 (1394)	173	18
EE 5	369	232	FTD 110	6.70 (1394)	178	16
EE 6	178	35	FTD 110	6.70 (1394)	553	103
FF 10	236	192	FTD 110	6.70 (1394)	138	14
FF 20	355	180	FTD 110	6.70 (1394)	220	21
FF 23	92	67	FTD 110	6.70 (1394)	154	25
GG 3	184	69	FTD 116	5.38 (1119)	239	34e
GG 4	149	40	FTD 116	5.38 (1119)	331	60
GG 5	130	43	FTD 116	5.38 (1119)	270	48
GG 6	129	66	FTD 116	5.38 (1119)	176	27
GG 9	80	18	FTD 116	5.38 (1119)	393	103
GG 10	58	33	FTD 116	5.38 (1119)	158	35
GG 13	51	26	FTD 116	5.38 (1119)	176	43
GG 16	102	57	FTD 116	5.38 (1119)	161	27e
GG 17	130	38	FTD 116	5.38 (1119)	305	57e
GG 19	143	50	FTD 116	5.38 (1119)	256	43e
GG 20	112	44	FTD 116	5.38 (1119)	228	41e

* ρ_d is the detector track density from the standard glass dosimeter (tracks per cm^2). No. of tracks counted shown in brackets.

† See footnote to Table 1.

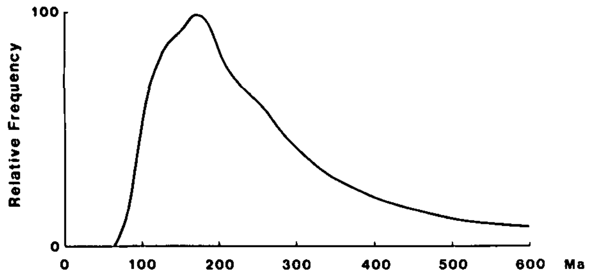

Fig. 1a

Figure 1*a*. Frequency distribution BK 1762, 90 crystals. Peak at 163 Ma.

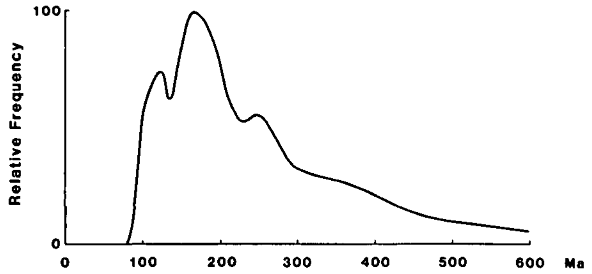

Fig. 1b

Figure 1*b*. As Figure 1*a* but s.d. multiplied by 0.5. Peaks at 119, 160, 243, 309* Ma. *Maximum not well defined.

findings from Figures 1 and 2 are set out in summary form in Table 3.

4. Geochronometric discussion

The computer analysis was aimed at extracting the greatest amount of information available, in the form of a most likely identification of any groupings of ages of the zircons in the sandstone. It became apparent that the most secure statistical approach was to aim at a large size of sample. This was achieved for BK 1762, but for BK 1761 the sample is limited by the scarcity of zircons of adequate quality. The results for the latter rock must therefore be considered more tentative than those for BK 1762.

The strongest indications of ages of source material are, for BK 1762 around 160 Ma (late mid Jurassic), and for BK 1761 around 175 Ma (early mid Jurassic) and 257–277 Ma (Permian). Both rocks show evidence of older material, and (in the case of BK 1762) some younger material encroaching near to or below the accepted age of early Wealden sedimentation. The oldest ages suggest a wide range of possible origin for some of the zircons. The very youngest ages are more difficult to explain. They may indicate that some zircons were inadequately etched despite the care that was taken. There is no reason to suspect contamination at any stage.

5. Palaeogeographical discussion

In the Weald of southern England, Allen (1975, 1981) suggests that two episodes of major fan-building produced the Ashdown and Lower Tunbridge Wells sandy outwash plains in the Lower Cretaceous. During both episodes, outwash spreading south from Londinia encountered and intermingled with similar deposits building north from Armorica. Allen's interpretation is based upon a careful study of the larger clasts and mineral suites contained in these rocks. For example, he finds that in Lower Wealden times sandy detritus

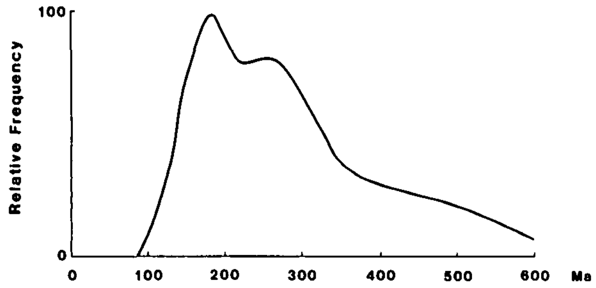

Fig. 2a

Figure 2*a*. Frequency distribution BK 1761, 44 crystals. Peaks at 179, 253 Ma.

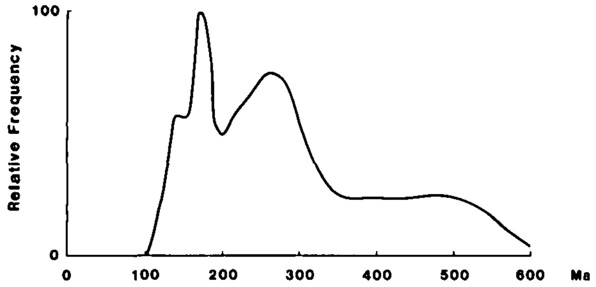

Fig. 2b

Figure 2*b*. As figure 2*a* but s.d. multiplied by 0.5. Peaks at 141, 173, 257, 393*–475* Ma. *Maximum not well defined.

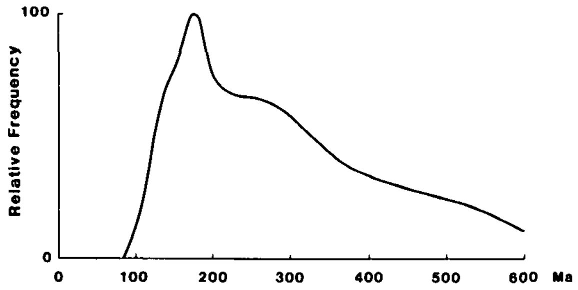

Fig. 2c

Figure 2*c*. Frequency distribution BK 1761, 34 crystals. Peaks at 177, 259 Ma.

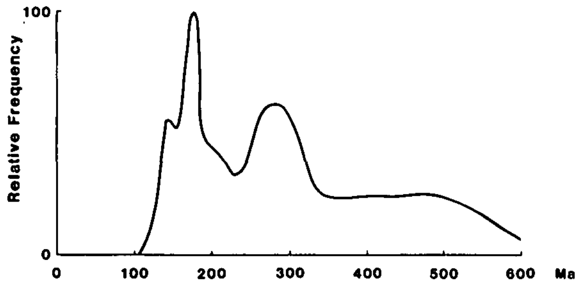

Fig. 2d

Figure 2*d*. As Figure 2*c* but s.d. multiplied by 0.5. Peaks at 141, 175, 277, 398*–453* Ma. *Maximum not well defined.

Table 3. Frequency modes indicated by the histograms

Rock	No. of zircons	s.d. multiplier	See Fig.:	Age frequency modes (Ma) (relative heights of maxima in parentheses			
BK 1762	90	1	1*a*	—	163	—	—
BK 1762	90	0.5	1*b*	119	160	243	309*
				(74)	(100)	(56)	(36)
BK 1761	44	1	2*a*	—	179	253	—
				—	(100)	(86)	—
BK 1761	44	0.5	2*b*	141	173	257	393*–475*
				(59)	(100)	(77)	(22, 25)
BK 1761	34	1	2*c*	—	177	259	—
				—	(100)	(68)	—
BK 1761	34	0.5	2*d*	141	175	277	398*–453*
				(58)	(100)	(63)	(24, 25)

Relative heights of maxima are in terms of largest = 100.
* Maximum not well defined, see Figures.

with high staurolite/kyanite ratios, indicative of high-grade metamorphic source rocks, entered southern England from the south but is confined to Sussex. Other lines of evidence include the petrography of the larger clasts and the argon-40/argon-39 ages of detrital tourmaline and other minerals (Allen, 1949, 1972, 1975, 1981).

A stratigraphical comparison between the age distribution of detrital zircons in the two Wealden sandstone samples we examined is given in Table 4. Zircon is a common accessory mineral in many volcanic and plutonic igneous rocks and in some metamorphic rocks. It is a resistant mineral during denudation. Thus detrital zircon is also common and may be reworked through many sedimentary cycles. Numerous reworked zircon grains are likely to be present in our samples. Nevertheless, it is most probable that the principal modal concentrations in the zircon age spectra represent either direct derivation from rock outcrops of the appropriate ages or reworking through intermediate sediments outcropping on *approximately* the same azimuth as the ultimate source rocks. Thus, taking into consideration the known Upper Palaeozoic and Mesozoic geology of western Europe, it would be reasonable to expect that outcrops of penecontemporaneous Lower Cretaceous, late mid Jurassic, late Permian/early Triassic and late Carboniferous rocks were important in the derivation of the Top Ashdown Sandstone sample and that, in addition, small areas of older Palaeozoic and Precambrian rocks might have been exposed at this time. Alternatively, some or all of these recognizable zircon age groups could have been concentrated in, and then reworked from, sedimentary rocks of intermediate age and location outcropping in the source massifs during lower Wealden times. The absence of prominent concentrations of zircons of late Jurassic/early Cretaceous, Lower Permian or Caledonian age is also important in characterizing the provenance of this rock.

The necessary combination of primary and/or secondary source outcrops to provide the zircon age distribution found in the Top Ashdown Sandstone was not present in the Londinia massif in early Wealden times because Permo-Trias, Lower and Middle Jurassic strata and Variscan granites must be virtually absent from the Londinian succession. To the south and southeast, however, rocks of the required ages are present, either in Armorica or beyond. Mid Jurassic volcanoes have been reported in the Massif Central and extensive late Permian/early Triassic volcanics occur in Aquitaine, Biscay and Iberia (Carte géologique

Table 4. Stratigraphical comparison between the age distribution of detrital zircons in the two samples of Lower Cretaceous sandstones (see Figures 1*b* and 2*d*)

	BK 1762 Dallington	BK 1761 Netherside
mid Lower Cretaceous	peak	trough
late Jurassic/earliest Cretaceous	trough	peak
mid Upper Jurassic		trough
late mid Jurassic	major peak	
early mid Jurassic		major peak
late Triassic/earliest Jurassic	trough	
early Upper Triassic		trough
late Permian/early Triassic	peak	
Lower Permian	trough	peak
late Carboniferous	peak	
early Carboniferous		trough
Caledonian		peak
Precambrian	present	present

de la France et de la marge continentale, 1980). Suitable late Carboniferous, older Palaeozoic and Precambrian source rocks outcrop in Armorica itself. Whilst the younger zircons are almost certainly derived from volcanics and their associated intrusions, the late Carboniferous zircons are more likely to have their main source in the granites and related post-orogenic intrusions of the Armorican sector of the Variscan fold belt (granites, mostly between 300 and 330 Ma, Chauris *et al.* 1956; Graindor & Wasserburg, 1962; Leutwein *et al.* 1969; and lamprophyres, around 300 Ma, e.g. Lees, 1974). The actual source volcanoes from which the Lower Cretaceous zircons were derived are as yet unknown, but explosive eruptions from volcanoes in the Channel Approaches may have spread ash over wide areas (Jeans *et al.* 1982). (Lower Cretaceous volcanism is also known in the northern North Sea, see Dixon, Fitton & Frost 1981.)

The Bathonian Fuller's Earth of southern Britain is not regarded as a probable source of the large population of mid Jurassic zircons in the Top Ashdown sample because at its present outcrops it is almost free of zircon (R. J. Merriman pers. comm., and our own observations) and was probably poorly exposed in early Wealden times. Major occurrences of mid Jurassic basic volcanism (with ages around 165 Ma) are known in both the Celtic and North Sea areas (Howitt, Aston & Jaque, 1975; Woodhall & Knox, 1979; Harrison *et al.* 1979, Dixon, Fitton & Frost, 1981) and the possibility that zircons of this age were introduced into the Weald from either Londinia or Armorica after reworking from Upper Jurassic sandstones cannot be ignored entirely. If, however, part or all of the late mid Jurassic zircon component of the Top Ashdown Sandstone was derived from either the north or west, it is puzzling that there is no evidence of late Jurassic/early Cretaceous (probably derived from the southern North Sea), Lower Permian (from Cornubia) and broadly Caledonian zircon components, all of which appear in the Netherside Sand sample. Thus, it would appear that examination of the age spectrum of the detrital zircon population of the Top Ashdown Sandstone sample does provide strong confirmatory evidence of Allen's southerly derivation for much, if not all, of its clastic detritus.

In later Wealden times in the western Weald, environmental conditions were such as to make deposition predominantly argillaceous. Short-lived arenaceous incursions did occur, however, and the Netherside Sand is one of several such intercalations within the Weald Clay Group. Allen (1981) demonstrated the appearance of a major detrital component derived from Cornubia in these sands, and a less important component that appears to have been brought in from the north along the northwestern shoreline of Londinia by invasions of the Boreal Sea. Armorican debris seems totally absent. Argon-40/argon-39 ages of 258 ± 11, 207 ± 16 or 237 ± 11 and > 372 ± 40 Ma obtained from detrital tourmaline (Allen, 1975) indicate a combination of Permo-Triassic and late Caledonian source rocks.

The zircon age spectrum of our Netherside Sand sample is quite different from that of the Top Ashdown Sandstone: it suggests either that extensive outcrops of late Jurassic/early Cretaceous, early mid Jurassic and early Permian volcanics are likely to have been present in its source areas or that zircons derived from them have been reworked from intermediate sediments. Zircons derived from the Caledonian fold belt are an important minor component. Precambrian zircons derived either directly or by reworking are also present as a minor component. Whilst early Permian volcanism is known in Cornubia (Exeter volcanics) (Tidmarsh, 1932; Miller, Shibata & Munro, 1962; Miller & Mohr, 1964) and volcanic clasts in the Lower Permian breccias and conglomerates of Devon (see Hatch, Wells & Wells, 1961, p. 484; Laming, 1966; Cosgrove & Elliott, 1976), neither mid nor late Jurassic volcanism has been recorded there. The source vents from which the Bathonian Fuller's Earth was erupted are unknown. The mid Jurassic zircons in our sample could have the same derivation. Nevertheless, it is still possible that many of the Jurassic and older zircons in the Netherside Sand were derived ultimately from further afield, either from the northern North Sea and from Caledonian Britain via the agency of the arm of the Boreal Sea, or from volcanism occurring in the Fastnet/Channel Approaches area or from as far away as the Mid Atlantic Rift. Possible source volcanics of Lower Permian and Mid Jurassic ages are widespread in the North Sea (Dixon, Fitton & Frost, 1981), but we have seen no reports of volcanism of late Jurassic/earliest Cretaceous age from the northern North Sea. Jurassic volcanism occurred frequently along the Mid Atlantic Rift zone. The Zuidwal volcano in Holland is 144 Ma old (Dixon, Fitton & Frost, 1981) and ashes of this age could have been reworked from Londinia and elsewhere in the north to provide a zircon component around that age consistent with our 141 Ma peak. Thus, it would appear that the zircon age spectrum of the Netherside Sand probably indicates a combination of Cornubian, Londinian and more distant westerly and/or northerly provenance. The indications of southerly provenance, so clearly seen in the Top Ashdown Sandstone, are totally absent. The palaeogeographical conclusions outlined above are compatible with the model proposed by Allen (1981).

6. Conclusions

Fission track ages were obtained from the individual detrital zircon crystals in the heavy mineral concentrates extracted from two Lower Cretaceous sandstones occurring in the Weald of England. The distribution of ages within the two populations was analysed taking into account the estimated uncertainty of each individual age determination. The Top Ashdown Sandstone sample (BK 1762) shows a marked concentration of zircon ages around 160 Ma (late Middle Jurassic) and lesser concentrations at both younger (119 Ma) and older ages (243 Ma and 309 Ma). These zircon concentrations can be compared with the groupings of ages in figure 10 of Allen, 1981, around 155 Ma, 230 Ma and 315 Ma. The contrast in relative abundance between Variscan and mid Jurassic ages in the two samples presumably results from the virtual absence of tourmaline in the mid Jurassic volcanic source rocks. Much older, often metamict, zircons are also present. The oldest datable crystal had an apparent age of 902 ± 203 Ma. This compares well with the two oldest (tourmaline) dates in figure 10 of Allen, 1981, one of which, from the top Lower Tunbridge Wells Pebble Bed, was 918 ± 83 Ma (Allen, 1975, p. 430). The distribution of zircon fission track ages from the Netherside Sand sample (BK 1761) on the other hand shows (slightly less certain) peak concentrations around 175 Ma (early mid Jurassic) and 257–277 Ma (Lower Permian) with lesser concentrations around 141 Ma (late Jurassic/earliest Cretaceous) and between 398 and 453 Ma (Caledonian). Older and metamict zircons are present also in this rock.

As would be expected, the results obtained above show that the detrital zircons in these two Lower Cretaceous sandstones range from Mesozoic to Precambrian age. Nevertheless, it seems clear that, at the localities sampled, each horizon shows a quite different and distinct spectrum of zircon ages. Although much further work remains to be done, the results of this pilot study do prompt the suggestion that fission-track age spectra obtained from one or more of their detrital mineral populations may enable the characterization of individual sediments in a way that will prove useful for correlation purposes. The spectrum obtained from any rock that has not undergone post-depositional heating (due to deep burial or metamorphism) of sufficient intensity and duration to cause the annealing of fission tracks in its constituent mineral must be related directly to the provenance of the clastic detritus. The Wealden of southern England meets these requirements. It appears never to have been buried to more than 2 km: its cover probably never exceeded 1.5 km (Allen, 1981).

Thus, the zircon age spectra of the two rocks sampled can be used to show that (i) the source of the clastic detritus in the Top Ashdown Sandstone sample from Dallington was very largely to the south and southwest, in Armorica and beyond, and (ii) the provenance of the Netherside Sand sample from Northchapel is to be found in a mixture of westerly (Cornubian or even further afield) and northerly (northern Britain, the North Sea and/or Londinian) sources, thus supporting Allen's suggestions in 1975 and 1981.

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