

Series, Cambridge University Press, London 1985, pp. 17–86.

13. Premoli, Silva I., Garzanti, E. and Gaetani, M., *Riv. Ital. Paleontol. Stratigr.*, 1992, **97**, 511–564.
14. Mathur, N. S. and Juyal, K. P., *J. Himalayan Geol.*, 1994, 21–33.

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On the origin of the artesian groundwater and escaping gas at Narveri after the 2001 Bhuj earthquake

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At Narveri, north of Khavada in the Great Rann of Kachchh, an outflow of groundwater continued even more than four months after the Bhuj earthquake of 26 January 2001, although at a considerably reduced rate compared to that immediately following the earthquake. Air or gas bubbling through the freshly oozing water has also been observed. We had collected a large number of samples from different parts of Gujarat, where post-earthquake groundwater outpourings were reported. Narveri, however, was the only site where the samples showed dissolved helium concentrations, significantly above the air equilibration value. Based on measurements of helium, radon, chloride, sulphate and sodium concentrations and temperature, we suggest that the flowing water and escaping gases at Narveri have a deep confined source with a reservoir age in excess of $\sim 10^4$ years.

THERE are persistent reports that the Bhuj earthquake of 26 January 2001 caused large-scale liquefaction, resulting in oozing of groundwater and release of gases at many places over a large area, extending from Rajasthan to south Gujarat¹. Several instances of spontaneous

bursting of fountains and outpouring of water have been observed in the coastal areas of Gujarat and the Little and Great Ranns of Kachchh^{1–3}. A large water body (few tens of km long) can be seen in the IRS-LISS III false colour composite image (Figure 1), covering parts of the Great Rann of Kachchh, taken on 29 January 2001, three days after the earthquake. In a pre-earthquake picture (Figure 1) of the same area taken on 4 January 2001, this channel does not exist, suggestive of its post-earthquake origin. Such occurrences have been variously described as reappearance of the lost River Saraswati or activation of the ancient buried channels of the River Sindhu and their tributaries that are once believed to have flowed through this region, 4 or 5 ka ago^{4,5}. However, no scientific basis for such a conclusion has been put forth. Many instances of groundwater outpouring may be related to mobilization of water from shallow confined/unconfined sources due to liquefaction at sites underlain by susceptible sediments¹. In most cases the outflow of groundwater stopped shortly after the earthquake, within a period of a few hours to a few days, indicating limited mobilization. However, in a place called Narveri, north of Khavada (Figures 1 and 2) close to the Border Security Force (BSF) post, the outpouring of groundwater continued at the time of sampling about four and a half months after the earthquake, although the rate had considerably reduced compared to that immediately following the earthquake. Air or gases bubbling through the freshly oozing water have also been observed at Narveri.

Water in equilibrium with the atmosphere usually shows low concentrations of helium (measured in Air Equilibration Unit (AEU) ~ 5.3 ppm) and radon ($\sim 7 \times 10^{-4}$ dpm/l). In groundwater, helium and radium can be high if injected or released through fissures and faults from deep sources where they are produced by the decay of uranium and thorium series radionuclides. Moreover, during an earthquake, because of rock dilation and fracturing during incipient fault movements, both helium and radon can get further enhanced in groundwater. Consequently, to understand the origin and source of these waters and gases, samples of flowing water from Narveri and groundwater from the bores in its vicinity were collected for a detailed investigation. Sampling details are given in Table 1 and locations are marked in Figure 2. Sample numbers 5, 6 and 7, from three separate outpouring vents of groundwater, are within ~ 5 m of each other and are located close to the foot of the Kaladungar hill, about 100 m from the Narveri BSF post. Figure 3 shows the well of sample 6 through which water and gas bubbles can be seen as they are released.

Measurements of pH, EC and temperature were made in the field at the time of sample collection. Water samples for measurements of helium, radon and dissolved

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chemical species were collected in 3-mm thick, 1.2 l capacity, soda-lime glass bottles using procedures standardized in our laboratory for these analyses. Briefly, after complete purging of the air, the bottle was filled with water sample up to a pre-determined level, keeping headspace for exsolving gases. The bottles were immediately sealed using bromobutyl synthetic rubber stoppers manufactured according to US Pharmacopoeia Standard (USP-II) and secured by additional triple aluminium caps fixed by a hand-held sealing machine. To ensure retention of the exsolving gases, the bottles were stored with the sealed face down. This sampling and storage procedure has been tested in our laboratory and the maximum loss of helium during storage has been found to be $< 0.15\%$ per day.

The samples were analysed for dissolved helium within 48 h after collection and within 5 days for radon (^{222}Rn), SO_4^{2-} and Cl^- . The helium concentrations were measured using a helium sniffer probe (ALCATEL Model ASM 100 HDS). The helium probe is a leak detector comprising a mass-spectrometer tuned for ^4He ions ($m/e = 4$). Any interference due to ^3He can be neglected, since its concentration on the earth is more than 6 orders of magnitude lower⁶ than ^4He . Helium concen-

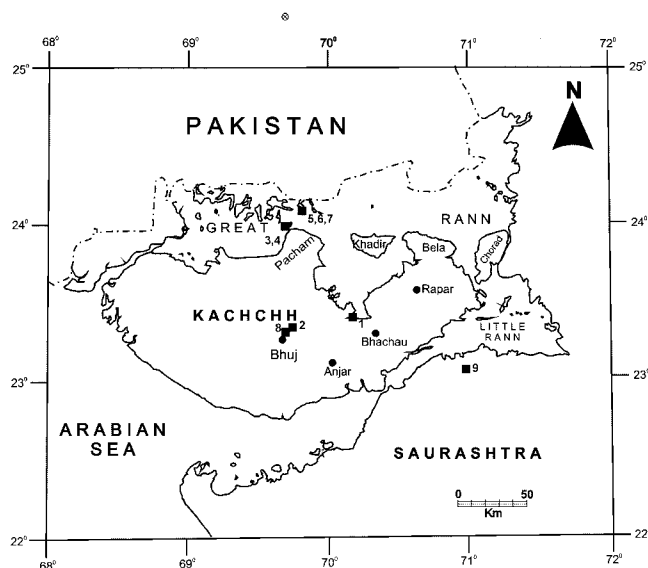


Figure 2. Map showing location of groundwater samples from Kachchh.



Figure 1. IRS false colour composite picture using LISS III covering parts of the Great Rann of Kachchh, taken on 29 January 2001 before the earthquake, showing the presence of several kilometre long water channel. Note the absence of water channel in another FCC of the same region taken on 4 January 2001.



Figure 3. Dug well at Narveri showing bubbles of gas (white) being released into the atmosphere and the ripples created by them.

trations are given in AEU, representing its concentration in water sample in equilibrium with air/gas at one atmospheric pressure and room temperature. Radon was measured by counting 609 keV gamma rays produced by the decay of its short-lived daughter ^{214}Bi using a High Purity Germanium (HPGe) γ -ray spectrometer, located in a low background, 10-cm thick lead shield. For this measurement, the water sample was transferred to a 620 ml PVC bottle after the helium measurement and sealed to prevent escape of gases. The counting efficiency of ^{214}Bi was determined using a ^{226}Ra source of known activity in the same configuration, to be 0.16% and the background in ^{214}Bi peak was 0.046 counts per minute. Concentrations of the parent ^{226}Ra and ^{230}Th in the water samples were found to be below our detection limit (≤ 25 dpm/l) indicating little dissolved U or Th or their daughter nuclides, except ^{222}Rn

and its daughters. Repeat counting after about a week confirmed that radon was unsupported. Alpha activity of the stripped radon from some samples (5 and 10) was also measured to confirm the radon concentration determined by γ -ray spectrometry (Table 2). Concentrations of ^{226}Ra measured by α counting are also given in Table 2. The concentration of ^{222}Rn in the PRL tubewell water has been measured earlier⁷ and is found to be in agreement with the measurements reported here (Table 2). Chloride and sulphate concentrations were analysed by ion chromatography using DIONEX 2000 ISP. Sodium and potassium measurements were made using atomic absorption spectrometer (PERKIN-ELMER, Model 4000). The results of various analyses are given in Tables 1 and 2.

Samples 1, 2, 4 and 8 show helium concentrations of ~ 5.3 ppm AEU, i.e. at a level expected in water in equilibrium with the atmosphere, whereas samples 3, 5,

6 and 7 show anomalously high helium concentrations ranging up to 14.1 ppm AEU. One of the outpouring vents containing high He concentrations (sample 6) is from a pre-existing dug well routinely used by local residents (Figure 3). Before the earthquake, water level in this dug well was ~ 2 m below the ground level. Our enquiry with local residents and BSF personnel revealed that there was no perceptible change of temperature (to feel) or quality (to taste) between the pre- and post-earthquake situations in case of the dug well water. Sample 3 is from a dug-cum-bore (DCB) well about 10 km from the Narveri BSF post. The helium concentration in this sample is only marginally in excess of the atmospheric equilibration value, but radon measurement could not be made on this sample. Sample 4 from another DCB, ~ 200 m from sample 3, however, does not have excess helium but has high salt content, indicating that shallow groundwater system can exhibit

Table 1. Sampling details and results of some chemical analyses of groundwater from Kachchh

Sample no.	Location	Sample date d.m.yr	Lat. °N	Long. °E	Well depth (m)	Well type	Temp. °C	pH	EC (μS)	Cl^{1-} ppm	SO_4^{2-} ppm	Na^+ ppm	K^+ ppm
1A, B	Morghar, Anjar	4.6.01	23.325	70.208	137	T	32	7.7	910	99	26	76	0.7
2A, B	Lakhond	4.6.01	23.265	69.781	152	T	31	7.1	1870	336	103	192	3.9
3A, B	Khavda	5.6.01	23.863	69.727	9	DCB	30	7.7	1250	179	77	162	10.9
4A, B	Khavda	5.6.01	23.864	69.728	15	DCB	31	7.1	5850	1579	481	834	29.7
5A, B	Nirveri, BSF Post	5.6.01	23.956	69.846	0	Flowing	33	7.0	8710	2243	1004	1653	28.0
6A, B	Nirveri, BSF Post	5.6.01	23.956	69.846	0	Flowing	31	7.1	8430	2225	995	1555	28.0
7A, B	Nirveri, BSF Post	5.6.01	23.956	69.846	0	Flowing DW	30	7.0	7900	2018	930	1523	26.3
8A, B	Madhavpur, Bhuj	5.6.01	23.235	69.732	61	T	29	7.1	4920	1064	111	662	14.3
9A, B	Juna Devalia	5.6.01	23.018	71.012	—	T	31	7.1	3770	727	356	589	2.7
10	PRL, Ahmedabad	13.6.01	—	—	213	T	—	7.7	3310	615	175	562	2.5

A and B refer to two sample bottles collected at the same time; T, Tube well; DW, Dug well; DCB, Dug-cum-bore well.

Table 2. Results of helium measurements and analyses of groundwater from Kachchh

Sample no.	^4He (ppm AEU)		Excess* ^4He (ppm AEU)	^{222}Rn dpm/l	$^{226}\text{Ra}^\&$ dpm/l	$(^4\text{He}/^{222}\text{Rn})$ age in years = $5.57 \times 10^6 \times ^4\text{He} \text{ (ppm AEU)} / ^{222}\text{Rn} \text{ (dpm/l)}$	
	A	B	C = Avg (A, B)-5.3	@	\$	\$	¥
1	5.3	5.3	Nil				
2	4.8	4.8	Nil				
3	5.9	5.9	0.6	—	—	—	—
4	5.3	4.8	Nil				
5	14.1	11.7	7.6	478 ± 33	450 ± 35	4.96 ± 0.12	8.9×10^4
6	11.7	10.6	5.9	904 ± 80	—	—	3.6×10^4
7	9.7	8.8	4.0	—	$1,900 \pm 140$	2.84 ± 0.19	1.2×10^4
8	4.8	4.8	Nil	98 ± 16	—	—	Modern
9	5.3	4.8	Nil				
10	5.3	5.3	Nil	781 ± 10	776 ± 28	—	Modern

AEU, Air Equilibration Unit representing concentration in air/gas in equilibrium with the water sample; *, Above atmospheric background; @, Values have been obtained by γ counting of 609 keV emission of ^{214}Bi ; \$, Value of ^{222}Rn is obtained by stripping the radon followed by α counting; &, Via ^{222}Rn measurement after decay of unsupported ^{222}Rn ; ¥, Based on the most common value of Th/U concentration ratio (~ 4) encountered in normal crustal rocks⁶. If the extreme Th/U concentration ratio of 1 or 5 represents the source rocks, the calculated ages using the Th/U = 4, will be over- or under-estimated by 59% or 13%, respectively. As discussed in the text, the overall error on the calculated ages is at most a factor of 2.

considerable variations even over short distances. Samples 5 and 7 represent freshly generated groundwater outflow due to the Bhuj earthquake. It may be mentioned that groundwater samples from Ahmedabad city and fresh vent samples from Motibaru (Taluka Dholka, District Ahmedabad) and Nada (Taluka Jambusar, District Bharuch) collected within a few days after the earthquake did not show anomalous helium above the atmospheric equilibration value. The concentrations of salts in various waters (Table 1) are high, but a correlation exists (Figure 4) between the temperature, Na^+ , Cl^- , SO_4^{2-} concentration in water samples from the three vents at Narveri, indicating the same source or passage through similar soil.

Both ^4He and ^{222}Rn are radiogenic, produced by radioactive decay of uranium and thorium series nuclides in soils and rock grains within the earth. The gases are released from grains by their etching, dissolution and fracturing and by alpha recoil and then exhaled into the atmosphere by diffusion and temperature variations. The earth's atmosphere has small concentrations of helium due to its escape, and of radon because of its radioactive decay. Since their production occurs in rocks and soils within the earth, their concentrations show a gradient decreasing towards the ground-atmosphere interface. Once exhaled into the atmosphere, the two gases rapidly mix with the tropospheric air. The mobility of radium in groundwater is to some extent, particle and salinity sensitive⁸. Since diffusivities (at 25°C) of helium and radon in water⁹ are small ($7.78 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}$ and $1.33 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}$, respectively), they generally follow mass flow of groundwater. Radon being radioac-

tive with a short half-life (3.825 d) is expected to be in steady state between production, decay and mobilization from rock/soil matrix. However, during and for short time following any disturbance such as an earthquake, the steady state conditions may not prevail. The ^4He on the other hand can go on accumulating in stationary or confined groundwater. Thus, measurement of $^4\text{He}/^{222}\text{Rn}$ ratio offers a way of estimating the pore-fluid age⁶. The solubility of helium in water depends upon the partial pressure of helium in the air/gas. According to Henry's law, the mole fraction of a gas A in water, X_A , is given by

$$X_A = K.P_A, \quad (1)$$

where P_A is the equilibrium partial pressure of gas in contact with water (in AEU) and K is Henry's constant = 6.997×10^{-6} (defining solubility of helium in water in mole fraction at one atmosphere partial pressure)⁹.

Knowing the helium concentration in AEU, eq. (1) can be used to estimate the number of helium atoms in any given volume of water. For example, $P_A = 1 \text{ ppm AEU}$ corresponds to 2.34×10^{14} atoms of $^4\text{He}/\text{l}$ of water.

Knowing the ^4He concentration ($C_4 = \text{atoms/l}$) and the radon activity ($A_{222} = \text{disintegration/l/year}$), the age of water can be calculated as follows. In the ^{238}U series, the decay chain yields 8 atoms of ^4He and one atom of ^{222}Rn . In the ^{232}Th series, the decay chain yields 6 atoms of ^4He . Although the concentration ratio of Th/U in rocks and soils varies in a wide range (1–5), the most

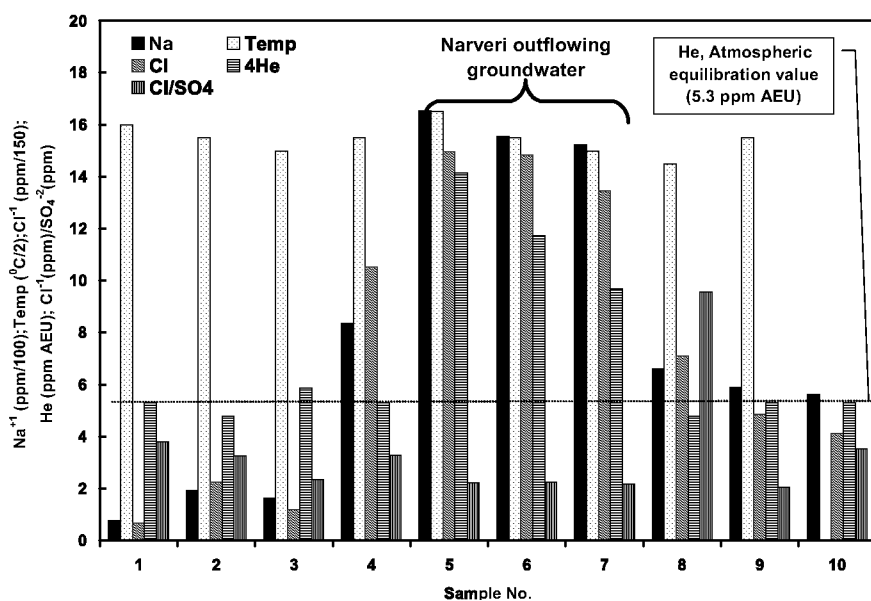


Figure 4. Histogram showing temperature, He, Na, Cl, Cl/SO₄ in various water samples. Note that the scales on the ordinate for individual parameters have been adjusted.

common value of Th/U in normal crustal rocks⁶ is ~ 4 . Adopting this value and the half-life of ^{232}Th (1.41×10^{10} a) and ^{238}U (4.91×10^9 a), the $A_{\text{Th}}/A_{\text{U}}$ activity ratio is estimated to be ~ 1.3 (= ratio of decay constants \times concentration ratio). Hence, the production ratio (P) of $^4\text{He}/^{222}\text{Rn}$ in rocks is given by $(8 + 1.3 \times 6) = 16$. Therefore

$$\text{Age (years)} = (R_{\text{Rn}}/R_{\text{He}}) \times 1/P \times C_4/A_{222}, \quad (2)$$

where R_{Rn} and R_{He} are the release factors representing fractions released from the solid phase into the pore fluid for ^{222}Rn and ^4He , respectively. The $^4\text{He}/^{222}\text{Rn}$ dating method assumes a close system and identical migratory properties for both the gases. These assumptions may not be strictly valid in hydrologic systems, resulting in uncertainties in the age calculated using eq. (2). We, therefore, discuss below the extent to which the $^4\text{He}/^{222}\text{Rn}$ ages can be affected by these uncertainties in natural systems.

It is easily seen that an increase or decrease in the assumed Th/U concentration ratio of ~ 4 will change the production ratio P and consequently decrease or increase the estimated age. If the extreme Th/U concentration ratio of 1 or 5 represents the source rocks, the calculated ages using the Th/U = 4 will be over- or under-estimated by 59% or 13%, respectively. The other important source of error is related to estimation of $R_{\text{Rn}}/R_{\text{He}}$ which depends on the release mechanisms⁶. Recoil of the decaying atom from the outer surface of the grains is one of the mechanisms by which radioactive products in the solid enter the pore fluid. The recoil path length for ^{222}Rn ($\sim 0.05 \mu\text{m}$)¹⁰ is considerably less than for ^4He ($30\text{--}100 \mu\text{m}$)⁶ and therefore the release factors depend on grain size. If R is the recoil path length of the particle in the grain and r the grain radius,

$$R_{\text{Rn}}/R_{\text{He}} = 1 \text{ to } < 7 \times 10^{-4} \text{ for } r < 0.025 \mu\text{m} \text{ to } 30 \mu\text{m}.$$

Apart from recoil, ^4He and ^{222}Rn can diffuse out of the solid through secondary pathways such as micro-cracks, grain boundaries, inter-phase cement or contacts in a multi-component grain. Andrews and Wood¹¹ from their study on sands, sandstones and limestones, showed a value of $R_{\text{Rn}} \sim 0.1$, constant for a large range of grain sizes. Laboratory studies of radon and thoron leakage from natural rocks and mineral fragments¹⁰ also indicated R_{Rn} in the range 1–20%, significantly more than expected due to recoil. These results have been explained¹² as a consequence of presence of a network of 100–200 Å wide nanopores throughout the rock or grain body. In addition, we must also consider the possibility that ^{226}Ra may not be homogeneously distributed in the rocks and mineral grains, with most of it residing on the outer periphery of the grains¹⁰, thereby increasing R_{Rn} .

Weathering, that includes dissolution, etching and fracturing of grains, also controls the release of gases. In addition to steady release (R_{He}), the remaining fraction ($1-R_{\text{He}}$) continuously accumulates in the grain with time and may get released in pulses due to rock dilation and fracturing and may dominate over steady-state release. ^{222}Rn , on the other hand, is more likely to decay quickly in view of its short half-life and will, therefore, not be much affected by this mechanism. In view of the large body of experimental data⁷ indicating 3 to 4 orders of magnitude higher activity of ^{222}Rn than its parent ^{226}Ra in some groundwaters, it seems reasonable to adopt $R_{\text{Rn}}/R_{\text{He}} \approx 0.2$. Taking this into account, eq. (2) corrected for release factors may be rewritten as

$$\text{Age (years)} \approx (0.2/16) \times C_4/A_{222}.$$

Alternatively,

$$\text{Age (years)} \approx 5.57 \times 10^6 \times (\text{ppm AEU } ^4\text{He}) / (\text{dpm/l } ^{222}\text{Rn}). \quad (3)$$

The concentrations of helium, radon and the ($^4\text{He}/^{222}\text{Rn}$) ages calculated using eq. (3) are given in Table 2. The inherent assumption is that within the reservoir both ^4He and ^{222}Rn have originated from the same U and Th parent atoms and their mobilization in groundwater is affected in a similar manner. In spite of the various factors of uncertainty, we believe that the ages calculated using eq. (3) are correct within a factor of 2.

The simultaneous outflow of gases and water indicates that due to stresses developed in the deep aquifer, the pore fluid is forced up and the dissolved gases get released due to drop in hydrostatic pressure during their ascent. We have, therefore, not considered the remote possibility of the gases and water having separate origins. Further, since our samples have been collected almost four and a half months after the earthquake, it is reasonable to assume that a steady state has been reached between the rock/soil grains and the pore fluid in respect of the release of the two radiogenic gases. Since ^{226}Ra concentration is extremely low in Narveri waters (Table 2), preferential dissolution of ^{226}Ra cannot be a significant factor of uncertainty in the ages. The uncertainty introduced in ages can at the most be a factor of 2, even if radium is not conserved. On the other hand, because solubility of helium in water is significantly less and diffusion coefficient ~ 5.5 times more than that of radon, the helium/radon ages may be underestimates. Radon in some brine samples from Kharaghoda in the Little Rann of Kachchh has also been measured earlier⁸ and its concentration (260–650 dpm/l) is lower than in the out-flowing groundwater at Narveri in the Great Rann of Kachchh. In case of Bhuj (Madhavpura) and Ahmedabad (PRL), the age is zero (i.e. very young) in comparison to $> 10^4$ years for Narveri

water. The calculated ages lead to the conclusion that there is a significant component of confined water (confined in terms of He and Rn) being injected into the shallow groundwater at Narveri.

In a perfectly 'closed box', ^4He , ^{222}Rn and $^4\text{He}/^{222}\text{Rn}$ ages should be identical for waters from the same source. However, in the three samples (5, 6 and 7) from Narveri, ^4He and ^{222}Rn show an inverse trend (Table 2). This can be understood in terms of a mixing model with two end members: shallow and deep. In Figure 5, we have plotted temperature, excess helium and ionic concentration in samples 5, 6 and 7 as a function of their estimated $^4\text{He}/^{222}\text{Rn}$ ages. It is seen that the data points for each parameter fall on a line within the error limit of a factor of 2 for age. Since Na, Cl and SO_4 in water act as conservative tracers and $^4\text{He}/^{222}\text{Rn}$ age estimates have larger errors due to various factors described above, we find that the data support a mixing model. We thus see that the chemical quality and temperature data of samples from the three vents at Narveri indicate

a situation wherein deep aquifer water is injected through the overlying shallow aquifer system, acquiring in the process a variable proportion of the shallow groundwater by mixing in the different vents. In such a case, the $^4\text{He}/^{222}\text{Rn}$ ages are likely to be underestimated and the highest estimate of the age is likely to be closer to the real age of the deep source.

The anomalously high helium concentration and high $^4\text{He}/^{222}\text{Rn}$ ages also suggest that the Narveri waters are not related to the Vedic Sarasvati or Sindhu rivers which are postulated to have got reactivated due to the January 2001 earthquake.

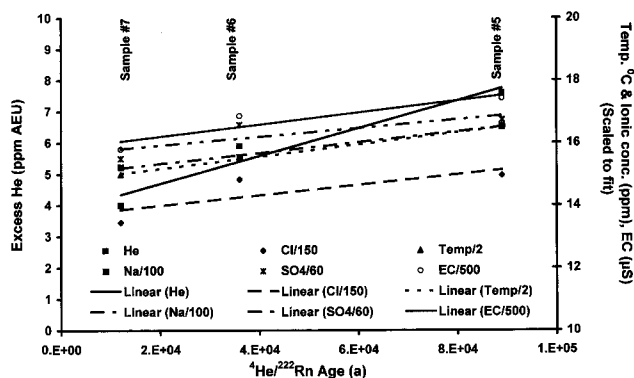


Figure 5. Correlation of excess He, temperature, ionic concentration and EC with estimated He/Rn ages of groundwater from three vents at Narveri. Ordinate scales are different for different tracers.

1. Rajendran, K., Rajendran, C. P., Thakkar, M. and Tuttle, M. P., *Curr. Sci.*, 2001, **80**, 1397–1405.
2. Gaur, V. K., *ibid.*, 338–340.
3. Singh, R. P., Bhoi, S., Sahog, A. K. and Ravindranath, S., *ibid.*, 2001, **81**, 164–166.
4. Thakkar, P. S., Rawal, M. H. and Dasgupta, A. R., *Pathik*, Pathik Karyalaya, Ahmedabad, 1999.
5. Yashpal, Sahai, B., Sood, R. K. and Agrawal, D. P., *Proc. Indian Acad. Sci. (Earth Planet. Sci.)*, 1980, **89**, 317–331.
6. Torgersen, T., *J. Geochem. Explor.*, 1980, **13**, 57–75.
7. Hussain, N. and Krishnaswami, S., *Geochim. Cosmochim. Acta*, 1980, **44**, 1287–1291.
8. Krishnaswami, S., Bhushan, R. and Baskaran, M., *Chem. Geol.*, 1991, **87**, 125–136.
9. Lide, D. R. (ed.), *CRC Handbook of Chemistry and Physics*, CRC Press, Boca Raton, 1999, 80th edn, pp. 6–190.
10. Krishnaswami, S. and Siedemann, D. E., *Geochim. Cosmochim. Acta*, 1988, **52**, 655–658.
11. Andrews, J. M. and Wood, D. F., *Trans. Inst. Min. Metall.*, 1972, **81**, B197–B209.
12. Rama and Moore, W. S., *Geochim. Cosmochim. Acta*, 1984, **48**, 395–399.

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