DATING THE TIME OF MOVEMENT OF FAULTS IN THE COAL MEASURES OF THE EAST MIDLANDS

by

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Summary

Potassium-argon dating studies of the time of fault movement, using fault gouge clay samples, suggested that geochronological information relating to dynamic metamorphism was not detectable, because the potassium-argon 'time-clock" involving argon loss had not been reset by frictional heat when a fault moved. By a delicate experimental technique which separated the samples into cleaned size-fractionated aliquots, followed by a graphical isochron method of data treatment, the date at which sedimentary diagenesis involving potassium fixation took place was determined.

Introduction

A geochronological investigation into the time of fault movement in Coal Measure strata was undertaken as part of a National Coal Board sponsored research project. The initial aim of the project was to investigate the hypothesis that by dating fault gouges it may be possible to differentiate pre-Permian from Permian and reactivated faults. This line of research was considered worth-while because the Permian is water-bearing, and if underground workings intersected a fault plane which cut the Permian aquifers, then the water could percolate into the mine workings via the fault plane, as in the Lofthouse Mine flooding when workings penetrated an old mine shaft (Calder, 1973).

It was envisaged that the formation of the fault gouge, during a dynamic metamorphic event, would have resulted in the cumulative potassium-argon 'time-clock" being completely reset by the release of pre-existing argon due to the frictional heat produced at that time. Subsequently argon would continue to be produced by the natural decay of the potassium-40 present in the clay minerals of the gouge. Radiogenic decay in the gouge would thus provide a potassium-argon date relating to the time of resetting of the potassium-argon "time-clock" by dynamic metamorphism.

Fault gouge sample collection

Sampling localities in the East Midlands Coalfield were selected by the use of colliery development plans at the Regional Offices of the National Coal Board. The majority of modern workings in the East Midlands Coalfield have been designed to avoid major faults and in most of the older workings where suitable areas had once been exposed, faults were now inaccessible due to flooding, or lack of ventilation in the roadway in question.

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There were additional problems associated with the collection of samples in accessible roadways where faults were known to occur. Not only were the faulted areas weak ground, and thus, for safety reasons, the most heavily reinforced and covered, but often the faults consisted of a zone of shattered shale, rather than a distinct fault plane with a parting of clay gouge. Only samples of true clay gouge were considered suitable for further analysis.

A further problem was encountered occasionally in the form of small faults which were drawn on the plans, but which, did not exist. The addition of these "bogus" faults to the mine plans in the days of private ownership was a common ruse for the non-payment of the full amount of royalties, that is, the faulted coal was taken tax-free. An example of such a non-existent 3.6 m fault is to be found on the Deep Hard plans of Glapwell Colliery. (SK 468669).

Despite the above difficulties 36 good clay gouges were collected from localities in the East Midlands Coalfield. (Table 1).

Initial potassium-argon dating of the fault gouges

Method

Clay, less than 2 μm in size, from the gouges was analysed for potassium using an Eel 450 Flame Photometer. The instrument underwent regular calibrations against laboratory standards in turn routinely checked with a known reference standard ('Biotite 133'). Argon was analysed in a mass spectrometer after the addition of a "spike" volume of argon-38. (Dalrymple & Lanphere, 1969). Calculations were made using the standard age equations (Aldrich & Wetherill, 1958). The data from the analyses are presented in Table 2.

Discussion of the initial potassium-argon dates

All the dates obtained from the analyses of the clay gouges were between 413 ± 5 Ma and 322 ± 4 Ma. The average result of the 36 analyses was 382 ± 5 Ma. It was apparent that the majority of the chronological information had to be reconsidered in terms of the age of the faults which cut Coal Measures strata. Few of the dates could bear a resemblance to the time of faulting, as the ages obtained were observed to be older than the chronological dates of the sedimentary rocks that the fault planes intersected.

In view of the results in Table 2, it seemed likely that the initial basic premise that the potassium-argon "time-clock" in the clay gouge could have been completely reset, either during the initial formation of the gouge, or during subsequent fault movement, was unfounded.

The second attempt to date fault movement

In view of the foregoing results, the basic premise that the potassium-argon 'time-clock" was completely reset during fault movement was modified. It was suspected that the chronological information present in Table 2 was the result of a 'memory" inherited from the original source area for the sediment from which the fault gouge had been generated, that is, a 'memory" of the Caledonian orogeny was present in the gouge, since the sedimentary particles had been derived from Lower Paleozoic outcrops.

The variation in the data from the East Midlands suggested that the calculated dates could possibly be considered to be the result of a mixture of material, which thus resulted in a mixture of ages, that is, a mixture of orogenic material, with orogenic dates, plus an element of younger chronological information. It was suspected that some of the clay fraction included particles, which despite their small size, were still too large for their isotopic "clocks" to have been completely reset during fault movement. A more delicate clay separation technique on the gouge material was devised in order to separate a sample which contain only particles small enough to have been completely reset by argon loss during dynamic metamorphism, and which would have no 'inherited memory".

Table 1: Sample Data for Selected Faults in the East Midlands

Sample	Colliery	Grid Reference	National Coal Board Reference	Throw m
K5	Cotgrave	SK 630 361	463 040/336 102	12
K8	Wrange Farm, nr. Chesterfield	SK 427 689	442 722/368 900	20.0
K10	Wrange Farm, nr. Chesterfield	SK 428 687	442 827/368 674	0.6
K12	Pit Houses, nr. Dronfield	SK 460 333	446 014/383 308	7.6
K16	Pit Houses, nr. Dronfield	SK 462 834	446 165/383 415	10.7
K21	Renishaw Park	SK 467 785	446 705/378 468	0.9
K22	Renishaw Park	SK 467 785	446 700/378 478	61
K23	Babbington	SK 533 436	453 250/343 614	73.2
K24	Babbington	SK 532 436	453 150/343 626	73.2
K26	Moorgreen	SK 501 491	450 120/349 105	9.1
K30	Newstead	SK 509 538	450 936/353 795	7.2
K33	Bentink	SK 488 543	448 765/354 812	6.4
K35	Cotgrave	SK 647 354	464 674/335 408	30.8
K37	Cotgrave	SK 645 345	464 488/334 450	4.9
K38	Bevercotes	SK 677 689	467 724/468 850	45.7
K39	Bevercotes	SK 700 735	470 020/373 543	62.5
K40	Thorsby	SK 664 727	466 427/372 686	12.2
K41	Thorsby	SK 629 671	462 888/367 121	9.1
K42	Thorsby	SK 628 673	462 785/367 320	11.0
K43	Pit Houses, nr. Dronfield	SK 461 834	446 122/383 410	10.7
K48	Whitwell	SK 539 753	453 876/375 260	27.4
K52	Blidworth	SK 636 556	463 581/355 634	11.0
K54	Warsop Main	SK 553 653	455 300/365 273	3.4
K56	Warsop Main	SK 551 656	455 111/365 684	7.6
K58	Warsop Main	SK 544 677	454 360/367 676	3.0
K60	Glapwell, nr. Chesterfield	SK 479 669	447 884/366 910	7.6
K64	Renishaw Park	SK 433 757	443 274/375 744	39.6
K68	Langwith	SK 540 718	454 030/371 780	6.1
K71	Markham (Derbys.)	SK 473 694	447 252/269 388	3.8
K72	Markham (Derbys.)	SK 467 697	446 728/369 700	6.1
K73	Markham (Derbys.)	SK 448 717	444 834/371 713	16.5
K74	Markham (Derbys.)	SK 448 719	444 760/371 888	2.1
K75	Clipstone	SK 578 635	457 749/363 465	4.3
K77	Creswell	SK 511 727	451 079/372 680	3.0
K78	Creswell	SK 605 722	450 644/372 225	33.5

Nevertheless, rather than obtain age data from the very finest of clays only (say 0.5 μm or less) the larger size clay fractions were analysed as well, in order to gain age information relating to the possible maximum size of particles which, according to the working hypothesis, should have possessed no "memory" inherited prior to the formation of the fault gouge.

Size fractionation of selected fault gouge samples

Three samples from the East Midlands were selected for size fractionation and analysis (K8, K10 and K24). These were selected in order to give as wide a range of fault types as possible.

Table 2: Potassium-Argon Fault Gouge Analyses

Sample Number	$\frac{v}{m} \times 10^{-2}$ $mm^3\,gm^{-1}$	K_2O %	% Atmos	"g"	Age (Ma)
K5	5.9803	4.42	16.1	.01354	370 ± 5
K8	3.4414	2.25	21.4	.01529	413 ± 5
K10	6.0360	4.13	13.2	.01462	397 ± 5
K12	4.4479	2.93	17.9	.01629	413 ± 5
K16	6.2075	4.36	16.1	.01423	388 ± 5
K21	6.3213	4.52	10.1	.01398	381 ± 5
K22	4.1722	3.01	12.4	.01386	378 ± 5
K23	3.6991	2.91	5.1	.01271	350 ± 5
K24	3.3418	2.48	7.9	.01348	369 ± 5
K26	6.3965	4.72	11.2	.01355	371 ± 5
K27	5.2228	3.66	17.1	.01427	389 ± 5
K30	4.2353	3.56	22.3	.01189	329 ± 4
K33	5.3434	3.73	15.4	.01433	390 ± 5
K35	5.8632	4.13	15.2	.01419	387 ± 5
K37	5.6662	4.27	15.5	.01326	364 ± 5
K38	5.5524	3.84	15.9	.01438	391 ± 5
K39	5.3320	3.71	14.5	.01437	391 ± 5
K40	5.5753	4.19	12.2	.01330	365 ± 5
K41	2.9914	2.01	22.5	.01488	403 ± 5
K42	4.1722	2.97	21.5	.01404	383 ± 5
K43	3.5562	2.59	21.9	.01373	375 ± 5
K48	5.7952	4.31	16.9	.01345	368 ± 5
K52	5.6308	4.05	17.2	.01390	379 ± 5
K54	6.1322	4.16	17.3	.01474	400 ± 5
K56	5.3032	3.84	14.2	.01381	377 ± 5
K58	6.6129	5.02	14.3	.01317	361 ± 5
K60	3.7483	3.23	23.2	.01160	322 ± 4
K64	5.6526	4.07	13.1	.01389	379 ± 5
K68	5.2942	3.79	17.0	.01397	381 ± 5
K71	4.6052	3.14	23.2	.01466	398 ± 5
K72	5.8032	3.94	21.9	.01473	400 ± 5
K73	1.5514	1.15	34.0	.01349	369 ± 5
K74	4.8899	3.34	21.3	.01464	397 ± 5
K75	6.0458	4.39	12.5	.01377	376 ± 5
K77	4.7600	3.26	20.0	.01460	397 ± 5
K78	4.8449	3.26	14.7	.01486	403 ± 5

K8 was collected from a fault with a 20 m throw from Wrange Farm Opencast Site, nr. Chesterfield. It was considered to be a typical pre-Permian fault of more than average throw.

K10, a sample of gouge from a fault with a throw of only 0.6 m had field evidence to suggest that this was a typical depositional fault, formed during sedimentation. It was anticipated that the difference in the throw of these two faults would provide information relating to any dependence of the "time-clock" resetting upon the displacement of similarly aged faults.

K24, a fault gouge collected from the Cinderhill Fault, one of the small number of large displacement faults (73 m throw) in the East Midlands Coalfield. The Fault is an excellent example of a post-Permian reactivated fault and prior to the tipping of coal-waste from Babbington Colliery at the surface, a well marked Permian fault scarp could have been observed.

Size fractionation technique

The size fractionation procedure involved the separation of the samples into aliquots. The fractions used by the author are included as suffix letters of the samples where A = 100-30 μm, B = 30-7 μm, C = 7-2 μm, D = 2-1 μm, E = 1-0.5 μm, and F was less than 0.5 μm. The larger A and B fractions were allowed to settle through a column of distilled water (Jackson, 1956) and the supernatent liquid centrifuged at various speeds in order to precipitate the finer particles. The centrifuge times for the various sizes were calculated using a modified Stokes Law equation (Hathaway, 1955) substituting the experimentally determined acceleration and deceleration times of the centrifuge used. The experimental procedure was repeated many times for each fraction in order to wash each particular size fraction clean of any smaller particles.

These fractions are analysed by the same methods as those used for the initial samples.

Results from the size fractionated fault gouges

The results from the potassium-argon analyses are presented in Table 3. It may be observed that there is a variation in the calculated age with grain size, that is, the larger size fractions give older dates than the smaller sizes. These variations were found to be similar to the variations found in size-fractionated sediments (Langley, 1978) and to the results reported by workers in the Gulf Coast of Mexico (Burst, 1969; Perry, 1974; Perry & Hower, 1970, 1972; Aronson & Hower, 1976; Hower *et al.*, 1976, 1963; Hurley, *et al.*, 1961, 1963; Weaver & Wampler, 1957, 1970; Weaver, 1958, 1965, 1967), by Hofmann, Mahoney & Giletti (1974) working on Pennsylvanian clays and by Hurley, Heezen, Pinson & Fairbairn (1963) from pelagic sediments in the North Atlantic.

The calculated ages from the size-fractionated fault gouges vary from 436 ± 5 Ma (K8B) to 351 ± 5 Ma (K8F). Clearly these dates are older than the strata in which the faults are located. Thus, taken at face value, it appears that even the delicate size fractionation technique was unable to segregate isotopic data from any particles which might have undergone argon loss during the process of dynamic metamorphism. Also, it was of considerable interest to note that the dates from K24, the post-Permian reactivated fault differed little from the dates from the other, Carboniferous faults.

Table 3: Potassium-Argon Analyses of Size Fractionated Gouges, Isochron Data

Sample Number	Ar^{40} $\times 10^{-3}$ $mm^3\ gm^{-1}$	Ar^{36} $\times 10^{-3}$ $mm^3\ gm^{-1}$	K_2O %	% Atmos	$\frac{Ar^{40}}{Ar^{36}}$	$\frac{K_2O}{Ar^{36}}$	Calculated Age (Ma)
K8B	53.03	.0259	2.79	14.9	2047.5	107.7	436 ± 5
K8C	62.48	.0279	3.44	13.0	2239.4	123.3	426 ± 5
K8D	78.78	.0390	4.38	14.6	2020.0	112.3	415 ± 5
K8E	84.82	.0384	5.21	13.9	2208.9	135.7	382 ± 5
K8F	82.76	.0272	5.85	9.0	3042.6	215.1	351 ± 5
K10C	68.51	.0395	3.62	15.9	1734.4	91.7	429 ± 5
K10D	81.44	.0370	4.95	12.5	2201.1	133.8	399 ± 5
K10E	82.90	.0359	5.16	11.9	2309.2	143.7	387 ± 5
K10F	94.89	.0689	5.80	20.0	1377.2	84.2	366 ± 5
K24C	26.66	.0242	1.32	25.3	1101.7	54.6	408 ± 5
K24D	34.27	.0323	1.72	26.9	1061.0	53.3	396 ± 5
K24E	41.94	.0354	2.28	23.8	1184.8	64.4	382 ± 5
K24F	63.13	.0377	4.04	17.5	1674.5	107.2	354 ± 5

FIGURE A

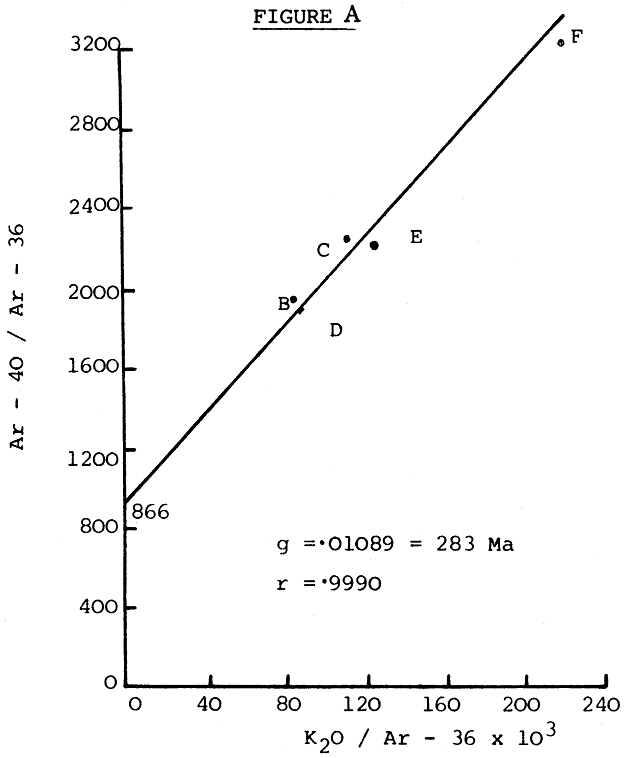


FIGURE B

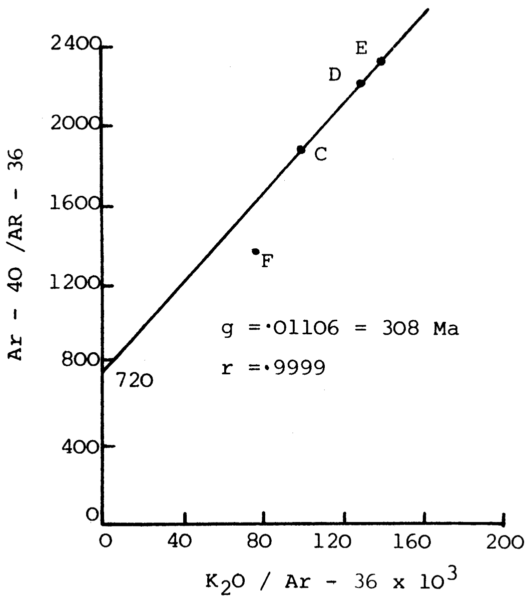
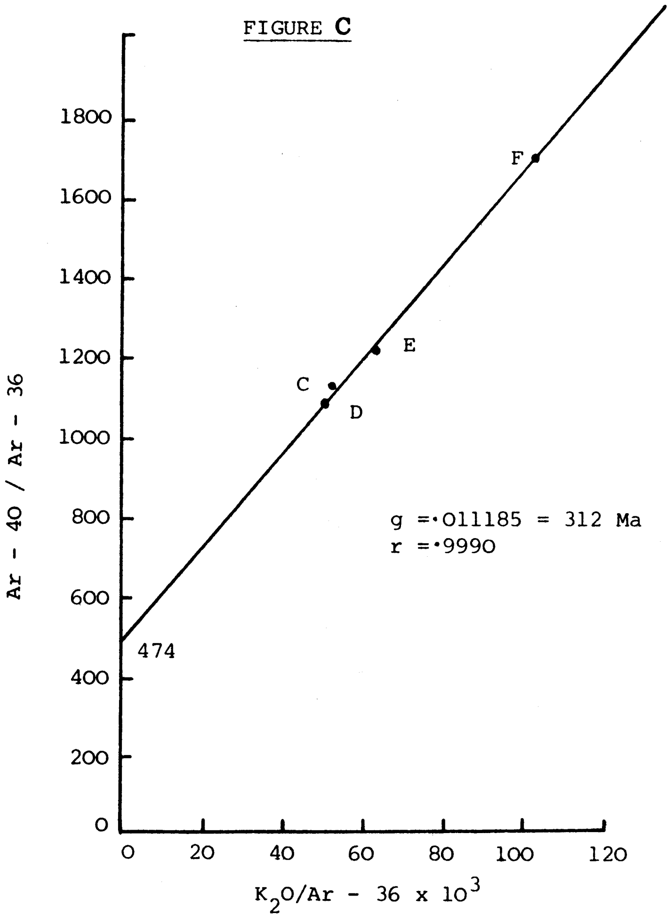


FIGURE C



Text-fig. 1: Potassium-argon isochron fault gouge

Fig. A - K8, a pre-Permian fault

Fig. B - K10, a small depositional Carboniferous fault

Fig. C - K24, the post-Permian reactivated Cinderhill fault

The isochron ages from the size fractionated fault gouges also show a marked resemblance to the isochron age from ordinary Carboniferous shale which had undergone the same analytical procedures as the fault gouges, that is, a date of 315 ± 8 Ma was obtained from Coal Measures shale, KS2, from Pit Houses Opencast Site, Derbyshire (SK 462833). (Langley, 1978).

The isochron method of data treatment

The "isochron" method of dating involves plotting a graph, Ar^{40}/Ar^{36} values against K_2O/Ar^{36} values. When joined the points form an "isochron" line, the gradient of which relates to the age of the material. This method has found application in igneous and metamorphic rocks which are thought to contain "excess" atmospheric argon of various types (Damon *et al.*, 1967). In cases where excess argon is present, the standard method of potassium-argon age calculation, which involves the use of the standard atmospheric ratio figure, normally taken to be 295.5 (Nier, 1950) is invalid (Hayatsu & Carmichael, 1970). However, the isochron method provides a way of dating which does not involve the use of this atmospheric ratio figure, and thus can be used for samples which contain excess or inherited argon relating to a previous orogenic potassium-argon "time-clock" setting events prior to weathering, transportation, deposition and/or dynamic metamorphism. Thus sedimentary or fault gouge material which contains inherited argon could be a candidate for treatment by the isochron method.

Results from the fault gouge isochrons

The isochron graphs are illustrated in text-fig. 1, A-C, for K8, K10 and K24 respectively. The dates calculated from these graphs are 283 ± 10 Ma for K8, 308 ± 6 Ma for K10 and 312 ± 6 Ma for K24. These isochron ages lie well within the expected age limits for Coal Measures strata, that is, 325 - 280 Ma. The Namurian/Viséan boundary was placed at 325 Ma on the basis of the 322 ± 12 Ma potassium-argon whole rock age obtained from the Lower Namurian Hillhouse Sill, Scotland (Francis & Woodland, 1964). A minimum potassium-argon age for the Upper Coal Measures of 308 ± 10 Ma was provided by the age of the Barrow Hill intrusion, Staffordshire, which cut sediments at the base of the Coal Measures (Fitch *et al.*, 1974). The Permo-Carboniferous boundary was placed at 280 Ma on the evidence of the 284 Ma age from metamorphosed Lower Permian Lava in the Oslo area of Norway, and Rb-Sr evidence on a number of dates from the Stephanian granites in France and Portugal (Francis & Woodland, 1964). Evidence from Britain relating to the Dartmoor granite confirmed a minimum age of 280 ± 5 Ma for the Permo-Carboniferous boundary (Kulp *et al.*, 1960).

Discussion of the isochron results

K24, the Cinderhill Fault sample is known to be a large fault, post-Permian reactivated, and yet the isochron, with a high correlation, provided a date of 312 ± 6 Ma. This age bears a close resemblance to the date obtained from a size-fractionated Coal Measures sediment, KS2, with an isochron date of 315 ± 5 Ma (Langley, 1978). These dates are too close to be the result of coincidence alone. If, however, the Cinderhill Fault gouge date related to the diagenetic age of the sediment from which the gouge was made, rather than to the time of a post-Permian reactivated fault movement, then it is apparent that, in this case, the fault movement has had little or no effect on the resetting of the potassium-argon cumulative "time-clock" during dynamic metamorphism. Fault movement produced a fault gouge, but it may be concluded that insufficient heat had been generated to reset the "time-clock" by argon loss.

K10, the small depositional fault, had an isochron date of 308 ± 6 Ma. The date, in this case, may be related to either diagenesis or fault movement. However, in consideration of the result from the much larger Cinderhill Fault, it seems that the age was more likely to be the time of potassium-fixation at diagenesis rather than fault movement. There was no reason why argon loss of a sufficient extent should have occurred in this small fault, and reset the potassium-argon "time-clock" when a fault gouge material from the larger fault (K24) was apparently unaffected.

K8 had an isochron date of 283 ± 10 Ma. Although this was a younger age than the two previous results, this still fell within the stratigraphical age range of the Coal Measures, and it seems very probable that this isochron date also relates to the time of diagenesis, rather than to the time of fault movement.

Conclusions

The initial method of dating bulk clay gouge produced only a mixture of ages which were "swamped" by the primary "time-clock" setting event which started prior to weathering, erosion and transportation of the sediment from which the fault gouge was made. The dates produced were thus Caledonian dates.

The geochronological information from the size-fractionated gouges showed a variation in age as had been observed from various sedimentary samples (Langley, 1978; Burst, 1969; Perry, 1974; Perry & Hower, 1970, 1972; Aronson & Hower, 1976; Hower *et al.*, (1963, 1967; Weaver & Wampler, 1957, 1970; Weaver, 1958, 1965, 1967; Hofmann, Mohoney & Giletti, 1974 Hurley, Heezen, Pinson & Fairbairn, 1963). Calculated dates from the delicately separated clay fractions gave only marginally more significant results than the bulk samples, in that all the fractions still gave calculated dates that were older than the stratigraphical ages of the faults.

When the data was treated by the graphical, or isochron method, the data was freed from the restraints due to the argon inherited from previous orogenic happenings. The isochron ages from the gradients of the graphs for the gouges all lay well within the expected age limits for the Coal Measures. However, the large Carboniferous and Permian Cinderhill Fault gave results which were not significantly different from the other smaller faults which were restricted to the Coal Measures strata. From the results, it was assumed that the Cinderhill Fault, with a 73 m throw had been unable to reset the "time-clock" in the fault gouge by dynamic metamorphism. Thus it was unlikely that the smaller faults would have been capable of such an isotopic event. Therefore it may be concluded that, if even large faults are incapable of producing enough frictional heat to cause argon loss, it is unlikely that smaller faults are capable of such an event. Alternatively any heat generated when a fault moves might be dissipated so quickly that the effect would be insignificant isotopically.

The chronological resemblance of the isochron ages from the fault gouges with the stratigraphical age of the strata from which the faults cut cannot be overlooked. As it was unlikely to be the result of mere coincidence that the dates fell within the 325-280 Ma age range of the Coal Measures strata, it is suggested that the dates obtained from the fault gouge isochrons related to a potassium fixation event which took place during the diagenesis of the sediment from which the clay gouge was made, and that it was this isotopic event which was detected by the isochron method of data treatment of the size-fractionated samples.

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