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Confined fission track lengths in apatite: a diagnostic tool for thermal history analysis

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Abstract. Fission-track ages in apatite are generally accepted as giving a measure of the time over which a sample has been exposed to temperatures below approximately 100° C. A compilation of the lengths of confined fission tracks in a wide variety of apatites from different geological environments has shown that the distribution of confined track lengths can provide unique thermal history information in the temperature range below about 150° C over times of the order of 10^6 to 10^9 years. The distribution of confined lengths of freshly produced induced tracks is characterised by a narrow, symmetrical distribution with a mean length of around 16.3 μm and a standard deviation of the distribution of approximately 0.9 μm. In volcanic and related rocks which have cooled very rapidly, and never been reheated above about 50° C, the distribution is also narrow and symmetric, but with a shorter mean of 14.5 to 15 μm, and a standard deviation of the distribution of approximately 1.0 μm. In granitic basement terrains which are thought never to have been significantly disturbed thermally, since their original post-emplacement cooling, the distribution becomes negatively skewed, with a mean around 12 or 13 μm and a standard deviation between 1.2 and 2 μm. This distribution is thought to characterise slow continuous cooling from temperatures in excess of 120° C, to ambient surface temperatures. More complex thermal histories produce correspondingly complex distributions of confined tracks. The continuous production of tracks through time, coupled with the fact that the length of each track shrinks to a value characteristic of the maximum temperature it has experienced, gives a final length distribution which directly reflects the nature of the variation of temperature with time. Most distinctive of the myriad possible forms of the final distribution are the bimodal distributions, which give clear evidence of a two-stage history, including high and low temperature phases. The study of confined length distributions therefore offers invaluable evidence on the meaning of any fission-track age, and bears the potential of providing rigorous constraints on thermal history in the temperature regime below about 150° C. The results of this study strongly suggest that any apatite fission-track age determination should be supported by a confined track length distribution.

1. Introduction

It is becoming increasingly recognized that amongst the available methods of geochronology, fission-track dating of apatite is the most sensitive to temperatures that normally occur in the upper several kilometres of the Earth's crust. Estimates of the "closure temperature" for fission track retention in apatite, below which tracks are effectively retained, are generally around 100° C (Wagner 1968; Naeser and Faul 1969; Wagner and Reimer 1972; Haack 1982). Gleadow et al. (1983) and Green et al. (1986) have shown that fission tracks in apatite can in fact provide information on paleotemperatures over the range 20° to at least 125° C and also pointed out the relevance of this to oil exploration. Because of the sensitivity to moderately elevated temperatures, apatite fission-track ages only rarely give a reliable measure of the age of formation of their host rock. Such formation ages are obtained only for rapidly cooled volcanic or very high-level intrusive rocks which have not been deeply buried (i.e. less than about 1 km). Apatites from rocks which have cooled slowly (from above about 130° C) to ambient surface temperatures, or which have been heated to temperatures in excess of approximately 70° C after formation (either by increasing burial, or by a thermal event) give ages which are less than the formation age, to a degree determined by the detail of the thermal history (Wagner 1981).

Recognition of this sensitivity has led to several attempts to "correct" apatite fission-track ages (henceforth "apatite ages") for thermal effects, either by the plateau method (Storzer and Poupeau 1973; Chaillou and Chambaudet 1981; Carpena et al. 1981) or by the track length method (Bigazzi 1967; Mehta and Rama 1969; Wagner and Storzer 1970; Wagner and Storzer 1972; Nagpaul et al. 1974). However when such corrections are made, it is often not clear what is being corrected for – i.e. what sort of thermal history produced the observed reduction in age. Nevertheless, some of this work (e.g. Wagner and Storzer 1970, 1972) has emphasised the importance of track length information for the proper geological interpretation of fission track ages. The primary purpose of this paper is to illustrate how investigation of the length distribution of confined fission tracks can provide considerable information on the nature of the thermal history.

The use of confined track lengths to assess the magni-

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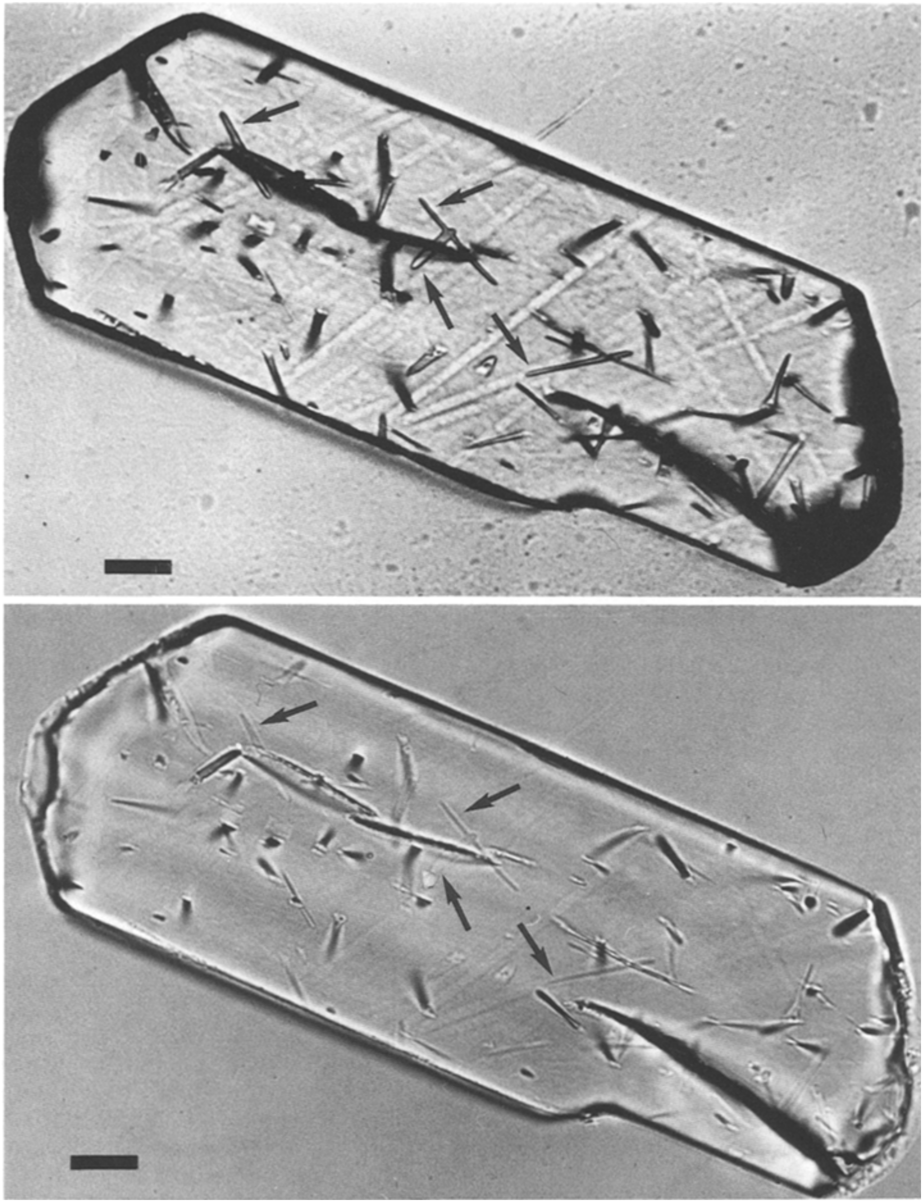

Fig. 1. Photomicrographs of the same apatite grain viewed using a dry objective (*upper*) and oil immersion (*below*). The scale bar represents 10 µm. When viewed under oil, the tracks in general, but the confined tracks in particular (*arrowed*), offer very little contrast. Dry observation is preferred for observing confined tracks

tude of thermal effects in apatite has been discussed previously by Bhandari et al. (1971); Green (1980) and Laslett et al. (1982). Green (1980) suggested that the observed shortening of spontaneous tracks in apatite could be produced even by residence at ambient surface temperatures, and also that all apatites were therefore likely to show shortening of spontaneous tracks. Although this has been disputed (e.g. Naeser et al. 1981) this dispute is usually based on measurements of projected track lengths, which as discussed by Laslett et al. (1982), are far less precise than confined track lengths. We will return to the relative merits of these two systems of track length measurements later in this paper.

This paper presents a compilation of confined track lengths in almost 200 apatite samples, from a wide variety of geological environments. The results clearly show that the mean confined track length, together with the form of the distribution of confined track lengths, can supply unique information on the temperature history of the sample. This information can be of great value in interpreting an apatite age, and should be considered before any attempt at age correction.

2. Experimental details

All apatites studied in this work were mounted in epoxy on glass slides, ground on wet silicon carbide paper on rotating laps (~400 r.p.m.) and polished using 0.3 µm alumina slurry. They were etched in 5 M HNO_3, for 20 s at room temperature (controlled 20 ± 1° C). Apatites in which induced tracks were to be studied were annealed at 500° C for several hours, sealed in either polythene or aluminum foil packets and irradiated in the X7 facility of the HIFAR reactor (Lucas Heights, NSW.). After irradiation, these were processed as above. In all samples, the mean confined track length, the shape of the length distribution and also the fission-track age were determined.

Confined track length measurements were made following the suggestions outlined by Laslett et al. (1982) in such a way that sampling bias is controlled and minimised. For the purpose of

Table 1. Confined fission-track length data for induced tracks in various apatites

Sample number	Locality details	Mean track length (μm)	Standard deviation (μm)	Number of tracks	Analyst[a]
7622-11	Fish Canyon	16.27	0.93	100	AJWG
70L-126	Fish Canyon	16.16	0.94	100	PFG
8122-03	Durango	16.24	0.93	100	AJWG
8122-03	Durango	15.91	0.90	100	PFG
8122-03	Durango	16.49	0.78	60	IRD
PFG200	Carrock Fell	15.83	0.83	100	PFG
PFG200	Carrock Fell	16.10	0.70	100	IBE
PFG165	Roshven	16.24	0.85	100	PFG
PFG165	Roshven	16.30	0.80	100	IBE
PFG201	Unknown	16.11	0.97	100	PFG
PFG201	Unknown	16.60	0.90	100	IBE
8322-39	Mt. Dromedary	15.89	0.93	100	PFG
8222-38	Lake Mountain	15.88	0.81	100	PFG
8322-38	Cooma	16.35	0.94	100	PFG
RP84-6	Romulus, NY	16.64	0.80	59	IRD
RP84-21	New York	16.43	0.74	50	IRD
8424-43	Renfrew	16.59	0.92	50	IRD
73-51	King Island	16.40	0.75	100	IRD
73-66	King Island	16.14	0.84	100	IRD
8122-02	Mud Tank	16.30	0.79	100	IRD
75-19	East Greenland	15.95	0.94	100	AJWG
7942-FL29	Flaxman's-1	16.57	0.90	100	AJWG
7722-53	West Kenya	16.41	0.84	100	AJWG

[a] *IRD* Ian Duddy; *PFG* Paul Green; *AJWG* Andrew Gleadow; *IBE* Ian Evans

this paper, all of the length data to be presented are uncorrected for this unavoidable bias, as we merely report observed length parameters from various environments. However it is important to note that bias correction becomes extremely important when unmixing of complex length distributions is undertaken (Laslett et al. 1982). The most important restriction on sampling is that only horizontal tracks were measured. Such tracks can easily be identified by their constancy of focus over their entire length, under a high power objective (~80×–100× dry), and by the strong reflection obtained from such tracks when viewed in incident illumination. To take advantage of this it is useful to have a microscope capable of viewing in both incident and transmitted light. In addition, tracks were only measured in grains with polished surfaces essentially parallel to the crystallographic c-axis. Within these prismatic planes tracks were measured over all azimuth orientations. This is important because of the anisotropy of the annealing process in apatite (Green and Durrani 1977; Laslett et al. 1984), which causes tracks perpendicular to the c-axis to be shortened more rapidly than tracks parallel to the c-axis. Thus horizontal track lengths measured in a grain polished parallel to the basal plane will be shorter than the true mean length, while in a grain polished parallel to a prismatic plane, the whole range of track lengths will be present, and can be sampled. It is very important that in any study of track lengths in apatite, such a strategy be adopted to avoid bias in the length measurement.

In the early parts of this study, track lengths were measured mainly by use of an eyepiece scale-bar divided into approximately 1 μm intervals (calibrated against a stage micrometer), with which tracks can be apportioned to these 1 μm intervals. In the later stages of the study, a HIPAD™ digitizing tablet plus projection tube arrangement was used, again calibrated against a 50×2 μm stage micrometer (#S12 supplied by Graticules Ltd., England). This latter method has the distinct advantage of measuring the track length precisely (with a reproducibility of approximately 0.2 μm) and absolutely, whereas the former method allows only a grouping into discrete length intervals. Confined tracks revealed from both etched tracks (TINTs of Lal et al. 1969) and from cleavages or cracks (TINCLEs) were grouped together.

During the study it became clear that small yet consistent differences exist between mean track lengths as measured by different observers. These differences are only of the order of 0.3 μm, and are thought to arise mainly from the way in which tracks were apportioned to the appropriate length interval in the eyepiece scale-bar. Such differences have no significant effect on the conclusions drawn below.

One important step in the observation of confined tracks which has not yet received sufficient attention is the desirability of observing the sample using dry objectives, rather than under oil immersion. When oil immersion lenses are used, the etched tracks become full of oil. Since the refractive index of common immersion oil and apatite are close (approximately 1.515 and 1.64, respectively), the tracks show very little contrast and are difficult to locate and identify. This is illustrated in Fig. 1 which shows the same apatite crystal viewed using dry and oil immersion objectives at the same overall magnification in each case. The illustrated crystal contains four prominent confined tracks (arrowed) which are plainly visible when viewed with the dry objective but are difficult to identify when viewed in oil.

All fission-track ages obtained in this study were measured using procedures similar to those outlined by Gleadow and Lovering (1978a). The emphasis of this paper is on the track length information, and thus the fission track ages are incidental to the main theme. Therefore, for the sake of brevity, the age data are not reported in detail. Most of the ages have been published elsewhere.

3. Induced track lengths

In a previous study, Bhandari et al. (1971), suggested that induced tracks in all apatites had roughly the same mean length of ~15.3 μm. Green (1980), however claimed that this was not the case, and that various apatites had different induced mean track lengths, ranging from 15.3 to 17.2 μm. In the present study, lengths of confined induced fission tracks have been measured in eighteen samples by up to four different observers, and the results are shown in Table 1. These results clearly show that the various apatite samples, which encompass a variety of parent rock types

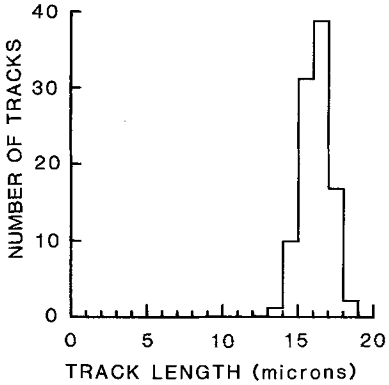

Fig. 2. Typical length distribution of confined induced tracks in apatite, obtained by summing the distributions from six of the samples listed in Table 1

from volcanic welded ash-flow tuffs (70L-126, 7622-11), through high level intrusive rocks (8322-39, 8322-38) and granites (75-19, 73-66) to apatites associated with mineralization (8122-03. PFG200), have mean induced track lengths which all fall within a narrow span between 15.8 μm and 16.6 μm. This conflicts with the rather broader range observed by Green (1980). We believe this to be due to the varying etch times up to 5 min (in 1% HNO_3) used by Green (1980), with repolishing to improve visibility, whereas in the present study etch time was standardised at 20 s (in 5MHNO_3). Thus the degree of etching of the tracks measured by Green (op. cit.) was rather variable, and more than likely explains the range of mean lengths he observed.

The results in Table 1 then indicate that induced tracks in all the apatites investigated have mean track lengths within a narrow range. Furthermore, the form of the length distribution is also very similar in all the samples studied, being approximately normal, with a standard deviation of approximately 0.9 μm (Table 1), with the majority of track lengths falling between 15 μm and 17 μm. A representative distribution, produced by summing distributions for six examples chosen at random (and normalised to 100 tracks), is shown in Fig. 2. It seems reasonable to conclude that induced tracks in all apatite samples will have a distribution which is typified by a mean of near 16.3 μm and a standard deviation of approximately 0.9 μm. This observation is highly significant in relation to the remainder of this paper, as it means that the track length distributions of spontaneous tracks in any of a wide variety of apatites can be discussed in their own right, without the need for reference to the lengths of induced tracks in the same sample, as had been suggested previously (Green 1980).

4. Track lengths in apatites from undisturbed "volcanic" rocks

Confined tracks have been measured in a number of apatites from rocks which can be shown, on geological grounds, to have cooled rapidly after formation, and thereafter have not been heated appreciably, so that the majority of tracks in these samples have been subject only to low temperatures

Table 2. Confined fission-track length data for volcanic apatites

Sample number	Locality details	Fission track age (Myr)	Mean track length (μm)	Standard deviation (μm)	Number of tracks	Analyst[a]
7622-12	Fish Canyon	28± 2	15.60	0.91	100	AJWG
7622-12	Fish Canyon	28± 2	15.00	1.14	100	PFG
7622-12	Fish Canyon	28± 2	15.30	1.00	100	IBE
7622-8	Mt. Dromedary	98± 5	14.76	0.91	100	AJWG
7622-8	Mt. Dromedary	98± 5	14.80	0.90	100	IBE
7622-8	Mt. Dromedary	98± 5	14.57	0.85	100	PFG
8322-39	Mt. Dromedary	98± 5	14.69	0.75	50	IRD
8322-158	Mt. Dromedary	98± 5	14.77	0.77	90	IRD
8122-03	Durango	31± 3	14.58	1.25	100	AJWG
8122-03	Durango	31± 3	14.68	0.64	50	IRD
8122-03	Durango	31± 3	14.24	0.77	100	PFG
8122-03	Durango	31± 3	14.80	1.20	100	IBE
R23084	Otways	120± 8	15.18	0.96	72	IRD
8142-164.3	Otways	120± 8	15.12	0.93	100	IRD
7942-157A	Otways	120± 8	14.97	1.15	100	IRD
7942-204X	Otways	120± 8	15.69	1.09	100	IRD
7942-202	Otways	120± 8	15.17	0.81	100	IRD
7942-123X	Otways	120± 8	15.31	0.83	100	IRD
7742-M8	Otways	121± 8	14.66	0.92	100	AJWG
7742-194	Otways	118± 8	15.08	1.25	100	AJWG
7742-95.3	Otways	128± 8	14.47	1.33	100	AJWG
8142-12	Tullich-1	120± 8	14.82	0.68	60	IRD
7742-OL1	Olney-1	117± 7	14.56	0.96	100	AJWG
7842-CP32	Cape Portland	98± 4	15.36	1.05	100	AJWG
8322-211	Mt. Warning	23± 2	15.20	0.90	100	IBE
PG2	Benambra	204±11	14.45	0.96	51	IRD
MB-4	Benambra	199± 9	14.04	1.09	54	IRD

[a] *IRD* Ian Duddy; *PFG* Paul Green; *AJWG* Andrew Gleadow; *IBE* Ian Evans

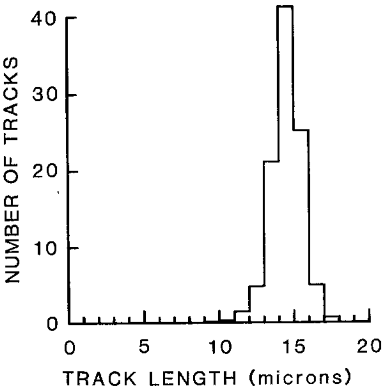

Fig. 3. Typical length distribution of confined tracks in rapidly cooled volcanic and related apatites, obtained by summing the distributions from six of the samples listed in Table 2

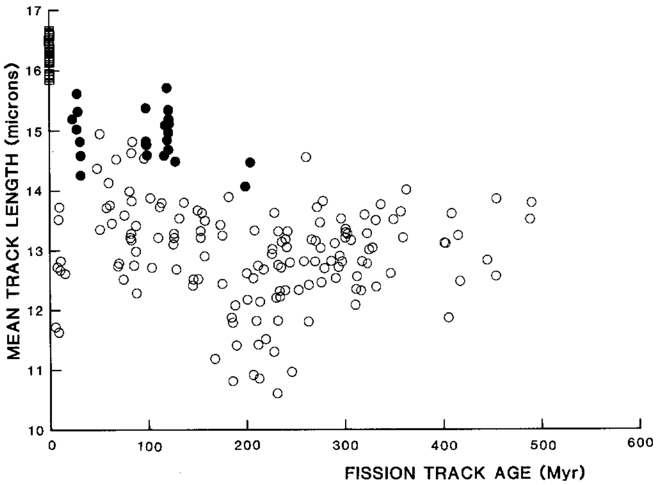

Fig. 4. Relationship between mean confined track length and fission track age for spontaneous tracks in a large number of apatites, from outcrop samples in a variety of geological environments. The *solid circles* refer to "undisturbed volcanic" apatites from Table 2, known to have cooled rapidly and never been significantly reheated. Also shown are the data for induced tracks, plotted with *square symbols* at zero age. The tight clustering of these data illustrate the similarity of induced tracks in different apatites. The "undisturbed volcanic" apatites have a restricted range of mean lengths, which seems to be independent of age, and characteristic only of the thermal history. A few of the remaining data (*open symbols*) fall into the "volcanic" field, suggesting a similar history for these apatites. All other points fall in a broad trend between 11 and 14 μm, regardless of apparent age, and again being determined more by thermal history than age

(say less than 50° C). The details of these measurements are shown in Table 2 together with sample information. The sample include volcanic rocks (*sensu stricto*) such as welded ash-flow tuffs (7622-12) and trachy-andesite lava (7842-CP32), as well as very high-level intrusives (8322-39, 7922-8 and 8322-211), volcanogenic sandstones (7742-M8, 7742-194), and the Durango apatite (8122-03) which occurs in a magnetite-apatite deposit within a volcanic sequence (Naeser and Fleischer 1975). Because of their volcanic orgin, and because they have not been thermally disturbed since formation, samples such as these share the characteristic that all isotopic systems give concordant ages (Green 1985).

Again from this data it is evident that in all cases the distribution of track lengths is similar in every sample studied. The mean values lie between 14.04 μm and 15.69 μm and the standard deviations of the distributions range from 0.77 to 1.33 μm with most between 0.8 and 1.0 μm. The majority of individual tracks have lengths between 13 and 16 μm. Fig. 3 shows a representative track length distribution again produced by adding six distributions from the examples in Table 2 and normalizing to 100 tracks. As in the case of induced tracks, although the number of samples studied is relatively small, the consistency of the form of the distribution of confined lengths (Table 2 and Fig. 3) suggests that this form is typical of any apatite which has cooled rapidly so that no track has been subjected to significally elevated temperatures. This distribution will be referred to as an *"undisturbed volcanic-type"* length distribution. It is important to realise that such a distribution will not necessarily be found in all volcanic rocks, but only in those which cooled very rapidly, and which have not been subsequently thermally disturbed. Furthermore an "undisturbed volcanic-type" length distribution can also be found in rocks of non-volcanic origin, where it is immediately diagnostic of a rapid cooling, followed by residence at low temperature.

5. Track lengths in apatites from crystalline basement rocks

In addition to the volcanic-type samples discussed above, with thermal histories that are known or can reasonably be deduced, we have measured confined track lengths in a large number of additional apatites recovered from presently outcropping crystalline rocks. These include plutonic intrusives, mainly granitic rocks, and high-grade metamorphic rocks. These rocks have all formed at high temperatures deep within the earths crust, and have now cooled to ambient surface temperatures, although for a large number of these samples there is little or no evidence from other techniques pertaining to the details of their intervening cooling history.

These rocks have been obtained from a wide variety of basement terrains, including Phanerozoic mobile belts and Precambrian shield areas in Australia (Gleadow and Lovering 1978a, b; Moore et al. 1986; Ferguson 1982), India, Antarctica (Gleadow and Fitzgerald, unpublished results), Greenland (Gleadow 1978; Gleadow and Brooks 1979), Africa (Gleadow 1980) Britain (Green 1986) and Europe (Hurford 1986). The data are summarized in Fig. 4, where the mean confined track length in each apatite is plotted against the fission-track age of that apatite. A tabulation of these data is available on request from the authors. Also shown in Fig. 4 are the confined track length results from Tables 1 and 2, with data for induced tracks plotted at zero age.

The data presented in Sects. 3 and 4 above demonstrate that the standard deviation of the distribution of confined lengths is also characteristic of the state of thermal history. Figure 5 shows the standard deviation of the distribution of confined track lengths of each of the samples represented in Fig. 4, plotted against the mean track length. In Figs. 4 and 5 data for induced tracks are shown as open squares, while those for "undisturbed volcanic" samples are solid circles. These results emphasise that confined tracks in apatites from "undisturbed volcanic" samples form a distinct group with mean lengths of ~14 to 15.6 μm and standard

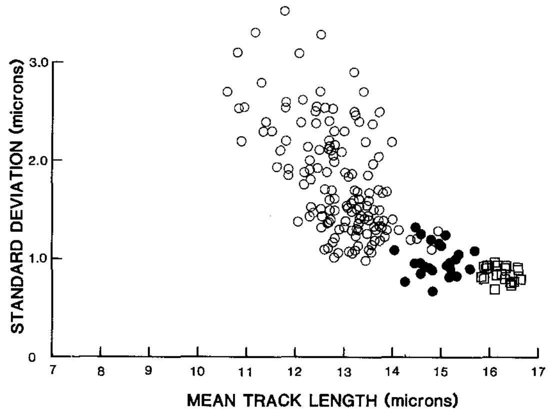

Fig. 5. Relationship between standard deviation and mean track length for the data shown in Fig. 4; coded in the same manner. The data for induced tracks and spontaneous tracks in "undisturbed volcanic" apatites again form distinct groups, emphasising that the two types of tracks possess distinct and characteristic distributions. The remaining data form an obvious trend, with a progressive broadening of the distribution as the mean track length decreases

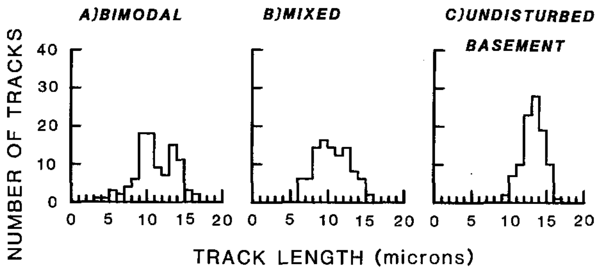

Fig. 6A–C. Typical track length distributions from the three characteristic types identified from the large number of apatites depicted in Fig. 4 and Fig. 5. These types are **A** bimodal, **B** mixed, and **C** undisturbed basement. The bimodal is a special case of the mixed distributions where two separate components can be readily identified

deviations of ~0.8 to 1.2 μm, both parameters being independent of the fission track age.

A few of the data for presently outcropping crystalline basement samples fall into the region defined by samples with a volcanic-type thermal history. This strongly suggests that these basement samples have also experienced a rapid cooling history. This is consistent with the geology of these samples where this is known, including two data points from Green (Green 1986), for rocks from the English Lake District, and two for rapidly upifted rocks from the Transantarctic Mountains of South Victoria Land, Antarctica (Gleadow and Fitzgerald, unpublished results).

The majority of the crystalline basement data forms another distinct group. In Fig. 4 this group forms a broad band with mean lengths generally between 14 and 11.5 μm. The data show no dependence on fission-track age, from Alpine samples at approximately 10 Myr (Hurford 1986) to apatites from the West Australian Shield with apparent ages of approximately 500 Myr (Ferguson 1982). A small group with means below 11.5 μm at ages around 200 Myr appear to have had more complex thermal histories, and will be discussed in more detail below (Sect. 5.2). In Fig. 5 the basement data show that as the mean length decreases, the standard deviation increases, illustrating the progressive broadening of the distribution towards shorter mean lengths.

The lack of any correlation between track length parameters and fission-track age shows that the style of the thermal history, rather than its duration, determines the details of the distribution of confined track lengths in apatite.

5.1. Transitional sequences of track length distributions

A key to understanding length distributions obtained in crystalline basement rocks is found in sequences from areas in which pre-existing tracks have been partially or completely annealed by exposure to elevated temperatures. Two such examples have recently been given by Moore et al. (1986) and Green (1986). Both of these studies show that the transition from unaffected ages, through partially overprinted ages to total resetting is accompanied by a profound change in the track length distribution, which reflects the mixture of two components. One, representing those tracks formed prior to and during the high temperature phase, shows a progressive shortening as the apparent fission track age is reduced, until it is reduced to zero in samples which have lost all pre-existing tracks. The second component, present in all samples, represents those tracks formed after subsequent cooling to lower temperatures.

The transition from zero to total overprinting is characterised by a broadening of the length distribution as the two components become more separated, through a series of *"mixed" distributions.* When the two components are well resolved, a *"bimodal" distribution,* results, which can be regarded as a special case of the "mixed" distribution. In the study of Moore et al. (1986) samples which show little or no sign of significant heating, with ages around 300 Myr, again show a characteristic distribution, with a mean of ~12.5 to 13.5 μm, standard deviation of ~1.3 to 1.7 μm, and a distinct negative skewness. We define this type of distribution as an *"undisturbed-basement" distribution.* Typical examples of these three distribution types taken from our compiled crystalline basement data set are shown in Fig. 6.

5.2. Interpretation of track length distributions in basement samples

Having defined these three type distributions, we can interpret many of the samples compiled in our crystalline basement data set as one of these three types. In assigning a particular distribution to a given type we have relied mainly upon the position of a sample within a sequence in which undisturbed basement and a transitional series can be identified, such as that described above. Isolated distributions often cannot be attributed to a particular type except in the case of obviously bimodal and some extreme cases of mixed distributions.

Having assigned the basement data into the three types, the parameters of the length distribution are found to be characteristic of each type as shown in Fig. 7. For instance, tracks in apatites from apparently undisturbed basement have distributions with mean lengths in the range 12 to 14 μm and standard deviations between 1.0 and 2.0 μm. Bimodal distributions fall in a distinct group, with means below 13 μm and standard deviations above 2 μm. Mixed distributions span the full range of the other two groups.

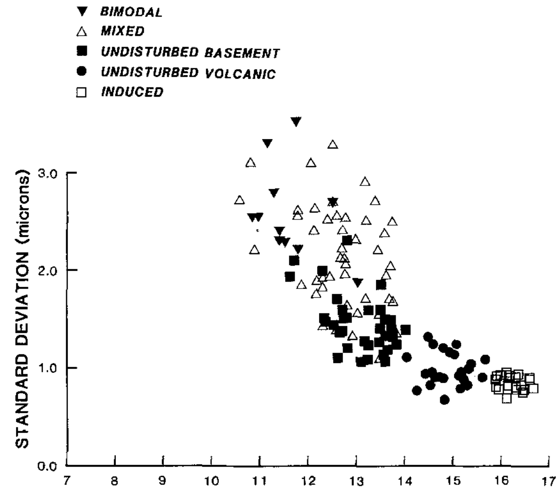

Fig. 7. Breakdown of the data shown in Fig. 5 into the five types of distribution identified in the text. The bimodal distributions are much broader than any of those for the undisturbed samples, while the mixed distributions span the range between the bimodals and the undisturbed samples

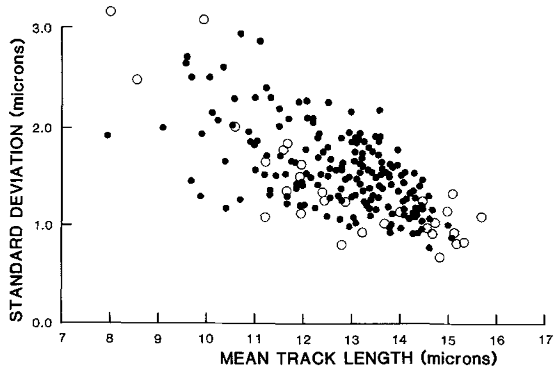

Fig. 8. Relationship between standard deviation of the confined track length distribution and mean track length observed in apatites from over 20 sedimentary basins, including both surface and sub-surface samples. Data from the Otway Basin reference trend (*open circles*) again show a broadening of the distribution as the mean length decreases, although this trend is distinct from that shown in Fig. 5 for outcropping basement rocks

The group of apatites mentioned in Sect. 4, with mean lengths of less than 11.5 μm and ages around 200 Myr all fall into the "bimodal" or "mixed" categories.

Investigation of the "undisturbed basement" data shows a tight cluster with standard deviations in the range 1.0 to 1.6 μm, and only a few extending up to approximately 2 μm. This suggests that those samples with higher standard deviations may have undergone thermal histories more complex than the majority of samples in this category. The most likely form of thermal history for samples with the "undisturbed basement" type of length distribution would seem to be a monotonic cooling from temperatures where tracks are not retained, down to ambient temperatures in surface outcrops (say 10–30° C). Therefore we suggest that the data in the pronounced grouping between mean lengths of 12.2 and 13.9 μm and standard deviations of 1.0 to 1.6 μm result from this type of thermal history. This conclusion gains support from the rudimentary analysis given by Gleadow et al. (1986).

As the thermal history experienced by a particular basement sample deviates from this simple pattern of monotonic cooling, the track length distribution will become more complex. In samples affected by a two-stage history, in which some tracks have been thermally shortened while others have formed since cooling, length distributions will be of the mixed or "bimodal" types illustrated above. More complex histories will produce correspondingly more complex length distributions, containing a wealth of information on the thermal histories of the rocks from which these apatites have been derived. The development of analytical techniques for the elucidation of these thermal histories represents a major challenge to fission-track dating in the near future.

Finally, an interesting point to note from Fig. 4 is the lack of apatite fission-track ages greater than about 500 Myr. The significance of this is not immediately apparent, but we believe this lack of older ages may result from a fundamental "cycle time" of basement rocks currently in outcrop of the order of 500 Myr. Whatever the reason, outcropping rocks with apatite fission-track ages older than 500 Myr are extremely rare in our experience, even from areas which on other evidence would appear to have been tectonically quiescent for much longer periods. The oldest apatite ages in Fig. 4, for example, come from Archean gneisses from the centre of the West Australian shield which are remote from known belts of late Proterozoic or early Paleozoic disturbance. We speculate that the presence of crystalline basement rocks in large areas of surface outcrop may be evidence for continued, albeit very slow, erosion over long periods of time. Indeed, the oldest apatite ages may well be found not in stable shield areas but in basement beneath a thin veneer of platform sediments, or at shallow levels in old sedimentary basins.

6. Spontaneous tracks in apatites from sedimentary basins

The presence of apatite in sedimentary rocks as a detrital component has recently opened a new field for the application of fission track dating (Naeser 1979; Storzer and Selo 1981; Gleadow et al. 1983). In a number of studies (Gleadow et al. 1983; Green et al. 1986; Gleadow et al. 1986; Gleadow and Duddy 1981a; Gleadow and Duddy 1981b), we have given particular attention to early Cretaceous sediments in the Otway Basin in southeastern Australia, which have proved invaluable in understanding the behaviour of fission tracks in apatite at temperatures between about 20° C and 150° C over tens of millions of years. We concentrate in this section on just one aspect of those data; the change in the form of the track length distribution as the mean length decreases with increasing down-hole temperature due to annealing. Apatites from these sediments have a contemporaneous volcanogenic origin and therefore had essentially no inherited tracks at the time of deposition. In addition to these Otway Basin results, we have compiled a large body of track length data from over 20 sedimentary basins, including both outcrop and subsurface samples.

Figure 8 shows the relationship between standard deviation and mean length for this extensive data set, with the Otway Basin reference trend defined by Green et al. (1986)

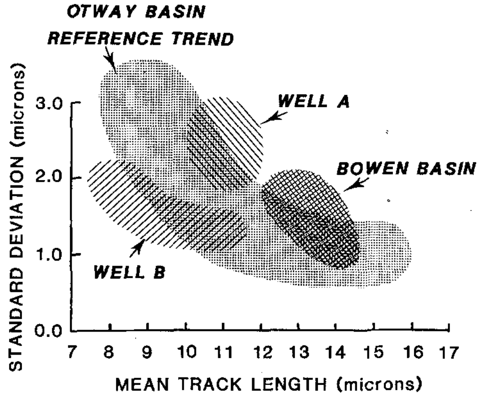

Fig. 9. Data from selected sedimentary basins depicted as in Fig. 8. The position of data from individual basins in relation to the main trend reflects the thermal history of the basin, as explained in the text

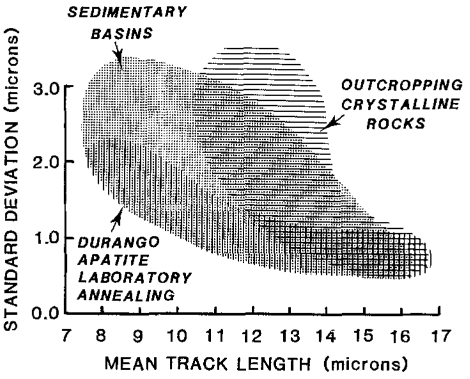

Fig. 10. Trend from Fig. 5 for outcropping basement rocks, and from Fig. 8 for sedimentary basins, compared with each other and with the trend observed by Green et al. (1986) in the laboratory annealing of induced fission tracks in Durango apatite. The three trends are distinct, reflecting the interplay between compositional effects, differing thermal histories and continuous production of tracks in natural samples

shown as open circles. It is clear that this sedimentary basin data has a distinctly different trend to that of the outcropping crystalline basement rocks shown in Fig. 7, extending to lower values of mean length, down to about 8 μm in samples where down-hole annealing is particularly pronounced.

Elsewhere (Green et al. 1986; Gleadow et al. 1986), we have shown that for the samples defining the reference trend, the increasing spread in the length distribution as the mean length is reduced arises dominantly from two sources; one "inherent" contribution due to the anisotropic nature of the annealing process, and another "compositional" contribution arising from the presence of apatites with a variety of compositions, each with slightly different annealing properties. A third contribution, due to the continuous production of tracks through time, is negligible in these particular samples, which have experienced only a simple thermal history with current temperatures at their maximum since deposition (Hegarty 1985).

The larger data set in Fig. 8 occupies a wider field than that defined by the reference wells alone. Data from a particular well or region often define specific sub-trends within this plot, and can provide some initial insight into the thermal history. To illustrate this, Fig. 9 shows the fields occupied by selected data from Fig. 8. Well "A" comes from a region known to have been thermally disturbed and length distributions in apatites from this well are broader than would be expected for a simple thermal history, since the data plot well above the reference trend. Outcrop samples from the Bowen Basin of eastern Australia are also known, from extensive vitrinite reflectance studies (Beeston 1981), to have been subjected to major thermal disturbance. The magnitude of the thermal effect varies across the basin, with maximum paleotemperatures from only 45–50° C to 150° C or more. Track length data (SJ Marshallsea, unpublished results) in apatites from correlative volcanogenic units across the basin are shown in Fig. 9. Data fall on the reference trend for those samples minimally disturbed, but as maximum paleotemperatures increase (i.e. as mean track length decreases) the influence of the thermally shortened tracks draws the data above the reference trend. The region in Fig. 8 above the reference trend seems to be occupied only by samples which have been subject to significantly higher temperatures than those now pertaining.

It should be noted that wells in which the apatites have a greater compositional spread (especially in F/Cl ratio) than those in the reference wells (see below) could also lie above the reference trend without resort to past higher temperatures. An accumulating body of data on apatite compositions suggests, however, that a compositional spread greater than that observed in the Otway Group will be very uncommon.

The data in Fig. 8 relating to Well "B" all fall below the reference trend, with a much reduced spread in lengths for a given mean length. This implies that these samples show less compositional spread than the Otway Group reference samples, since other contributions to the spread in lengths can only take data above the reference trend. A narrow compositional range in these samples has recently been confirmed by electron microprobe studies of these apatites, which has shown them all to be close to end member fluorapatite.

To summarise this section, Fig. 10 shows the trends of the relationship between standard deviation and mean length for the crystalline basement data from Fig. 5 and the sedimentary basin data from Fig. 7. Also shown in Fig. 10 is the trend observed in laboratory annealing of a single mono-compositional apatite (Durango apatite) by Green et al. (1986). The three very distinct trends illustrate fundamental differences in the length distributions to be found in the three different types of sample.

7. Discussion

The evidence presented above shows that the confined track length distribution of spontaneous fission tracks in any given apatite contains a great deal of information on the thermal history of that apatite at temperatures typically encountered in the upper few kilometres of the Earth's crust. This information provides a basis for interpreting any apatite fission-track age. For instance, a volcanic-type distribution immediately identifies a sample which has cooled extremely rapidly, as for example in a volcanic rock or high level intrusive. Such a distribution could also be found in basement terrains which have undergone a single-stage rapid uplift, followed by equally rapid erosion, as long as temperatures have remained relatively low since. Only apatites with such track length distributions will have fission track ages which can be interpreted in terms of single well-defined events. Any apatite suitable for use as an age standard (Green 1985) must have an "undisturbed volcanic" type length distribution. The reason for the small but consistent difference in mean length between "induced" and "undisturbed volcanic-type" distributions has been discussed elsewhere by Green (1980). In sedimentary basin applications any apatite fission track ages interpreted as being of stratigraphic significance, due to volcanism contemporaneous with sedimentation, must also have an undisturbed volcanic-type length distribution.

Outcropping rocks in shield areas and crystalline rocks in fold belts which have not been thermally disturbed since cooling to temperatures at which fission tracks are retained, have confined track length distributions similar to that shown in Fig. 6c. Such distributions reflect the more or less continuous uplift and cooling of such regions, albeit at very low rates in some cases, and contain tracks produced at all temperatures from about 130° C to present day ambient temperatures. As we have pointed out elsewhere (Gleadow et al. 1986), it is the uniformity of cooling, rather than its rate, that is important in defining the form of this distribution. Essentially similar distributions may result from very slow cooling rates in ancient shield areas and extremely rapid, but continuous, cooling in young fold belts such as the Alps (Hurford 1986). The apatite ages in these two extreme cases would, of course, be very different.

Departures from this simple pattern are thus of great significance and reveal details of the thermal history which are not otherwise accessible. The most obvious examples of this are bimodal distributions as discussed above. In such cases it should be possible to extract a great deal of useful information about the thermal history once all the relevant controlling factors are understood (e.g. Laslett et al. 1982). Clearly bimodal distributions, however, are at one end of a spectrum of possibilities where a track length distribution represents the combination of two components, one being tracks partially shortened by elevated temperatures, the other being tracks formed after subsequent cooling. It is only when the temperature is sufficient to shorten tracks to a mean of about 9 or 10 μm that the two peaks will be well resolved. When the shortened component has a mean length greater than 10 μm, this peak will merge with the longer component to give a unimodal distribution with an intermediate mean but a greater standard deviation than would be obtained from a simple cooling history. When the mean length of the annealed component is below 9 μm the track length distribution lacks a well defined peak (Gleadow et al. 1986) and when added to the longer component, may resemble a tail to shorter lengths. The relative proportions of the two components of bimodal distributions is also important in resolving two clear peaks. These will be related to the timing and magnitude of the thermal event. So the conditions for obtaining clearly bimodal distributions are quite strict. In the majority of cases we will instead see a broad, unimodal distribution of the "mixed" type (Fig. 6b), with a shape characteristic of the particular thermal history.

In any of these cases, it is important to realise that the fission track age obtained on these apatites is a composite age and does not relate to a single event. Only by investigating the details of the confined track length distribution can an apatite fission track age be confidently interpreted. An age alone can generally be interpreted in a number of ways, but the confined track length distribution allows firm constraints to be placed on the meaning of the observed age.

We can now consider the meaning of any attempt to correct a fission track age. In the case of an apatite with an undisturbed volcanic-type length distribution, any attempt at correction is meaningless if the ages are derived from a calibration system based on the use of apatite age standards, since the age standards also have this type of distribution. In apatites with length distributions typical of undisturbed basement, or bimodal or other complex distributions, it is by no means clear what either a plateau-corrected age, or an age corrected simply for the reduction in mean track length, will mean, as both procedures ignore the detail of the length distribution. Clearly considerable information on the variation of temperature with time is present, but more sophisticated mathematical treatments will be necessary to extract the details.

An age correction procedure based on track lengths may be viable for borehole samples in wells which have undergone a burial history similar to that of the reference wells of the Otway Basin and which contain a similar compositional spread. As discussed by Green et al. (1986), and as employed by Gleadow and Duddy (1984) the relationship between length reduction and age reduction in the Otway data allows an estimation of the reduction in age which has occurred in another well from the observed reduction in length.

8. Confined track lengths vs. projected track lengths

Various authors (e.g. Wagner and Storzer 1970, 1972) have advocated the use of the projected lengths of tracks intersecting a polished mineral surface to reveal detail of thermal history. However Dakowski (1978) and Laslett et al. (1982) have shown how projected lengths obscure any detail present in the distribution of etchable ranges into an ideally triangular distribution, with its apex at zero length. In practice this distribution is modified at short lengths by the difficulty of identifying and measuring tracks shorter than approximately 1 or 2 μm, resulting in a dip in the distribution at the shortest lengths. The triangular form of the projected length distribution, with its abundance of short lengths, is the result of the intersection of randomly oriented tracks, at various points along their length, with the polished surface. Thus projected length distributions can never contain genuine peaks corresponding to different components of tracks. Instead, different components supply different triangular contributions which are summed to produce the final distribution of projected lengths.

Confined track lengths however give the closest approximation to the distribution of etchable ranges which can be measured (Laslett et al. 1982) and as illustrated above can reveal important detail about thermal history. To illustrate the difference between the capabilities of the two measurement techniques, Fig. 11 shows a comparison of confined track lengths and projected lengths measured in a variety of apatites selected to encompass the type distributions identified in the above study. These projected length measurements were made using the digitising tablet and

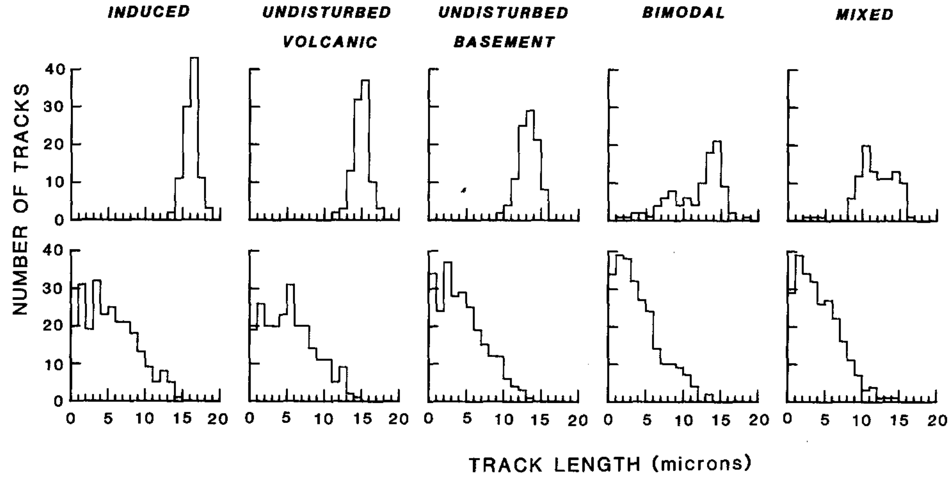

Fig. 11. Comparison of projected lengths vs. confined lengths in five samples chosen to represent each of the type distributions identified in this study. The projected length distributions contain only subtle evidence of the considerable differences between the confined track length distributions in these samples, and offer little useful information for thermal history studies. 100 confined tracks and 500 projected tracks were measured in each case

projection tube system described above, and in each case at least 500 tracks were measured. In Fig. 11, whereas the distinctive forms of each type of confined length distribution are easily identifiable, the accompanying projected length distributions are all basically triangular, with only minor subtleties belying the fundamental differences between each sample. Even the bimodal confined length distribution expresses itself only as a slight change of slope in the projected length distribution, which could easily be lost in the random variations inherent in the measurements.

9. Conclusions

The results of the compilation of track length data presented above, from a wide variety of geological terrains, provide a basis for the understanding of the behaviour of fission tracks in apatite over geological time. They also provide a foundation for the development of analytical techniques for the interpretation of fission track parameters in apatite. As our understanding of length distributions improve, it should be possible in the near future to separate the two components of a bimodal distribution, and ascribe a detailed interpretation to each. For any type of distribution, recognising the importance of the precise form of the length distribution will enable tight constraints to be placed on the detail of the variation of temperature with time. The wide variety of possible confined track length distributions suggests that any fission track age which is not complemented by a confined length determination contains only a small fraction of the total information available.

These conclusions apply only to measurements of confined fission tracks, which maximise the information that can be extracted regarding thermal history. Comparison of confined and projected length measurements shows that projected lengths are insensitive to major differences in thermal history. Confined fission track lengths however can supply information of unique value, either in simple geochronological studies, in cooling history and uplift studies in metamorphic terrains, or as a tool for the study of paleotemperatures in sedimentary basins. Measurement of confined tracks is simple, rapid, and can be made with great precision. We believe that fission-track age determinations on apatite should be complemented by confined track length measurements whenever possible.

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