to heights of $\lesssim 600$ km, beyond which the atmosphere gets forbiddingly light. Angular-momentum conservation during this last rise, through $\lesssim 10\%$ of the earth's radius, will make it move westward at $\lesssim 10\%$ of a full revolution per day.

Whilst the gas rises, its load, the snow flakes, will stay at a much lower temperature T_f, near 10^2 K, given by the equilibrium between partial solar absorption plus particle bombardment balanced by thermal radiation:

$$T_f \gtrsim (\pi n k T_g v_{th}/\sigma_{SB})^{1/4} \lesssim 10^2\ K\ T_3^{3/8}. \quad (8)$$

They will scatter the sunlight and give rise to bright nights. Note that such small flakes, or ice crystals, even though heavy, would not fall fast because Stokes' friction grows inversely with the dynamic viscosity η which is independent of density, and grows with the square root of gas temperature: $v_{ff} = mg/6\pi R\eta$, $\eta \sim T_g^{1/2}$. Their free-fall speed can be smaller than that in the troposphere.

1. Gold, T. and Soter, S., *Science*, 1979, **204**, 371–375.
2. Krinov, E. L., *Giant Meteorites*, Pergamon, 1966, pp. 125–265.
3. Gallant, R. A., *Sky and Telesc.*, 1994, **87**, 38–43.
4. Schäfer, W. A., *Feur über Tunguska, Star Obs.*, 1998, **12**, 52–56.
5. Vasilyev, N.V., *Planet Space Sci.*, 1998, **46**, 129–143.
6. Kundt, W., *Star Obs. Spec.*, 1999, **5**, 44–49.
7. Ol'khovatov, A. Yu., Internet: www.geocities.com/Cape Canaveral/Cockpit/3240, 1999.
8. Brauner, B., *Nature*, 1908, **78**, 221.
9. Denning, W. F., *Nature*, 1908, **78**, 221; 247.
10. Wolf, M., *Astron. Nachr.*,1908, **178**, 297–300; see also p. 239.
11. Pasechnik, I. P., in *Space Matter in the Earth*, Nauka Publishers, Siberian Branch, Novosibirsk, 1986, pp. 25–54 (in Russian).
12. Dawson, J. B., *Kimberlites and their Xenoliths*, Springer, Berlin, 1980.
13. Haggerty, S. E., *Earth Planet. Sci. Lett.*, 1994, **122**, 57–69.
14. Chyba, C. F., Thomas, P. J. and Zahnle, K. J., *Nature*, 1993, **361**, 40–44.
15. Svetsov, V. V., *Nature*, 1996, **383**, 697–699.
16. Foschini, L., *Astron. Astrophys.*, 1999, **342**, L1–L4.
17. Svetsov, V. V., Kolesnikov, E. M. and Kolesnikova, N. V., *EOS*, 1999, **80**, 92.
18. Kolesnikov, E. M., Boettger, T., Kolesnikova, N. V., *Planet. Space Sci.*, 1999, **47**, 905–916.
19. Gold, T., *The Deep Hot Biosphere*, Springer-Verlag, New York, 1999.
20. Longo, G., Serra, R., Cecchini, S. and Galli, M., *Planet. Space Sci.*, 1994, **42**, 163–177.
21. Serra, R., Cecchini, S., Galli, M. and Longo, G., *Planet. Space Sci.*, 1994, **42**, 777–783.
22. Bronshten, V. A., *Planet. Space Sci.*, 2000, **8**, 855–870.
23. Bronshten, V. A., *Solar Syst. Res.*, 1991, **25**, 490–504.
24. Pichler, H., *VULKANISMUS*, Spektrum der Wissenschaft, Heidelberg, 1985.
25. Cox, A., *Allen's Astrophysical Quantities*, Springer 1999, 4th edn.
26. King-Hele, D. G., *Satellite Orbits in an Atmosphere: Theory and Applications*, Blackie, 1987.
27. Ol'khovatov, A. Yu., pers. commun., 2000.
28. Wexler, H. and Hass, W. A., *J. Geophys. Res.*, 1962, **67**, 3875–3887.
29. Krinov, E. L., *Principles of Meteorites*, Pergamon, 1960.
30. Alvarez, W., *T. rex, and the Crater of Doom*, Penguin Books, 1997.
31. Walker, D. A., *Science*, 1985, **227**, 607–611.
32. Kundt, W. and Jessner, A., *J. Geophys.*, 1986, **60**, 33–40.
33. Kundt, W., in *Strategies for Future Climate Research* (ed. Mojib Latif), Klaus Hasselmann's 60th anniversary, Hamburg, 1991, pp. 375–383.
34. Landau, L. D. and Lifshitz, E. M., VI, *Hydrodynamik*, 1966.
35. Zahnle, K., *Nature*, 1996, **383**, 674.
36. Chapman, C. R. and Morrison, D., *Nature*, 1994, **367**, 33–39.
37. Rabinowitz, D., Helen, E., Lawrence, K. and Pravdo, S., *Nature*, 2000, **403**, 165–166.
38. Jewitt, D., *Nature*, 2000, **403**, 145–147.

ACKNOWLEDGEMENTS. The idea that the Tunguska catastrophe was not a meteoritic event was handed out to me by Daniel Fischer in the Spring of 1998, in the form of Andrei Ol'khovatov's internet article (version 2, which he could not believe). In the meantime, I owe much of my technical understanding to dozens of e-mail consultations by him. I should likewise like to thank Thomas Gold and Richard Spalding for correspondences on mystery clouds, and Gerd Prölß for information on the thermosphere. Finally, my thanks go to Hans Baumann and Gernot Thuma for a lot of feedback during our weekly seminars, and to Axel Jessner for an agitated exchange after working hours.

Received 26 February 2001; revised accepted 19 April 2001

Detrital zircons constraining basement age in a late Archaean greenstone belt of south-eastern Rajasthan, India

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We report a $^{207}Pb/^{206}Pb$ age of ca. 3230 Ma age for detrital zircon grains from the quartzite of the greenstone association in the Rakhiawal area, east of Udaipur, south-eastern Rajasthan. The age helps to constrain the maximum age of the greenstone belt of the region.

IN central and south-eastern Rajasthan, in the north-western part of the Indian Shield, a number of large outcrops of gneissic basement rocks of Archaean age occur within the belts of Proterozoic supracrustal rocks assigned to the Aravalli and the Delhi Supergroups[1] (Figure 1). Structural investigations[2] and available geochronological data[3-5] indicate that some of the basement

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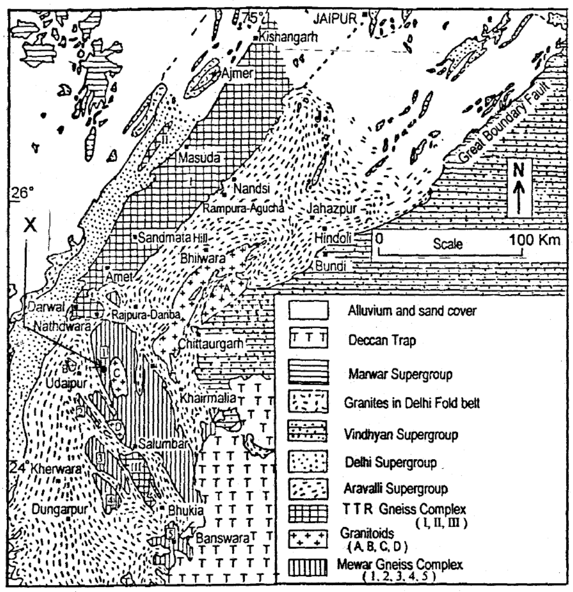

Figure 1. Generalized geological map of central and south-eastern part of the Aravalli mountains (modified after GSI map and Roy[1]). 'X' marks the map area in Figure 2.

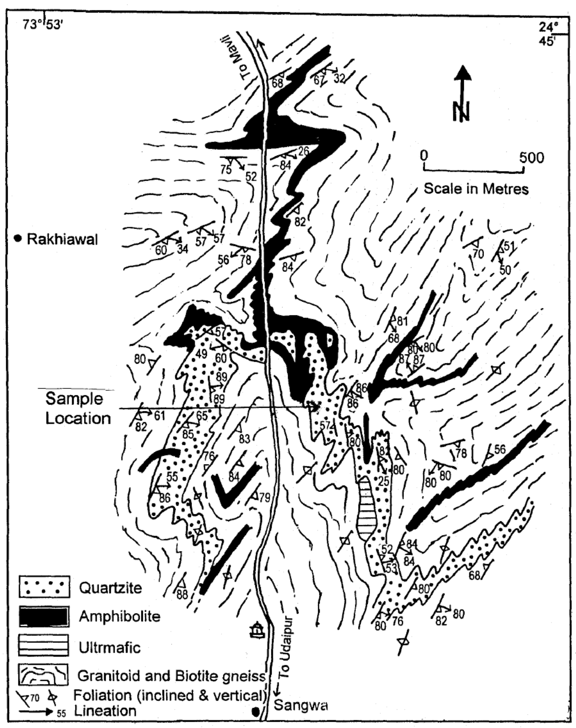

Figure 2. Geological map of Rakhiawal area, north-east of Udaipur, showing complex outcrop pattern of rocks of the greenstone association (after Roy *et al.*[13]).

blocks (the Sandmata Complex, for example) experienced extensive Palaeoproterozoic reconstitution. Some other blocks of the basement rocks on the other hand (the Mavli block, for example), remained tectonically passive (low-strain zone) during the Palaeoproterozoic orogenic cycles. It is from these basement blocks that records of Archaean crustal history have recently been recorded[6–9].

Several workers have mapped isolated remnants of greenstone belts in different parts of the Mavli block[10–12]. More recently, Roy *et al.*[13] mapped patches of greenstone belts in detail in the region around Rakhiawal, about 15 km south-east of Mavli (Figure 2). We analysed a few grains of detrital zircons from quartzite, which constitutes an important component of the greenstone association along with marbles and mafic and ultramafic rocks. In this note, we report an early-to-middle Archaean age for these zircons, which we interpret as the possible age of the rocks of the pre-greenstone basement.

The area around Rakhiawal exposes a variety of supracrustal rocks with granitoids and biotite gneisses of granitoid origin (Figure 2). The latter rocks are mineralogically and lithologically similar to 3.3 Ga-old tonalitic gneisses of the Jhamarkotra region, south-east of Udaipur[6,7]. The youngest granitoids that occur in the region display intrusive relationships with all the other rocks of the region. Ion-probe data on zircons from the latter type of granitoid from the Mavli region (the Untala Granite) yielded an age of 2505 ± 3 Ma (ref. 8). We presume that this late Archaean granitic activity marks the closing stage of the Mavli–Rakhiawal greenstone belt evolution.

There are no age data to confirm the maximum age for these greenstone belt rocks, i.e. the age of the pre-greenstone belt basement. The map pattern and structural data of the rocks of the greenstone association[13] indicate presence of a number of layers of amphibolite. The major one, which intrudes into quartzite beds, was folded together with the latter. Sm–Nd isochron age for these amphibolites is 2828 ± 46 Ma (ref. 6). The sedimentary character of quartzites, which yielded zircon is confirmed by rare presence of cross-bedding in these rocks. Based on chemical composition and the positive initial $\Sigma_{Nd(t)}$, we suggest that the presumably gabbroic protoliths of the amphibolites were products of mantle melting. Presuming that there may not have been much difference in age between the protolith of the amphibolites and deposition of quartzite, we may not be far off the mark in assuming 2830 Ma as the age of formation of the Rakhiawal–Mavli greenstone belt. There are no age data on the biotite gneisses of the area, nor do the field relationships prove the basement status of these gneisses.

Initial methodology involved mechanical separation of zircon grains from the samples using a roller mill, followed by gravity (Wilfley table) and magnetic separation and handpicking of grains. Zircons separated from the quartzite samples are long prismatic, having

Table 1. Isotopic data from single grain of zircon evaporation (Sample no. RKL 99/1)

Zircon colour and morphology	Grain #	Mass scans[a]	Evaporation temperature in °C	Mean $^{207}Pb/^{206}Pb$ ratio[b] and 2-σ_m	$^{207}Pb/^{206}Pb$ age (Ma) error with 2-σ_m error
Pink to light red,	1	104	1596	0.257611 ± 53	3232.2 ± 0.3
short prismatic,	2	62	1597	0.257624 ± 46	3232.2 ± 0.3
well rounded	3	66	1599	0.257645 ± 51	3232.4 ± 0.3
terminations	4	85	1596	0.257633 ± 54	3232.3 ± 0.3
Mean of 4 grains	1–4	317		0.257627 ± 26	3232.3 ± 0.2

[a]Number of $^{207}Pb/^{206}Pb$ ratios evaluated for age assessment.

[b]Observed mean ratio corrected for non-radiogenic Pb where necessary. Errors based on uncertainties in counting statistics.

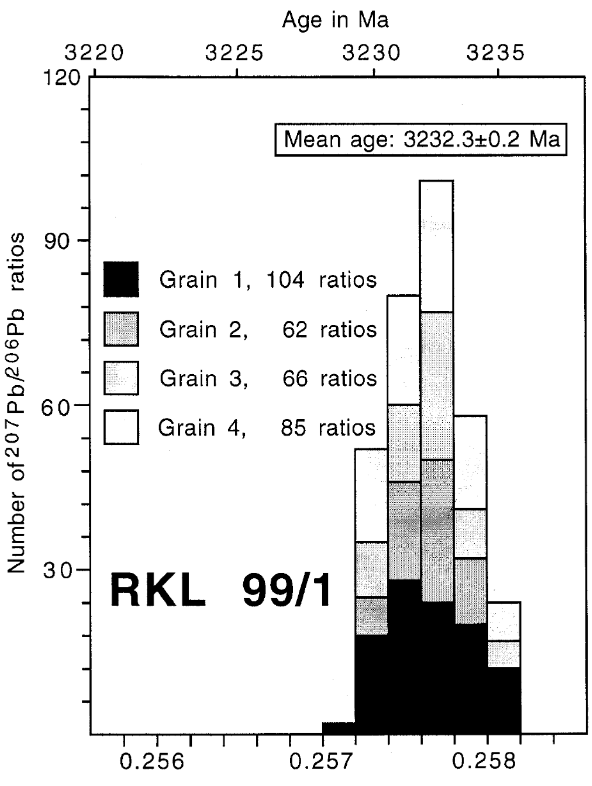

Figure 3. Histogram showing distribution of Pb isotope ratios derived from evaporation of 4 zircons from quartzite sample RKL 99/1. The pattern is integrated from 317 ratios. Mean age is given with 2-sigma error.

abraded terminations. Most grains were transparent. The colour varied from very light brown to light honey-yellow.

Isotopic measurements were carried out on a Finnigan-MAT 261 mass spectrometer at the Max Plank Institut für Chemie in Mainz, Germany. In the present study, Kober's[14,15] single zircon evaporation technique was used with slight modifications[16]. This involved repeated evaporation and deposition of Pb-isotopes from chemically untreated single zircons in a double-filament arrangement. No correction was made for mass fractionation, which is of the order of 0.03% (Todt, pers. commun.), significantly less than the relative standard deviation of the $^{207}Pb/^{206}Pb$ ratios, and insignificant at the range considered in this study. The measurement yielded a $^{207}Pb/^{206}Pb$ age 564.8 ± 1.4 Ma, identical to the adopted age of 564 Ma for this standard[17]. Evaporation temperatures were gradually increased in 20–30 steps during repeated evaporation-deposit cycles, until no further changes in the $^{207}Pb/^{206}Pb$ ratios were observed. Only data from high-temperature runs or those with no changes in the Pb isotopes were considered for geochronological evaluation. The calculated $^{207}Pb/^{206}Pb$ ratios and their 2-sigma (mean) errors are based on the means of all measurements evaluated and are presented in Table 1. The $^{207}Pb/^{206}Pb$ spectra are shown in the histogram in Figure 3 that permits visual assessment of the date distribution from which the age was derived.

Four grains were evaporated individually and yielded comparable $^{207}Pb/^{206}Pb$ isotope ratios (Table 1) that provide a mean age of 3232.3 ± 0.2 Ma (Figure 3). The fact that all grains are of the same age, strongly suggests that they were derived from a homogeneous granitoid source. It is thus likely that the detrital material contained in the quartzite reflects a granitoid basement predating sequence in the Rakhiawal region.

Study by Roy and Kröner[7] confirmed a virtually 600 million-year history (from ca.3230 to 2620 Ma) of the Archaean Aravalli craton of the north-western Indian Shield. Within this long span of Archaean crustal history, a number of greenstone belts have evolved in different parts of the Archaean crust. Ca. 3230 Ma age of detrital zircons separated from the quartzite of the Mavli–Rakhiawal region, therefore, helps to constrain the maximum age of the greenstone belts. The age is quite compatible with that of the TTG-type granitoid gneisses of the Jhamarkotra region[6–8], about 30 km south-southeast of the Mavli–Rakhiawal region. Our study, therefore, implies the presence of early to middle

Archaean granitic basement for the greenstone belts, which evolved during middle Archaean and late Archaean periods.

1. Roy, A. B., *Mem. Geol. Soc. India*, 1988, **7**, 3–31.
2. Naha, K. and Roy, A. B., *Precambrian Res.*, 1983, **19**, 217–223.
3. Choudhary, A. K., Gopalan, K. and Sastry, C. A., *Tectonophysics*, 1984, **105**, 131–140.
4. Fareeduddin and Kröner, A., in *The Indian Precambrian* (ed. Paliwal, B. S.), Scientific Publishers (India), Jodhpur, 1998, pp. 547–556.
5. Sarkar, G., Ray Barman, T. and Corfu, F., *J. Geol.*, 1989, **97**, 607–612.
6. Gopalan, K., Macdougall, J. D., Roy, A. B. and Murali, A. V., *Precambrian Res.*, 1990, **48**, 287–297.
7. Roy, A. B. and Kröner, A. *Geol. Mag.*, 1996, **133**, 333–342.
8. Wiedenbeck, M., Goswami, J. N. and Roy, A. B., *Chem. Geol.*, 1996, **129**, 325–340.
9. Wiedenbeck, M. and Goswami, J. N., *Geochem. Cosmochem. Acta*, 1994, **58**, 2135–2141.
10. Bose, U. *et al.*, *J. Geol. Soc. India*, 1996, **47**, 325–338.
11. Sahoo, K. C. and Mathur, A. K., *J. Geol. Soc. India*, 1991, **38**, 299–302.
12. Upadhyaya Rajani, Sharma, B. L., Jr., Sharma, B. L., Sr. and Roy, A. B., *Curr. Sci.*, 1992, **63**, 87–92.
13. Roy, A. B., Kataria, P., Kumar, Sanjay and Laul, Vivek, in *Tectonomagmatism, Geochemistry and Metamorphism of Precambrian Terrains* (eds Gyani, K. C. and Kataria, P.), University Department of Geology, Udaipur, 2000, pp. 143–157.
14. Kober, B., *Contrib. Mineral. Petrol.*, 1986, **93**, 482–490.
15. Kober, B., *Contrib. Mineral. Petrol.*, 1987, **96**, 63–71.
16. Kröner, A. and Todt, *J. Geophys. Res.*, 1988, **93**, 15,329–15,337.
17. Pidgeon, R. T., Furfaro, D., Kennedy, A. and Van Bronswjk, W., *US Geol. Surv. Circular*, 1994, **1107**, 251.

ACKNOWLEDGEMENTS. Thanks are due to the Head, Geology Department, Mohanlal Sukhadia University for providing facilities for the work. We are grateful to Prof J. N. Goswami, Physical Research Laboratory, Ahmedabad for facilitating zircon separation. Our sincere thanks to Dr P. Kataria for his help during fieldwork, and to Dr S. R. Jakhar who assisted in preparation of line drawings. Financial assistance received from the Indian National Science Academy in the form of a Senior Scientist fellowship to A.B.R. is acknowledged.

Received 18 December 2000; revised accepted 11 April 2001