

calibrations based on analysis of modern material would not be precisely applicable to fossil material.

The author is indebted to A. Danin for identification of plant material and to O. Bar-Yosef for discussion and information concerning archaeological matters. Radiocarbon dates were provided by I. Carmi. J. Rounick performed isotope analysis of some of the samples, and he, S. Weiner and M. DeNiro advised on methodology. Two of the samples analysed were provided by R. Amiran and by R. Gerson and M. Kaplan. This research was supported by a grant from the Fund for Basic Research, administered by the Israel Academy of Sciences and Humanities.

Received 3 November 1987; accepted 4 May 1988.

- DeNiro, M. J. & Epstein, S. *Science* **201**, 906-908 (1978).
- Vogel, J. C. *Bothalia* **14**, 391-394 (1983).
- Krishnamurthy, R. V., DeNiro, M. J. & Pant, R. K. *Nature* **298**, 640-641 (1982).
- Dzurec, R. S., Boutton, T. W., Caldwell, M. M. & Smith, B. N. *Oecologia* **66**, 17-24 (1985).
- DeLaune, R. D. *Chem. Geol. (Isot. Geosci. Sec.)* **59**, 315-320 (1986).
- Dorn, R. I. & DeNiro, M. J. *Science* **227**, 1472-1474 (1985).
- Danin, A. *Desert Vegetation of Israel and Sinai* (Cana, Jerusalem, 1983).
- Teeri, J. A. in *Topics in Plant Population Biology* (eds Solbrig, O. T. et al.) 356-374 (Columbia University Press, New York, 1979).
- Hare, P. E. & Abelson, P. H. *Yearbook Carnegie Inst. Wash.* **64**, 223-235 (1965).
- Poulicek, M. *Cochilles et Autres Structures Squelettiques des Mollusques: Composition Chimique, Biomasse et Biodégradation en Milieu Marin*, thesis, Univ. Liège (1982).
- Stuiver, M., Burk, R. L. & Quay, P. D. *J. geophys. Res.* **89**, 11,731-11,748 (1984).
- Goodfriend, G. A. *Quat. Res.* **28**, 374-392 (1987).
- Goodfriend, G. A. *Geology* **15**, 698-700 (1987).
- Goodfriend, G. A. *Radiocarbon* **29**, 159-167 (1987).
- Goodfriend, G. A., Magaritz, M. & Carmi, I. *Climatic Change* **9**, 349-356 (1986).
- Weinstein, J. M. *Radiocarbon* **26**, 297-366 (1984).
- Klein, C. *Israel J. Earth Sci.* **31**, 67-94 (1982).
- Pearson, G. W., Pilcher, J. R., Baillie, M. G. L., Corbett, D. M. & Qua, F. *Radiocarbon* **28**, 911-934 (1986).
- Neev, D. & Emery, K. O. *The Dead Sea: Depositional Processes and Environments of Evaporites* (Bull. no. 41, Geological Survey of Israel, Jerusalem, 1967).
- Horowitz, A. *The Quaternary of Israel* (Academic, New York, 1979).
- Van Zeist, W. & Bottema, S. in *Palaeoclimates, Palaeoenvironments and Human Communities in the Eastern Mediterranean Region in Later Prehistory* (eds Bintliff, J. L. & van Zeist, W.) 277-321 (BAR Intl. Ser. no. 133, Oxford, 1982).
- Amiran, R. *Israel Expl. J.* **36**, 74-76 (1986).
- Broshi, M. & Gophna, R. *Bull. Am. Sch. archaeol. Res.* **261**, 73-90 (1986).
- Cohen, R. *Archeological Survey of Israel. Map of Sede-Boqer—West (167) 12-03* (Dept of Antiquities and Museums, Jerusalem, 1985).
- Fargo, V. M. *Settlement in Southern Palestine during Early Bronze III*, Thesis, Univ. Chicago (1979).
- Rosen, A. in *L'Urbanisation en Palestine à l'Age du Bronze Ancien: Bilan et Perspectives des Recherches Actuelles* (ed. de Miroschedji, P.) (Editions Recherche sur les Civilisations, Paris, in the press).
- Cole, K. L. & Webb, R. H. *Quat. Res.* **23**, 227-235 (1985).
- Shomer-Ilan, A., Nissenbaum, A. & Waisel, Y. *Oecologia* **48**, 244-248 (1981).
- Ziegler, H., Batanouny, K. H., Sankhla, N., Vyas, O. P. & Stichler, W. *Oecologia* **48**, 93-99 (1981).
- Winter, K. *Oecologia* **48**, 100-106 (1981).
- Meteorological Service of Israel. *Map of Average Annual Rainfall*, 2nd edn (Bet Dagan, 1977).

Identification of inherited radiogenic Pb in monazite and its implications for U-Pb systematics

Peter Copeland, Randall R. Parrish* & T. Mark Harrison

Department of Geological Sciences, State University of New York at Albany, Albany, New York 12222, USA

* Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario K1A 6O1, Canada

The simplest interpretation of uranium-lead mineral ages in igneous rocks embodies the assumption that melting of pre-existing rocks leads to homogenization of the lead isotopes, thus resetting the radiometric 'clock'. Zircons often violate this assumption by only partially dissolving and preserving a component of lead 'inherited' from before the melting episode, but until now such behaviour has not been observed in monazite. Here we report U-Pb data for zircons and monazites from a Tertiary granite from the Himalayas, in which zircons and monazites contain inherited radiogenic lead. An analysis of a single entirely igneous zircon crystal

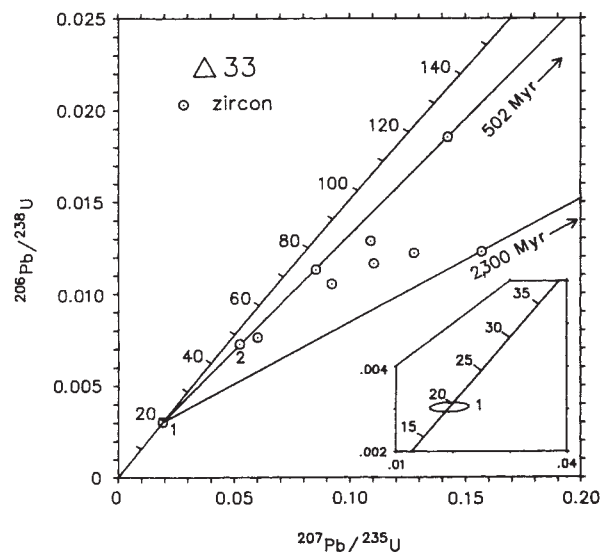


Fig. 1 Concordia diagram for ten zircon fractions from sample $\Delta 33$: data are bounded by two discordia from 19.5 Myr on concordia to upper intercepts of ~ 500 and 2,300 Myr. Inset shows blowup of 2 sigma error ellipse for analysis of a single zircon crystal concordant at 19.5 Myr. Numerals 1 and 2 refer to zircon analyses in Table 1.

plots on concordia at 19.5 ± 0.4 Myr. Eight monazite fractions lie on a line from an upper intercept of 471 ± 10 Myr to the youngest fraction, which plots slightly above concordia at 21 Myr. The presence of excess ^{206}Pb in the youngest monazite fractions indicates that the monazite data represent a mixing line between young magmatic monazite and an older inherited component, rather than a resetting of 471 Myr monazites at ~ 20 Myr. These data suggest a closure temperature for Pb in monazite significantly higher than previously published estimates.

We have obtained separates of zircon and monazite from a weakly foliated, unmetamorphosed, two-mica tourmaline granite (sample $\Delta 33$) which intrudes rocks that have been deformed in response to the Tertiary collision of India and Asia. This 30 kg sample was collected by B. C. Burchfiel, K. V. Hodges and L. Royden from north-east Everest ($86^\circ 50'$ E, $28^\circ 10'$ N) as part of their ongoing research on the tectonics of the Himalayas and southern Tibet. U-Pb analyses were obtained on carefully selected zircon and monazite fractions, using current procedures at the Geological Survey of Canada¹⁻⁴. U and Pb were isotopically analysed on a MAT261 multicollector mass spectrometer using simultaneous ion collection of all Pb isotopes and similarly for U as outlined by Roddick *et al.*³. U blanks were all less than 1 pg for these analyses. The Pb blank was 6-15 pg for the zircons with the exception of zircon 1 (Table 1), in which the 65 pg of common Pb was entirely blank-derived, and 15-28 pg for the monazites. The chemical composition of this rock was determined by X-ray fluorescence chemical analyses (major elements, V, Ni, Nb, Zr, Y, Sr, Rb, Pb), and instrumental neutron activation analysis (other trace elements). All quoted errors in the text and tables are at the level of one sigma, whereas error ellipses on concordia plots are at the two sigma level. Results of U-Pb isotope analyses are listed in Table 1.

Nine of the ten zircon fractions analysed from sample $\Delta 33$ plot in a triangular region on the concordia diagram (Fig. 1) bounded by lines drawn from 19.5 Myr to ~ 500 and 2,300 Myr. These upper intercepts are similar to the range of Nd model ages for other Tertiary granites and metamorphic rocks from this region⁵⁻⁷. This pattern is typical of zircons from Tertiary leucogranites in southern Tibet⁸⁻¹⁰ and can be attributed to variable amounts and ages of inherited radiogenic lead (Pb^*) in residual zircon. Two separate zircon crystals showing no visible core or other evidence of an inherited component under the petrographic microscope were selected and analysed separ-

Table 1 U-Pb zircon and monazite data for $\Delta 33$

Analysis # size*	wt (mg)	U p.p.m.	Pb† p.p.m.	$^{206}\text{Pb}/$ $^{204}\text{Pb} \ddagger$	Pb $\S$ (pg)	$^{208}\text{Pb} \dagger$ (%)	$^{206}\text{Pb}/^{238}\text{U} \parallel$	$^{207}\text{Pb}/^{235}\text{U} \parallel$	$^{207}\text{Pb}/^{206}\text{Pb} \parallel$	$^{207}\text{Pb}/^{206}\text{Pb}(\text{Ma}) \P$
Zircon										
1. flat $n = 1$	0.0008	4,629	12.51	2 ^o	65	<1	0.003024 (1.9)	0.01928 (10.4)	0.04525 (9.2)	10.8 (390)
2. euh $n = 1$	0.001	3,939	26.99	553	19	4.0	0.007266 (0.12)	0.05258 (0.23)	0.05249 (0.17)	306.6 (7.6)
3. euh $n = 21$	0.0116	4,149	30.03	666	36	4.3	0.007622 (0.12)	0.06034 (0.23)	0.05742 (0.16)	507.7 (7.2)
4. euh $n = 3$	0.0008	6,349	67.73	523	7	3.9	0.01131 (1.19)	0.08531 (0.25)	0.05473 (0.19)	401.2 (8.5)
5. euh < 74	0.0237	3,440	35.87	2,987	18	7.7	0.01052 (0.10)	0.09222 (0.13)	0.06356 (0.05)	727.1 (2.2)
6. euh > 74	0.119	3,407	41.88	6,822	48	4.4	0.01287 (0.16)	0.1091 (0.17)	0.06148 (0.04)	656.0 (1.9)
7. euh < 74	0.093	4,378	49.29	5,265	57	4.9	0.01164 (0.18)	0.1105 (0.19)	0.06883 (0.04)	893.8 (1.8)
8. euh > 74	0.064	3,710	44.27	5,218	35	5.3	0.01222 (0.13)	0.1279 (0.15)	0.07591 (0.04)	1,092.6 (1.7)
9. nd > 74	0.037	3,820	42.22	3,820	27	6.4	0.01853 (0.10)	0.1423 (0.12)	0.05570 (0.05)	440.4 (2.2)
10. euh > 74	0.0143	3,528	42.68	3,173	12	4.6	0.01228 (0.11)	0.1571 (0.13)	0.09277 (0.05)	1,483.3 (1.8)
Monazite										
1. cyd, $n = 2$	0.0534	5,447	65.99	805	78	75.0	0.003355 (0.17)	0.02056 (0.27)	0.04445 (0.18)	<0
2. cdy, $n = 10$	0.195	6,374	77.22	672	421	73.9	0.003504 (0.89)	0.02147 (0.93)	0.04444 (0.24)	<0
3. $n = 3$	0.073	7,969	95.43	856	154	73.5	0.003509 (0.80)	0.02141 (0.83)	0.04425 (0.17)	<0
4.	0.0491	6,145	77.79	690	101	74.7	0.003542 (0.26)	0.02177 (0.34)	0.04457 (0.19)	<0
5. $n = 25$	0.171	7,242	103.1	807	403	74.2	0.004063 (1.0)	0.02561 (1.0)	0.04571 (0.19)	<0
6. $n = 27$	0.0568	7,832	146.3	1,537	98	74.3	0.005285 (0.16)	0.03585 (0.20)	0.04919 (0.09)	156.8 (4.4)
7. $n = 7$	0.184	8,051	183.5	1,054	1,085	52.0	0.01202 (0.51)	0.08846 (0.54)	0.05336 (0.13)	344.2 (5.9)
8. $n = 4$	0.0305	8,361	466.4	5,438	67	62.9	0.02267 (0.13)	0.1723 (0.15)	0.05512 (0.05)	417.3 (2.0)

Weighing error 0.001 mg, except for the three zircon fractions, which weighed 0.001 mg or less, and whose weights were estimated from photomicrographs.

* Sizes (>74) refer to length of zircons in microns; euh, euhedral with 3:1 to 6:1 aspect ratios; nd, needles with up to 8:1 aspect ratio; cdy, cloudy, zircons were all selected to be generally to extremely clear with sharp crystal faces and some contain faint visible evidence of core material.

† Radiogenic Pb.

‡ Measured ratio, corrected for spike and fractionation.

§ Total common Pb in analysis corrected for fractionation and spike.

|| Corrected for blank Pb and U, common Pb, errors quoted are 1 standard error of the mean in per cent.

¶ Corrected for blank and common Pb, errors are 1 standard error of the mean in Ma.

ately (Fig. 1, Table 1). One contained isotopic evidence for inheritance, but the other shows no such evidence and plots on concordia at 19.5 Myr with an uncertainty in the $^{206}\text{Pb}/^{238}\text{U}$ age of 0.4 Myr. Although the special handling procedures for this sample resulted in a high blank contribution, the isotopic composition of our blank is accurately known, accounting for the relatively low uncertainty.

The observation of zircon saturation in this rock allows calculation of the peak temperature encountered during melting^{11,12}. Table 2 gives the chemical composition of this sample and the calculated cation ratio (M) value $[(\text{Na} + \text{K} + 2\text{Ca})/(\text{Al} \cdot \text{Si})]$ which has been shown to embody the chemical variables which control zircon saturation in crustal magmas¹¹. Given the compositional similarity to all other Himalayan Tertiary leucogranites¹³, we can conclude that this body has not experienced significant fractionation and the whole rock chemistry reflects the liquid composition. Even if significant crystals were present at peak conditions, M would not vary significantly for our purposes. Therefore the Zr concentration of 66 p.p.m. and M value of 1.2 indicates a melting temperature of $\sim 730^\circ\text{C}$ (ref. 11). This calculation overestimates the actual temperature because of the presence of a portion of undissolved restitic zircon. Through optical and isotopic evidence of 'average' zircons in this sample, a liberal estimate of this portion is between 20 and 50%. Recalculation using 80–50% of the Zr in the whole rock yields a reduction of the calculated temperature to between 710 and 680°C .

Results from the eight fractions of monazite fall on a line from an upper intercept of 471 ± 10 Myr (mean square of weighted deviates (MSWD) = 19.7) to the youngest fraction, which lies above concordia at 21 Myr (Fig. 2b). Four other monazite fractions also plot above concordia between 22 and 26 Myr. That these points plot above concordia can be explained by the incorporation during crystallization of ^{230}Th into the monazites and subsequent decay. ^{230}Th decays to ^{206}Pb with a half-life of 75,400 yr, thus producing excess (or unsupported) ^{206}Pb (ref.

8). The Th/U ratio of the monazite (calculated from Pb isotope ratios) with the youngest apparent age (Table 1) and the Th/U of the whole rock (Table 2) indicate that $\sim 10\%$ of the ^{206}Pb in this fraction is from the decay of ^{230}Th , given that the crystallization age is 20 Myr—virtually identical to that observed (Table 1).

The rocks that melted to produce this granite were probably older metasedimentary rocks. The excellent linear array of monazite analyses suggests that the upper intercept of $471 \pm$

Table 2 Chemical composition of sample $\Delta 33$

SiO ₂	73.12	V	<10
TiO ₂	0.13	Cr	7
Al ₂ O ₃	15.18	Ni	<10
Fe ₂ O _{3t}	1.11	Ba	432
MnO	0.02	Nb	9
MgO	0.20	Ta	1.0
CaO	0.66	Zr	66
Na ₂ O	3.44	Hf	2.0
K ₂ O	4.91	Sr	104
P ₂ O ₅	0.61	Rb	259
LOI	0.90	Pb	11
		Th	8
Total	99.87	U	15
		La	15
$M = 1.2$		Ce	35
		Pr	0.29*
		Nd	20*
		Sm	5.5
		Eu	0.66
		Gd	0.24*
		Tb	0.6
		Yb	1.2
		Lu	0.15

Major elements in per cent; trace elements in p.p.m.; M equals the cation ratio $(\text{Na} + \text{K} + 2\text{Ca})/(\text{Al} \cdot \text{Si})$; LOI, loss on ignition.

* Interpolated value.

10 Myr reflects an earlier metamorphism of these source rocks, although this age may reflect averaging of discrete populations. The four essentially collinear zircon results which define the top of the triangular region yield an upper intercept of 502 ± 10 Myr (MSWD = 5.1). These two results are similar to U-Pb zircon, $^{40}\text{Ar}/^{39}\text{Ar}$ hornblende, and Rb-Sr whole rock ages obtained from orthogneisses from the Himalayas and southern Tibet (refs 14, 15 and M. S. Hubbard, personal communication). The line defined by monazite analyses clearly represents a mixture between an inherited component (with the possibility of some Pb loss) and a magmatic component at 20 Myr. The possibility that this line represents *only* lead loss at ~ 20 Myr from a population of monazite with a U-Pb age of 471 Myr is precluded by the presence of excess ^{206}Pb in the fractions with the youngest apparent ages. Pb loss will displace points along a chord ending at concordia, whereas incorporation of ^{230}Th into a monazite during crystallization from a melt will displace points above concordia. Many workers (for example, see refs 16 and 17) have argued that the degree of concordancy is the criterion by which U-Pb monazite analyses should be judged when determining crystallization ages. Note, however, that the presence of a nearly concordant monazite fraction at about 26 Myr does not give the age of this granite, but rather it coincidentally plots near the intersection between concordia and the discordia from the upper intercept to the young fractions which contain excess ^{206}Pb . The crystallization age for this granite is taken to be 20 ± 1 Myr, given by the agreement between the single concordant zircon and the monazite fraction with the youngest apparent $^{207}\text{Pb}/^{235}\text{U}$ age.

As with the presence of undissolved zircon, the identification of a restitic component in these monazites allows a second method for calculation of the temperature of melting for this granite^{18,19}. Based on monazite solubility systematics and a whole rock light rare earth elements (LREE) concentration of 76 p.p.m. (Table 2), a maximum temperature of $\sim 727^\circ\text{C}$ is indicated. The pattern of discordance for these monazites (highest U in oldest fractions, substantial magmatic ^{230}Th) suggests the inherited component to be ~ 10 –20%. If we then take 90–80% of the total LREEs, the temperature of monazite saturation is calculated to be ~ 720 –710 $^\circ\text{C}$. This range is similar to that calculated from the zircon saturation systematics.

The U-Pb systematics of monazite from this sample confirm the conclusion of Sawka and Harrison²⁰ that residual monazite can retain an inherited Pb* signature through a crustal melting episode. Three pieces of information are required for us to infer closure temperature significance of these data²¹. (1) The degree of isotopic equilibration, (2) the peak temperature of melting and (3) the duration of peak heating. The degree of equilibration is complicated by the significant growth of new monazite evidenced by the ^{230}Th disequilibrium, but our view is that no more than ~ 10 –20% of this monazite can be residual, implying a relatively low degree of diffusive equilibration of the restitic monazite ($< 50\%$). The zircon and monazite saturation temperatures are consistent with experimental studies of water saturated or near saturated anatexis systems^{22,23} and their internal consistency leads us to take the peak temperature to be $710 \pm 30^\circ\text{C}$. To explain the age contrast between leucogranite belts in the Higher and Tethyan Himalaya, Pinet and Jaupart²⁴ have proposed a thermal model which involves heat refraction from the Tibetan Slab/Tethyan sedimentary rock interface. This model predicts a duration for the melting event of about 5 Myr. Although more specific predictions must await a Pb diffusion law for monazite, these parameters imply a closure temperature of 720–750 $^\circ\text{C}$ for a cooling rate of 20 $^\circ\text{C}$ per Myr and a crystal dimension of 10 to 100 μm . This closure temperature for Pb in monazite is significantly higher than the value of 530 $^\circ\text{C}$ suggested by Wagner *et al.*²⁵, and somewhat higher than estimates of 650–700 $^\circ\text{C}$ (ref. 26) inferred from monazite analyses in high-grade paragneisses and other Himalayan leucogranites. Sawka and Harrison²⁰ observed that U-Pb monazite results from S-type

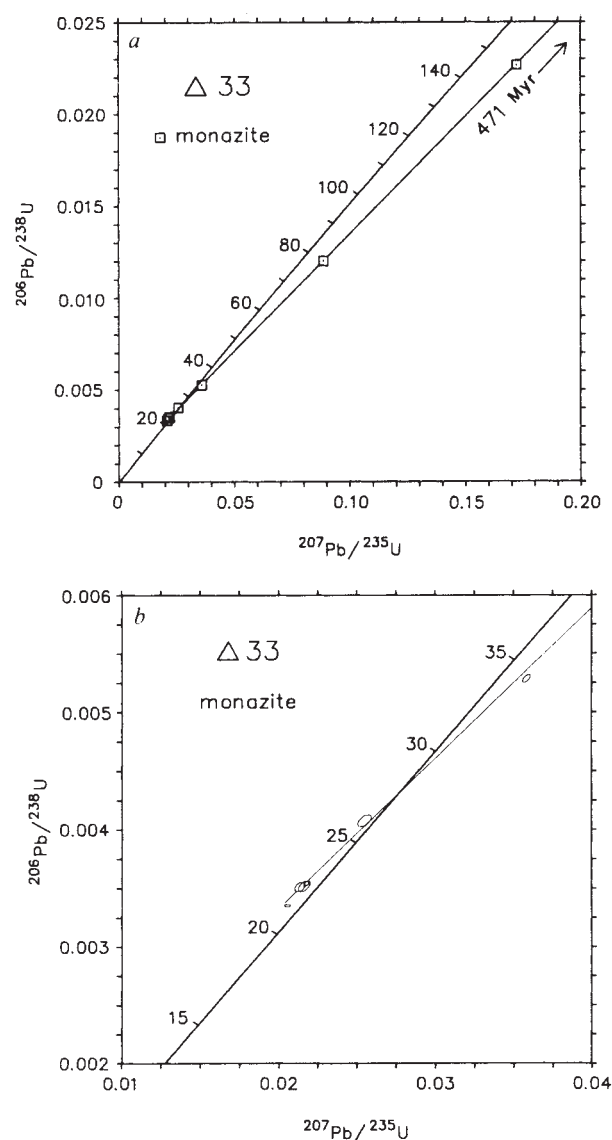


Fig. 2 Concordia diagram for monazites from $\Delta 33$: a, eight monazite fractions shown plot on a discordia from an upper intercept of 471 ± 10 Myr to the youngest monazite fraction which plots above concordia at 21 Myr. b, Blowup of area around the monazites which contain excess ^{206}Pb from the decay of ^{230}Th showing two sigma error ellipses.

granites^{27,28} are often older than independently established crystallization ages, and speculated that this might reflect Pb* accumulation in monazite after crystallization by dehydration of LREE-rich hydrous phosphates (such as rhabdophane) during prograde metamorphism of a metasedimentary lower crust²⁹. Although this mechanism may ultimately account for the origin of the restitic monazite, our data clearly suggest that this monazite growth did not occur during the Tertiary orogenic cycle, but during a Palaeozoic event.

The identification of inherited Pb* in the monazites in this sample suggests caution should be used in interpreting U-Pb monazite ages from S-type granites where only one or two 'concordant' fractions were analysed, especially in magmas with high U/Th. Proper interpretation of monazite U-Pb systematics requires full understanding of its pattern of discordance based on analysis of multiple fractions of monazite.

We thank Karl Wirth of Cornell University for the neutron activation analysis. XRF analysis was performed at McGill University. This research was supported by the NSF.

Received 1 March; accepted 5 May 1988.

- Parrish, R. R. *Isotope Geosci.* **66**, 99-102 (1987).
- Parrish, R. R., Roddick, J. C., Loveridge, W. D. & Sullivan, R. W. *Geological Survey of Canada Paper* 87-2 (1987).
- Roddick, J. C., Loveridge, W. D. & Parrish, R. R. *Isotope Geosci.* **66**, 111-121 (1987).
- Parrish, R. R. & Krogh, T. E. *Isotope Geosci.* **66**, 103-110 (1987).
- Deniel, C., Vidal, P., Fernandez, A., LeFort, P. & Peucat, J.-J. *Contr. Miner. Petrol.* **96**, 78-92 (1987).
- Gariépy, C., Xu, R. H. & Allegre, C. J. *Terra Cognita* **3**, 265 (1983).
- Vidal, P. *et al. Phys. Earth planet. Inter.* **35**, 179-190 (1984).
- Schärer, U. *Earth planet. Sci. Lett.* **67**, 191-204 (1984).
- Schärer, U. & Allegre, C. J. *Earth planet. Sci. Lett.* **63**, 423-432 (1983).
- Schärer, U., Xu, R. H. & Allegre, C. J. *Earth planet. Sci. Lett.* **77**, 35-48 (1986).
- Watson, E. B. & Harrison, T. M. *Earth planet. Sci. Lett.* **64**, 295-304 (1983).
- Harrison, T. M. & Watson, E. B. *Contr. Miner. Petrol.* **84**, 66-72 (1983).
- LeFort, P. *et al. Tectonophysics* **134**, 39-57 (1987).
- Xu, R. H., Schärer, U. & Allegre, C. J., *J. Geol.* **93**, 41-57 (1985).
- Jäger, E., Bhandari, A. K. & Bhanot, V. B. *Eclogae Geol. Helv.* **64**, 521-528 (1971).
- Barreiro, B. & Eusden, J. D. Jr *Geol. Soc. Am. Abstr. Progm.* **20**, 4 (1988).
- Köppel, V., Günther, A. & Grünfelder, M. *Schweiz. min. petrogr. Mitt.* **61**, 97-119 (1980).
- Rapp, R. P. & Watson, E. B. *Contr. Miner. Petrol.* **94**, 304-316 (1986).
- Rapp, R. P., Ryerson, F. J. & Miller, C. J. *Geophys. Res. Lett.* **14**, 307-310 (1987).
- Sawka, W. N. & Harrison, T. M. *Geol. Soc. Am. Abstr. Progm.* **18**, 64 (1986).
- Dodson, M. H. *Contr. Miner. Petrol.* **40**, 259-274 (1973).
- Bernard, F., Moutou, P. & Pichavant, M. *J. Geol.* **93**, 271-291 (1985).
- Huang, W. L. & Wyllie, P. J. *J. geophys. Res.* **86**, 10515-10544 (1981).
- Pinet, C. & Jaupart, C. *Earth planet. Sci. Lett.* **84**, 87-99 (1987).
- Wagner, G. A., Reimer, G. M. & Jäger, E. *Mem. Inst. Geol., Univ. Padova* **30** (1977).
- Parrish, R. R. *Geol. Assn. Canada Abstr.* **13**, A94 (1988).
- Williams, I. S. thesis, Australian National Univ. (1977).
- Harrison, T. M., Aleinikoff, J. N. & Compston, W. *Geochim. cosmochim. Acta* **51**, 2549-2558 (1987).
- Sawka, W. N., Banfield, J. F. & Chappell, B. W. *Geochim. cosmochim. Acta* **50**, 171-175 (1986).

Percussion marks on bone surfaces as a new diagnostic of hominid behaviour

Robert J. Blumenschine & Marie M. Selvaggio

Department of Anthropology, Rutgers University, New Brunswick, New Jersey 08903, USA

Since stone tool cut marks and carnivore tooth marks were first described systematically on Plio-Pleistocene archaeological bone^{1,2}, bone surface modification has played a prominent role in interpreting early archaeological site formation and hominid behaviour³⁻¹⁵. Here we introduce a new class of bone surface modification, which we call percussion marks. Percussion marks were produced during experimental breakage of marrow bones, and occur as pits or grooves impressed on a bone's surface by natural protrusions on the granitic hammerstone and anvil used. Although percussion marks can superficially mimic carnivore tooth marks, they nonetheless are closely associated with hammerstone impact notches and show consistent micromorphological features which distinguish them from tooth marks and other classes of bone surface modification. Given indications of prehistoric hammerstone breakage of marrow bones^{1,7}, an awareness of percussion marks is critical for accurately identifying the biological agents of bone modification at archaeological sites and provides a new diagnostic of carcass processing by hominids.

Fresh long bones of Thompson's and Grant's gazelle, impala and wildebeest were broken after skinning and defleshing by resting each bone horizontally on a rounded anvil surface opposite the point of intended hammerstone impact. Bones were broken so that all marrow could be efficiently removed with a 12-inch probe (see ref. 6 for details) and were subjected to no further modifying influence. 327 fragments longer than 2 cm were generated from the three main bones of 12 limbs of seven animals.

Percussion pits (roughly circular in plan) and/or grooves (displaying clear linearity) were produced on the surface of 123 specimens, or 37.6% of the sample. Marked specimens bear an average of over two pits and/or grooves, many of which become macroscopically apparent only after cleaning (boiling) and inspection under low-incidence light. To our knowledge, Free-

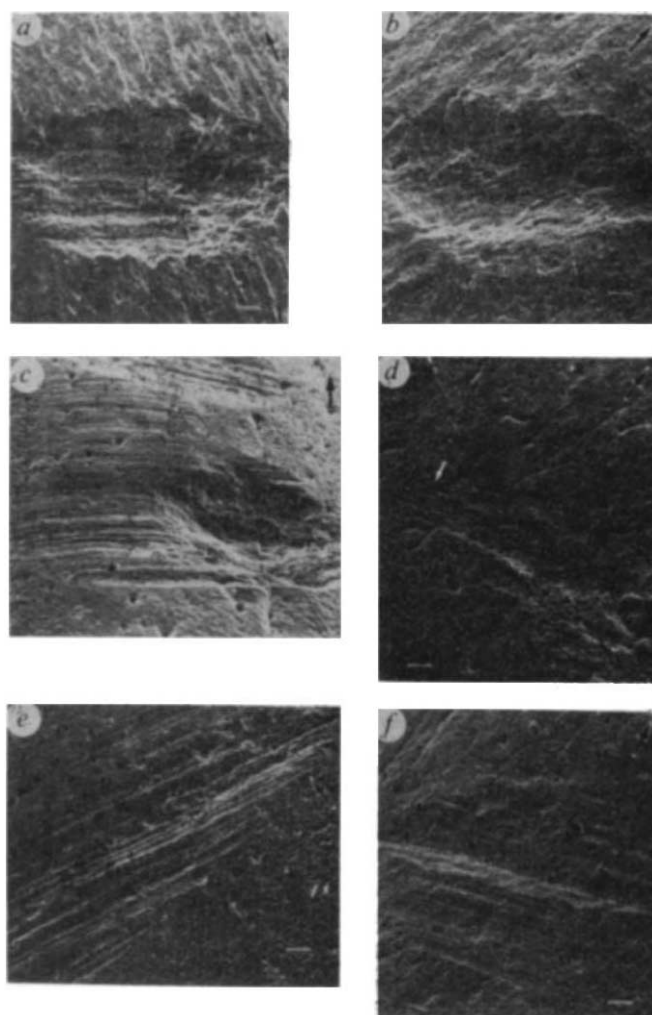


Fig. 1 *a*, Scanning electron micrograph of percussion pit with microstriations restricted mainly within pit boundaries. Uncharacteristically, microstriations were not readily visible macroscopically, but were apparent under incident-light stereomicroscope at thirty-power. *b*, Typical spotted hyena tooth pit lacking microstriations, but otherwise superficially similar to *a*. *c*, Percussion pit more typical than *a*, with microstriations emanating from it. Microstriations were conspicuous macroscopically under strong low-incidence light. *d*, Spotted hyena tooth pit with four wider, shorter and less densely packed microstriations (small arrow) than in *c*. Microstriations, which accompany tooth pits infrequently, macroscopically resemble tooth-scoring, but on a smaller scale. *e*, Percussion groove containing and flanked by microstriations. Groove is actually embedded portion of otherwise shallow patch of microstriations. *f*, Same as *e*, but groove is bevelled and its upper margin forms edge of patch of microstriations. Arrows in upper right corner indicate direction of bones' longitudinal axes. Scale bars: *a*, *c* and *d*, 0.15 mm; *b* and *e*, 0.14 mm; *f*, 0.13 mm.

man's¹⁶ incidental remark on what appear to be similar modifications to several experimental bone tools is the only previous mention of such marks.

Because percussion pits (Fig. 1*a*) can mimic carnivore tooth pits (Fig. 1*b*), and percussion grooves are less easily confused macroscopically with tooth scores or other marks, we conducted a morphological comparison of 20% random samples of percussion-pitted ($n = 21$) and spotted hyena tooth-pitted ($n = 32$) specimens. The latter sample derives from observed episodes of spotted hyena destruction of marrow bones in natural settings^{5,6}. After macroscopic analysis using a ten-power hand lens, pits were moulded^{7,15} and examined under a light microscope at 30 magnifications.