

this study. Hence it should be possible to pick up promising sites from detailed geochemical surveys. We recommend future investigations on these lines.

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**ACKNOWLEDGEMENTS.** MS's studies in Japan were supported by an invitation from the Japan Society for Promotion of Science and the INOUE Foundation of Science. We thank Prof. Y. Nakayama of the Ritsumeikan University for access to accelerator facilities. Critical review and helpful comments from the anonymous referee were useful in improving our presentation.

Received 21 May 1991; revised accepted 5 August 1991

## Stable isotopic evidence for the origin of ground water in Lakshadweep islands

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The origin of shallow ground water present in the Lakshadweep islands in the Arabian Sea has so far been assumed to be meteoric. We collected samples of ground water from 10 major islands and measured the stable-isotope ratios of hydrogen and oxygen. Our results indicate that these ground waters are indeed of meteoric origin. Sea water intrusion into these freshwater bodies appears to be small (within analytical uncertainties).

GROUND waters can be of different origins<sup>1</sup>. Meteoric ground waters are derived directly from precipitation or recharge from fresh surface water bodies through an unsaturated soil zone. Palaeo ground waters can be meteoric waters that originated in the more distant past during which different climatic conditions prevailed; or they can be formed from the remnants of interstitial marine (saline) waters retained at the time of formation of a marine sedimentary bed. The original isotopic composition could be altered in geothermal conditions, leading to the formation of geothermal waters. The isotopic composition can also change because of the inclusion of sea water in a fresh-water aquifer. Stable isotope composition of waters ( $\delta D$  and  $\delta^{18}O$ ) helps in determining the origin of ground waters.

Lakshadweep is a group of about 37 small islands with a total area of about 28.5 km<sup>2</sup> situated between 8°

and 12°13'N and 71° and 74°E (Figure 1). These are coral islands built up on a submarine ridge off the west coast of India<sup>2</sup>. To determine the origin of ground water in Lakshadweep Islands, we collected water samples from open dug wells (2 to 3 m below ground level) during April and December 1988. Three samples were usually collected from each island (wherever possible) with a gap of 0.5 to 1 km. Usually one was from a well near the jetty, one near the light house and the third at the other extremity of the island, the jetty being the central point. In the capital, Kavaratti, we collected samples in summer and winter. In addition, three rain water samples were also collected (Table 1).

The oxygen isotopic composition ( $\delta^{18}O$ ) was determined by equilibrating a tank CO<sub>2</sub> gas with 2 ml

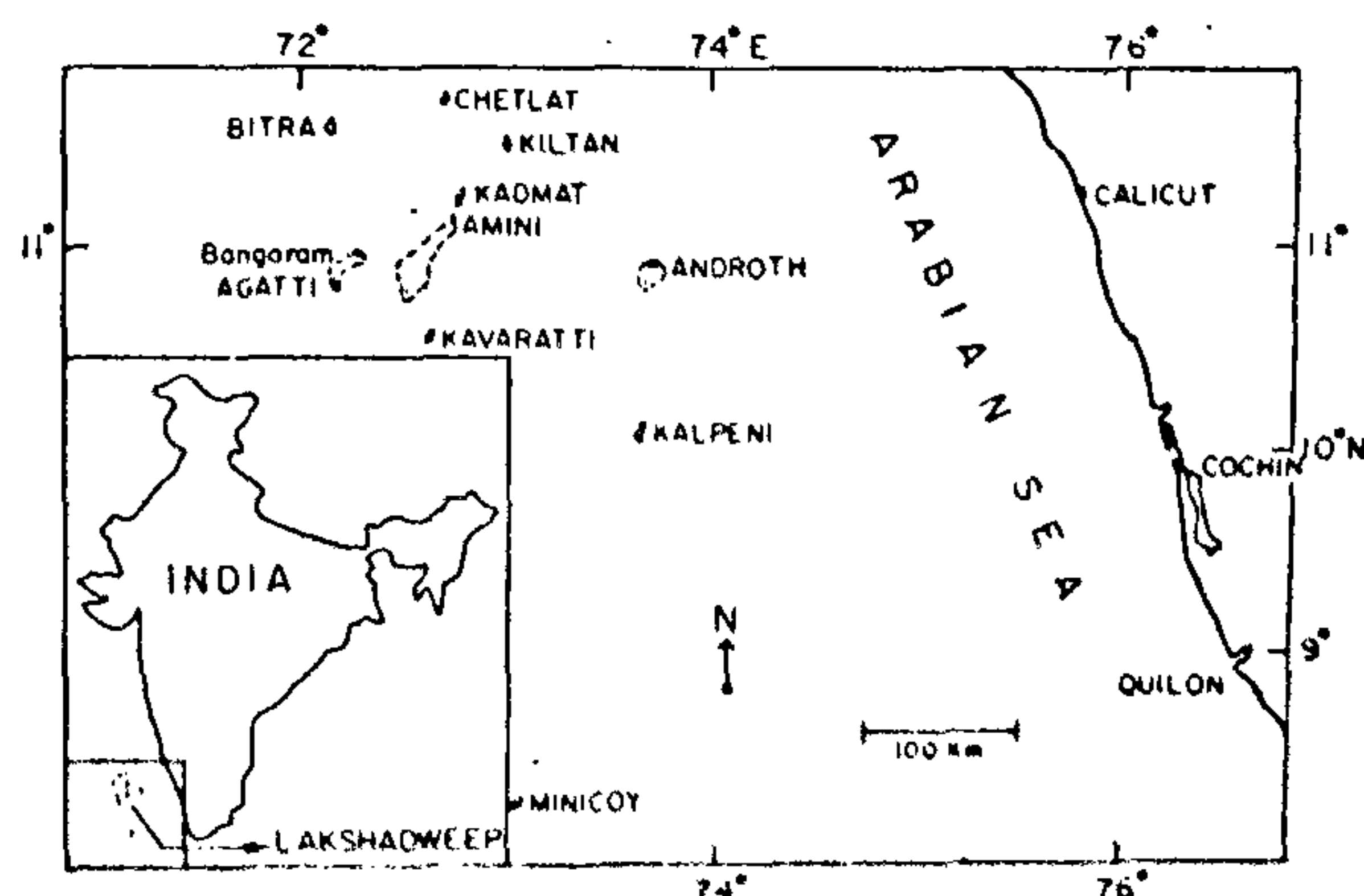


Figure 1. Lakshadweep islands.



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**Table 1.** Stable hydrogen ( $\delta D$ ) and oxygen ( $\delta^{18}O$ ) isotope ratios of ground water and rain water samples from Lakshadweep islands. (The deuterium excess parameter  $d$  is also shown in the last column.)

Island	Date	Location	$\delta^{18}O_{SMOW}$ (‰)	$\delta D_{SMOW}$ (‰)	$d$ (‰)
Minicoy	8.4.88	Jetty	-2.8	-13	9
		West	-2.1	-8	9
		LH	-2.0	-12	4
		Rain	-2.0	-5	11
Kalpeni	9.4.88	Subtreasury	-2.3	-12	6
		Jetty	-2.3	-12	6
		LH	-2.4	-11	8
Kavaratti	11.4.88	Jetty	-2.7	-12	10
	12.4.88	LH	-1.7	-7	7
	5.12.88	Tourist hut	-2.9	-16	7
		LH	-2.5	-12	8
		Rain	-3.2	-11	15
		Rain	-4.4	-18	17
		CMFRI	-2.9	-14	9
Kiltan	15.4.88	Jetty	-3.1	-13	12
		Jetty	-2.1	-12	5
		LH	-2.2	-8	10
		West	-2.1	-8	9
Chetlat	16.4.88	LH	-2.4	-8	11
		Jetty	-2.2	-13	5
		South	-2.0	-16	0
Agatti	6.12.88	Airport	-3.1	-9	16
	8.12.88	LH	-3.0	-15	9
		Dak tap	-2.9	-11	12
Bangaram	11.12.88	Hotel	-2.5	-14	6
Kadmat	14.12.88	LH	-2.6	-10	11
		Helipad	-2.5	-15	5
Amini	17.12.88	LH	-2.2	-13	5
		Dak tap	-2.8	-13	9
		Helipad	-2.5	-13	7
Bitra	19.12.88	Jetty	-1.6	-5	8
		LH	-3.9	-9	22
		Helipad	-1.8	-4	10

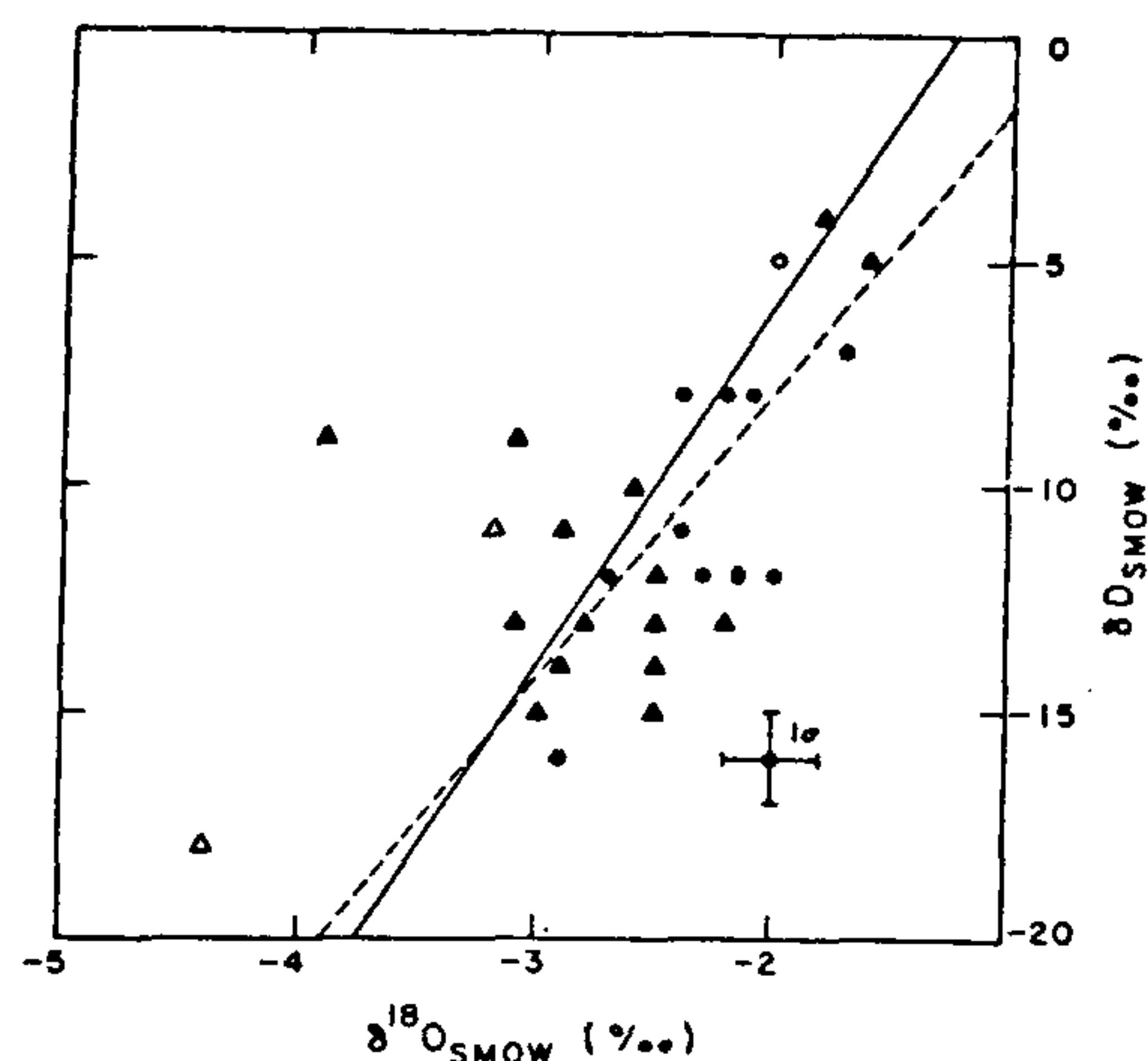
LH, Light House; CMFRI, Central Marine Fisheries Research Institute.

water at 25°C. The gas was then let into a VG Micromass 602D mass spectrometer for the  $\delta^{18}O$  measurement. The overall precision was  $\pm 0.2\text{‰}$ . The hydrogen isotopic composition ( $\delta D$ ) was determined by reducing 10  $\mu\text{l}$  of the water sample to hydrogen gas over uranium filings kept at 800°C. The hydrogen gas was then let into another VG Micromass 602D mass spectrometer for the  $\delta D$  measurement. The overall precision was  $\pm 1.2\text{‰}$ . The data are presented (Table 1) relative to the international standard V-SMOW<sup>3</sup>.

A plot of  $\delta D$  versus  $\delta^{18}O$  is shown in Figure 2. Data points that have identical  $\delta$  values overlap in Figure 2. There are four such sets (see Table). The world meteoric water line is shown for reference (solid line). Precipitation samples collected and analysed by the International Atomic Energy Agency (IAEA) from 144 different stations in the world obey the relationship<sup>4</sup>

$$\delta D = (8.17 \pm 0.08) \delta^{18}O + (10.56 \pm 0.64). \quad (1)$$

A best fit line<sup>5</sup> through the 30 ground water sample



**Figure 2.** Plot of  $\delta D$  versus  $\delta^{18}O$  values of the ground water (closed symbols) and rain water samples (open symbols) from Lakshadweep islands. Circles represent April 1988 collection and triangles December 1988 collection. Solid line is the meteoric water line (see text) and dashed line is the best fit line through the ground water data. Four sets of points in Table 1 overlap in this plot.

points (weighted with the analytical uncertainties) is also shown as a dashed line in Figure 2. They obey the relation

$$\delta D = (6.8 \pm 2.0) \delta^{18}O + (5.6 \pm 4.8) \quad (2)$$

with a correlation coefficient of 0.6, significant at  $< 0.01$  level (Student's  $t$  test). Within error, the slope of this line is similar to that of the meteoric water line, indicating that these waters are of meteoric origin. The deuterium excess parameter<sup>4</sup> defined as  $d = \delta D - 8\delta^{18}O$  has been calculated and is shown in Table 1. The mean value is  $9 \pm 4\text{‰}$ , which is in good agreement with the global average of 10 for precipitation, supporting the above conclusion.

The rain water data for the Lakshadweep islands fall on a line

$$\delta D = (5.4 \pm 1.0) \delta^{18}O + (6.0 \pm 3.2) \quad (3)$$

with a correlation coefficient of 1, significant at  $< 0.01$  level. Though only three points are available the  $\delta D$ - $\delta^{18}O$  relationship for Lakshadweep is similar to that reported for other tropical islands<sup>4</sup> like Barbados, Canton, Johnston, Wake, Midway, Bermuda and Diego Garcia

$$\delta D = (6.2 \pm 0.5) \delta^{18}O + (4.0 \pm 1.4) \quad (4)$$

The slope of the  $\delta D$ - $\delta^{18}O$  line in the case of tropical rain water is significantly less than that of the meteoric water line (eqn (1)) because of evaporation of raindrops while passing through the atmosphere<sup>6</sup> and consequent enrichment in the heavier isotopes. The ground-water data show some scatter probably due to the varying degrees of seepage of sea water and its consequent



mixing, which might lead to ground water isotopic values falling between the values of rain water and sea water (which is 0,0 by definition); there could be an evaporative enrichment of the heavier isotopes (undetectable due to a large uncertainty in the slope of eq. (2)) during the pre-monsoon months of relatively lower humidity, thus reducing the slope of the  $\delta D$ - $\delta^{18}O$  line.

Notwithstanding the above possible perturbations, our result clearly shows that the ground water in Lakshadweep mainly originates from local precipitation and recharge. Limited data on the rain water samples are in agreement with the data from other tropical islands.

The mean  $\delta$  values for the ground waters during April are  $-2.3 \pm 0.3\text{‰}$  ( $\delta^{18}O$ ) and  $-11 \pm 3\text{‰}$  ( $\delta D$ ); and during December  $-2.7 \pm 0.6\text{‰}$  ( $\delta^{18}O$ ) and  $-11 \pm 3\text{‰}$  ( $\delta D$ ). (These averages do not include rain water data.) It is clear that there is no significant seasonal difference in the isotopic composition of the ground waters as is expected in tropical regions<sup>4</sup>.

Furthermore, when we compare the  $\delta^{18}O$  and  $\delta D$  values of ground waters from two islands separated by a few degrees latitude (Minicoy at  $8^{\circ}17'N$  and Chetlat at  $11^{\circ}41'N$  during April and Kavaratti at  $10^{\circ}33'N$  and Bitra at  $11^{\circ}36'N$  during December), we see no significant difference. However, there seems to be a small difference in the  $\delta$  values of the precipitation between summer and winter. Ground waters average out such variations. The slopes and intercepts of eqs. (2) and (3) are in agreement within  $1\sigma$  errors. The sea water intrusion cannot be estimated accurately because of the scatter. We can only conclude that it is too small to show up with these uncertainties.

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**ACKNOWLEDGEMENTS.** We thank S. Krishnaswami for criticism, S. Chakraborty for assistance in sample collection, M. P. K. Kurup and K. K. Sivasankaran for help. We also thank P. Ravindran of NIO for help and S. Ananthakrishnan and an anonymous reviewer for comments and suggestions. This study was partly funded by the Indian National Science Academy, New Delhi.

Received 7 February 1991; revised accepted 6 July 1991

## Use of the sphalerite geobarometer for estimation of pressure of formation of metamorphosed sulphide deposits

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The variation in FeS content of sphalerite enclosed in pyrite is useful for estimation of the lithostatic pressure of formation. Its applicability on two metamorphosed sulphide deposits from Rajasthan and Gujarat has been tested. The computation of pressure by this method comes close to the estimation of pressure by traditional geobarometry.

THE variation in FeS content of sphalerite, when buffered by coexisting pyrite and hexagonal pyrrhotite, is a function of pressure and is independent of temperature over a considerable range. This has given rise to the concept of sphalerite geobarometer<sup>1-4</sup>. This geobarometer has been widely used to estimate the pressure successfully<sup>4-6</sup>.

Scott<sup>7</sup> suggested the use of sphalerite inclusions that are totally encapsulated in pyrite for pressure calculation, because such inclusions were equilibrated during or near the peak metamorphic condition and had been isolated from further reaction during subsequent retrograde conditions. As such, these may provide reliable computation of pressure.

This method is used to estimate the pressure and to check its validity in case of metamorphosed sulphide deposits at Deri-Ambaji and Rampura-Agucha which are highly metamorphosed.

The sphalerite inclusions, showing such equilibrium conditions as stated above<sup>7</sup>, were selected for electron microprobe analysis (Figure 1, a and b). These sphalerite inclusions are totally encapsulated in pyrite and are accompanied by pyrrhotite. The pyrrhotite in association with sphalerite was etched by HI to see its nature which revealed the hexagonal form of pyrrhotite. X-ray diffraction was also carried out to confirm the nature of pyrrhotite which also showed the hexagonal form of pyrrhotite due to its single sharp (102) peak. Blebs of chalcopyrite are totally absent in the grains of sphalerite. Sphalerite inclusions were analysed by Jeol 733 Superprobe electron microprobe in the Dionyz Stur's Institute of Geology, Bratislava (Czechoslovakia). The operating conditions of the electron microprobe were as follows: The accelerating voltage of 15 kV, a beam current of  $0.1\mu A$ , 10 sec counting time. Standards were triolite (stoichiometric, natural) and pure Zn and Mn metals. The analysis from the sphalerite inclusions encapsulated in pyrite from both deposits are listed in Table 1. In Table 1, only Fe%, FeS mole% and the computed pressures are shown.

From Table 1, it can be observed that Fe% varies in