events were penecontemporaneous. Weaver[5], in discussing the generation of the K-rich charnockites at Pallavaram, considered that they represent an unusual component of an otherwise fairly typical Archaean grey gneiss—granulite terrain. He suggested that these K-rich rocks had developed due to a change of the fluid composition which allowed metasomatism and partial fusion to occur before the formation of charnockite by the advance of a CO_2 front. At the present level of erosion, the exposure is interpreted as having been well below the former position of the CO_2 front and all the rocks have been completley converted to charnockite.

At Kabbaldurga it appears that there is evidence not only of the arrested process of charnockite formation, but also of the process of crustal fusion induced by an accumulation of H_2O in advance of an ascending CO_2-rich volatile phase. Thus, this area of the Peninsular Gneiss complex and the Closepet Granite is fundamental to the understanding of the processes of both charnockite formation and granite formation deep in the crust.

A British Council ALIS award is acknowledged enabling the continuation of work begun ealier under a YSES fellowship. I also thank Professor C. Naganna and Dr B. Mahabaleswar, of Bangalore University, for financial assistance and for help in the field respectively and Drs B. P. Radhakrishna and A. S. Janardhan for discussions on the Closepet Granite and the Kabbaldurga area and M. Brown, V. R. McGregor and C. G. Topley for helpful comments.

Received 12 May; accepted 6 October 1981.

1. Pichamuthu, C. S. *Nature* **188,** 135 (1960).
2. Ramiengar, A. S., Ramakrishnan, M. & Viswanatha, M. N. *J. geol. Soc. Ind.* **19,** 411–419 (1978).
3. Janardhan, A. S., Newton, R. C. & Smith, J. V. *Nature* **278,** 511–514 (1980).
4. Heier, K. S. *Phil. Trans. R. Soc.* **A273,** 429–442 (1973).
5. Weaver, B. L. *Contr. Miner. Petrol.* **71,** 271–279 (1980).
6. Weaver, B. L., Tarney, J., Windley, B. F., Sungavaran, E. B. & Venkata Rao, V. in *Archaean Geochemistry* (eds Windley, B. F. & Naqvi, S. M.) 177–204 (Elsevier, Amsterdam, 1978).
7. Radhakrishna, B. P. *Mysore geol. Ass. Bangalore Spec. Bull.* **3,** 1 (1956).
8. Crawford, A. R. *J. geol. Soc. Ind.* **10,** 117–166 (1969).
9. Beckinsale, R. D., Drury, S. A. & Holt, R. W. *Nature* **283,** 469–470 (1980).
10. Venkatasubramanian, V. S. & Narayanaswamy, R. *J. Ind. Inst. Sci.* **56,** 19–42 (1974).
11. Divakara Rao, V., Aswathanarayana, U. & Qureshy, M. N. *J. geol. Soc. Ind.* **13,** 1–12 (1972).
12. Divakara Rao, V., Aswathanarayana, U. & Qureshy, M. N. *Mineral. Mag.* **38,** 678–686 (1972).
13. Streckeisen, A. L. *Earth Sci. Rev.* **12,** 1 (1975).
14. Menhert, K. R. *Migmatites and the Origin of Granitic Rocks* (Elsevier, Amsterdam, 1968).
15. Brown, M. *Proc. geol. Ass.* **84,** 371–382 (1973).
16. Quensel, P. *Ark. Mineral. Geol.* **1,** 227–322 (1951).
17. Perkins, D. & Newton, R. C. *Nature* **292,** 145–146 (1981).
18. Newton, R. C., Smith, J. V. & Windley, B. F. *Nature* **288,** 45–49 (1980).
19. Schuiling, R. D. & Kreulen, R. *Earth planet. Sci. Lett.* **43,** 298–302 (1979).

Limitations on the scale of mantle heterogeneities under oceanic ridges

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The scale of mantle heterogeneities has been debated ever since the first observations of isotopic variations along mid-oceanic ridges[1,2]. Subsequent studies on lead and strontium isotopic variations along the Mid-Atlantic Ridge[3–5] have shown that these isotopic compositions may vary with a major wavelength of ~100–1,000 km. The immediate question is that of the scale (if any?) at which one may consider a piece of suboceanic mantle under a ridge to be homogeneous. We have studied two segments of oceanic ridges at the scale of a few kilometres. One of these portions of oceanic ridge, the CYAMEX zone in East Pacific Rise is typical, with a strongly 'depleted' chemistry. The other one, with an 'intermediate' chemistry, is the FAMOUS zone of the Mid-Atlantic Ridge. Our results show isotopic homogeneity for both zones even though small Pb variations persist on a small scale.

The general geology of the FAMOUS area has been described elsewhere[6,7]. In the central valley of this slow spreading ridge (2 cm yr^{-1}), we can distinguish two types of structures, real volcanoes such as Mount Venus, and lava flows, probably of fissural type. Several samples were collected from each structure. Figure 1 shows the location of the 16 samples analysed; the area covered was a few square kilometres.

The CYAMEX zone is located on the East Pacific Rise at a latitude close to 21° N. The mean spreading rate of this ridge is ~6 cm yr^{-1}. In contrast with the FAMOUS area, the CYAMEX zone presents no clearly defined central valley. Detailed tectonic[8], petrographic[9] and geochemical[10] studies are available. The area is characterized by more abundant fluid lavas than in FAMOUS, some in the form of the peculiar 'lava lakes'[8]. Hydrothermal circulation has been discovered in this area where the massive sulphide or manganese deposits originate[11].

Measurements and normalization of lead and strontium isotope ratios were completed using techniques described in refs 12, 13: the results are presented in Table 1.

In the FAMOUS area the strontium isotope values for whole rocks vary from 0.70287 to 0.70347. Such variations may *a priori* be ascribed to several causes. After leaching, using O'Nions and Pankhurst's[14] differential solution technique, samples yield values which are very close to 0.70287, in agreement with analyses by White[15,16] and O'Nions and Pankhurst[14] for neighbouring areas. Therefore, the variation mentioned above can be attributed to seawater alteration and within the experimental error, the isotopic composition of Sr seems to be very constant.

The lead isotope values are rather uniform and close to mean values of $^{206}\text{Pb}/^{204}\text{Pb} = 18.7$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.53$, $^{208}\text{Pb}/^{204}\text{Pb} = 38.20$ with a maximum variation of 0.2 for $^{206}\text{Pb}/^{204}\text{Pb}$. Such a variation is quite small, compared with those observed for the North Atlantic as a whole[17] (1.9 for $^{206}\text{Pb}/^{204}\text{Pb}$). No marked difference can be observed between different types of lavas from volcanoes and fissural lava flows.

In the CYAMEX area the strontium isotope values on whole rocks and glasses are uniform and average about 0.7025 which is

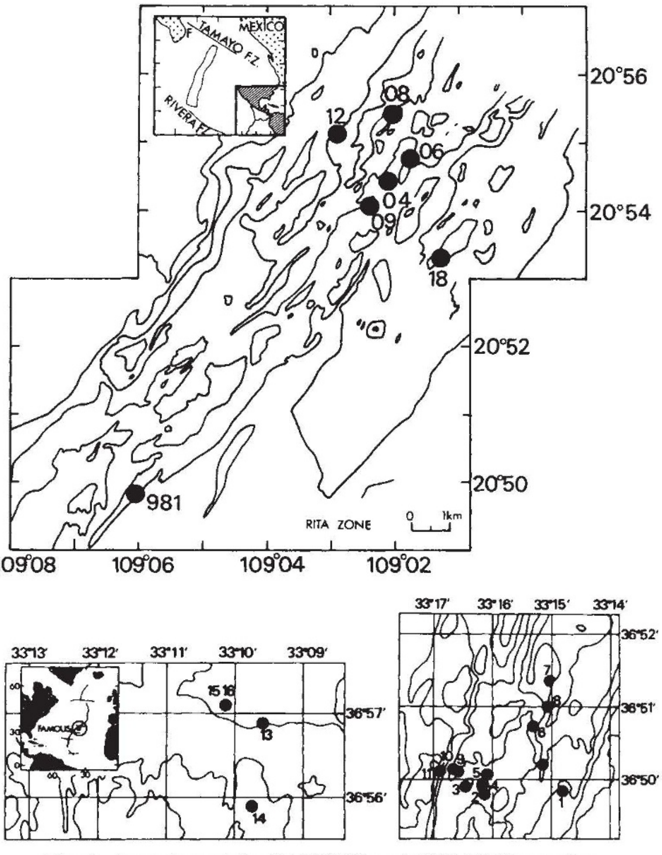

Fig. 1 Location of the FAMOUS and CYAMEX samples.

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Table 1 Sr and Pb isotopic compositions of the samples studied in the FAMOUS and CYAMEX areas

FAMOUS Samples	$^{87}Sr/^{86}Sr$ WR	$^{87}Sr/^{86}Sr$ WR leached	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	
ARP 74 7-5 C (IG)	0.70292±7	0.70280±10	18.79±0.02	15.53±0.02	38.35±0.05	1
ARP 74 7-5 S (IG)	0.70295±7					
ARP 74 9-12 (IG)			18.69±0.02	15.52±0.02	38.28±0.1	2
ARP 74 9-13 (IG)	0.70295±10	0.70288±6	18.74±0.02	15.52±0.02	38.33±0.05	3
ARP 74 10-14 (IG)		0.70289±8	18.65±0.02	15.53±0.02	38.28±0.05	4
ARP 74 10-15 (IG)			18.83±0.02	15.52±0.02	38.36±0.06	5
ARP 74 11-11 (IG)			18.68±0.02	15.52±0.02	38.20±0.05	6
ARP 74 11-18 (IG)	0.70290±6		18.60±0.02	15.53±0.02	38.23±0.06	7
CYP 30-32 (IG)	0.70302±7	0.70285±6				8
CYP 31-36 (IG)	0.70302±10	0.70285±6				9
		0.70286±6				
CYP 31-37 (IG)	0.70343±17	0.70296±6				10
CYP 31-39 (IG)	0.70315±7	0.70281±7	18.67±0.02	15.50±0.02	38.20±0.07	11
ARP 73 1003 (IG)	0.70287±10	0.70285±7	18.73±0.02	15.53±0.02	38.20±0.07	12
ARP 74 13-21 (FZ)		0.70276±11	18.60±0.02	15.52±0.02	38.20±0.05	13
ARP 74 13-24 (FZ)			18.89±0.02	15.55±0.02	38.45±0.06	14
ARP 74 14-32 (FZ)	0.70309±12	0.70285±8	18.84±0.02	15.52±0.02	38.39±0.08	15
	0.70312±13		18.79±0.02	15.52±0.02	38.31±0.05	
ARP 74 14-33 (FZ)	0.70313±9					16
CH31 DR2 301	0.70315±7					
CH31 DR6 325	0.70329±17		18.54±0.02	15.55±0.02	38.24±0.05	
CH31 DR 10 100	0.70320±8		18.62±0.02	15.54±0.02	38.30±0.07	
CYAMEX						
CYP 78 04 07		0.70254±7	18.33±0.02	15.49±0.02	37.77±0.06	
CYP 78 06 11			18.42±0.02	15.49±0.02	37.85±0.06	
CYP 78 09 12			18.39±0.02	15.51±0.02	37.83±0.07	
CYP 78 12 33			18.37±0.02	15.46±0.02	37.73±0.05	
CYP 78 12 35		0.70250±9				
CYP 78 12 36	0.70307±6	0.70247±7				
CYP 78 18 65		0.70264±8	18.47±0.02	15.49±0.02	37.88±0.06	
981 R10			18.45±0.02	15.49±0.02	37.86±0.06	
981 R23		0.70247±6	18.39±0.02	15.49±0.02	37.83±0.06	

We have divided the samples from the FAMOUS zone into two groups: IG, international ground; FZ fracture zone. The total blank for ~1 g of sample has been maintained below 1 ng for Pb and below 200 pg for Sr. WR, whole rock.

typical of the depleted mid-oceanic ridge basalts (MORB). The lead isotope values are also rather uniform but yield a less radiogenic character than for FAMOUS: $^{206}Pb/^{204}Pb = 18.35$, $^{207}Pb/^{204}Pb = 15.48$, $^{208}Pb/^{204}Pb = 37.85$.

The (Sr, Pb) or (Pb, Pb, Pb) isotope correlation diagrams (Fig. 2) show that both CYAMEX and FAMOUS data plot on the main trend defined for MORB[17-19]. Therefore, both zones have quite 'normal' chemical characteristics of an oceanic ridge. The uniformity of their isotopic compositions which contrasts with the variations observed in the North Atlantic[16,17] and with the local heterogeneities observed in peridotite xenoliths and 'high temperature' peridotites[20,21] has important implications. In this case, the source of basalts at the scale of 10 km is statistically homogeneous, the formation of a basaltic liquid compensates for any local minor heterogeneity in the mantle source.

Although the Pb values are roughly homogeneous, some small variations in the Pb isotope ratios remain and cannot be ascribed to secondary processes such as seawater alteration. These variations are about one-tenth of the global variation for the North Atlantic (when using the Sr–Pb correlation diagram, we may estimate the corresponding variation for the values obtained close to 0.0001, which for $^{87}Sr/^{86}Sr$ is virtually the same as those expected from the analytical error). Thus, the small variations in Pb isotopic ratios are not inconsistent with the uniformity of the Sr isotope ratios. Improvements in measuring the Sr isotopic ratio are necessary before we can study Pb–Sr correlation on such a small scale. However, on this scale these Pb isotope variations are not correlated with variations in ratios of incompatible elements like Hf/Th, Ta/Th, La/Th or La/Sm. Therefore, such small heterogeneity is not an argument against the trace element discussion made by Langmuir *et al.*[22] who

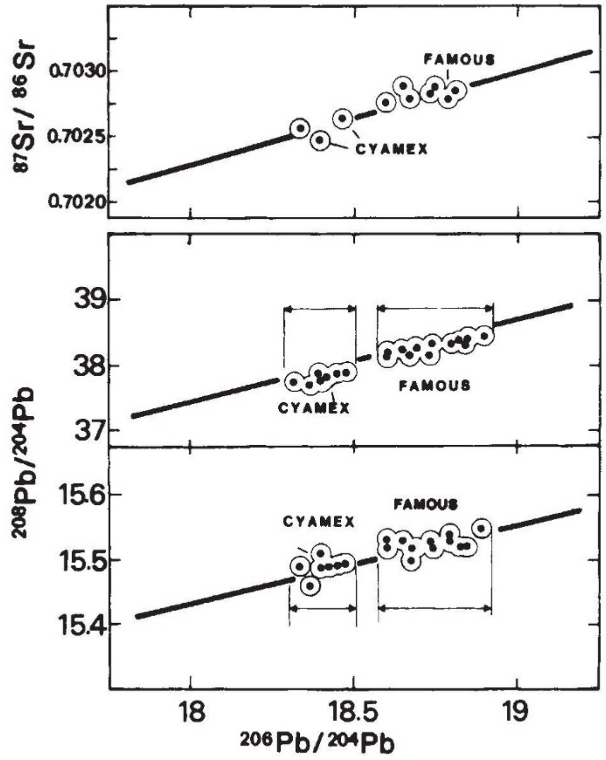

Fig. 2 Results for CYAMEX and FAMOUS areas: *a*, ($^{87}Sr/^{86}Sr$) vs ($^{206}Pb/^{204}Pb$); *b*, ($^{208}Pb/^{204}Pb$) vs ($^{206}Pb/^{204}Pb$); *c*, ($^{207}Pb/^{204}Pb$) vs ($^{206}Pb/^{204}Pb$).

reject the equilibrium partial melting model and propose a new model for partial melting called dynamic-melting.

We now compare the homogeneity observed on a small scale (10 km) with that observed on a larger scale (100–1,000 km). Results from the North Atlantic[3,5,17], and those on the oceanic crust of the Indian Ocean[23] indicate that the cause of isotopic variations obtained along the Atlantic Ridge is linked to mixing between the lower and upper mantle by injection of blobs (or hot spots). Our results show that, on a small scale, the mixing does not generate large isotopic heterogeneities but this conclusion should be evaluated in the light of the type of models discussed in ref. 18. Note that the Pb heterogeneity is larger in the case of FAMOUS than for CYAMEX. Considering that FAMOUS is on a ridge with some blobs mixing while CYAMEX is on a quite 'normal' ridge, such a difference is probably significant. With improvement of the accuracy, it will be quite interesting to study the small variations of Sr isotope ratios in these areas to decipher more precisely the processes of blob mixing and basalt genesis.

This study was supported by CNEXO. Samples were provided by the Centre Océanographique de Bretagne. We thank J. Francheteau and H. Bougault for assistance. This is IPGP contribution NS/530.

Received 29 June; accepted 2 October 1981.

1. Tatsumoto, M. *Science* **153,** 1094 (1966).
2. Tatsumoto, M., Hedge, G. E. & Engle, A. G. J. *Science* **150,** 886 (1965).
3. Sun, S. S., Tatsumoto, M. & Schilling, J. G. *Science* **190,** 143 (1975).
4. Hart, S. R., Schilling, J. G. & Powell, J. L. *Science* **246,** 104 (1973).
5. White, W. M. & Schilling, J. G. *Geochim. cosmochim. Acta* **42,** 1501 (1978).
6. Hekinian, R., Moore, J. C. & Bryan, W. B. *Contr. Miner. Petrol.* **58,** 83 (1976).
7. ARCYANA *Deep Sea Res.* **24,** 565 (1976).
8. Rise Project Group *Science* **207,** 1421 (1980).
9. Juteau, T. *et al. Oceanol. Acta* **3,** 487 (1980).
10. Bougault, H. (in preparation).
11. Francheteau, J. *et al. Nature* **277,** 523 (1979).
12. Birck, J. L. & Allègre, C. J. *Earth planet. Sci. Lett.* **39,** 37 (1978).
13. Manhes, G., Minster, J. F. & Allègre, C. J. *Earth planet. Sci. Lett.* **39,** 14 (1978).
14. O'Nions, R. K. & Pankhurst, R. J. *Earth planet. Sci. Lett.* **31,** 255 (1976).
15. White, W. M. *Yb Carnegie Instn Wash.* 325 (1979).
16. White, W. M. & Bryan, W. B. *Bull. geol. Soc. Am.* **88,** 571 (1977).
17. Dupré, B. & Allègre, C. J. *Nature* **286,** 17 (1980).
18. Allègre, C. J., Brevart, O., Dupré, B. & Minster, J. F. *Phil. Trans. R. Soc.* **297,** 447 (1980).
19. Cohen, R. S., Evensen, N. M., Hamilton, P. J. & O'Nions, R. K. *Nature* **283,** 149 (1980).
20. Polve, M. & Allègre, C. J. *Earth planet. Sci. Lett.* **51,** 71 (1980).
21. Dupre, B., Hamelin, B. & Allègre, C. J. *EOS,* **60,** 414 (1979).
22. Langmuir, C. H., Bender, J. F., Bence, A. E., Hanson, G. N. & Taylor, S. R. *Earth planet. Sci. Lett.* **36,** 133 (1977).
23. Dupré, B. & Allègre, C. J. *TERRA Cogn. Proc. 1st EUG Meet.* Strasbourg, 79 (1981).

Palaeooceanographic significance of bottom-current fluctuations in the Southern Ocean

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Hiatuses in the sedimentary record of the Southern Ocean are usually attributed to erosion by high-velocity bottom currents[1–3]. To test for palaeoclimatic mechanisms which intensified bottom circulation, however, the timing of increases in bottom-current velocity must be known. As the sedimentary record of the period of initial erosion is lost within the hiatus, the timing of increased velocity must be determined in cores which are adjacent to the axis of highest velocity[4,5]. In those cores the accumulation rates are reduced due to the current but a record of the period of initiation of scour is preserved as a zone of particle-size winnowing of the fine-fraction[3–4]. The timing of major episodes of bottom-current intensification in the South Australian Basin for the past 4.5 Myr are reported here for the first time and may be used to examine the role of palaeoclimatic fluctuations on bottom-current intensity.

A series of piston cores across the axis of a high-velocity current (near a modern contour current[6]) which has produced hiatuses in the sedimentary record[2] in the South Australian Basin (Fig. 1) are used to demonstrate a method of dating erosional pulses of bottom water. These disconformities are of varying length depending on width, intensity and duration of the high-velocity bottom current responsible for scouring the sea floor. Two of the cores (E48-5 and E45-86) near the axis of flow during an expansion of the contour current have a hiatus which extends from the Miocene to latest Pleistocene while hiatuses in two adjacent cores (E49-53 and E50-2) are shorter (Fig. 2). One core (E45-21) in the area has not recorded a hiatus due to its position at the margin of the bottom water even at its greatest extent during the past 3 Myr. Because three of the cores were the site of deposition during the time span lost due to erosion in the axial-cores (Fig. 2), the particle-size distribution in those cores may be examined for evidence of winnowing which is associated with the erosion.

The mean particle-size of the non-carbonate silt fraction (4–62 μm, 8–4 ϕ) was analysed using an electronic particle counter[7] (Elzone, Particle Data). The carbonate fraction was not analysed as variations in carbonate grain-size may be affected by dissolution of carbonate rather than bottom-current velocity[8]. The silt fraction was analysed because the fine fraction is more sensitive to the magnitude of bottom-current velocity observed in the deep sea[9,10]. As the cores studied are too far from Antarctica to have a significant ice-rafted debris component[11], the grain size of the non-carbonate silt-sized component chiefly reflects bottom-current transport. The mean silt particle size in three cores was plotted against age (Fig. 3) determined from magnetostratigraphy[1,3]. The mean value of the data in each core is used as an arbitrary reference level to separate periods of relatively high and low inferred bottom-water velocity (Fig. 3).

The period of erosion (or non-deposition) in core E50-2 is characterized by coarse particle sizes in the two cores (E49-53 and E45-21) marginal to the high-velocity zone (Fig. 2). Therefore, the erosional event(s) in E50-2 is 'felt' in the more distant cores by winnowing of the fine fraction. When the period of erosion or non-deposition ceased in core E50-2 the mean particle size deposited was still coarse under the waning current. In the adjacent cores, the mean particle size decreased at the same time that sedimentation resumed above the disconformity. Therefore, the marginal cores have recorded the cessation of high-velocity bottom current at ∼2.6 Myr.

The initiation of the high-velocity episode may be dated at the beginning of the winnowing of particles in the marginal cores. While sediment is missing for the period 5.5–4.6 Myr, it is possible to examine the record of bottom-current velocity for the past 4.5 Myr and for a short period at ∼5.5–5.6 Myr (Fig. 3). The first episode of high-velocity is marked by a coarsening of the mean particle size at ∼4.3 Myr which persisted until ∼3.8 Myr. Several shorter pulses with lower magnitude followed the initial coarsening of mean particle size and may record periods of current intensification which either eroded or inhibited deposition at the site of core E50-2. The episodic nature of the inferred bottom-water velocity fluctuations imply that sediment was deposited and subsequently eroded in the scour zone so that the hiatus is a result of multiple high-velocity events.

Unfortunately, the bottom-current velocity record of the lower Gilbert Chron cannot be examined due to the lack of recovery of sediment of that age in the South Australian Basin[2]. If, however, the initial increase in bottom-current velocity occurred at 3.8–4.3 Myr, then ∼1 Myr of sediments were eroded at the site of core E50-2 (Fig. 3). Based on average sedimentation rates after the disconformity of 0.35 cm kyr^{-1} in cores E50-2 and E45-21, the episodes of increased velocity eroded ∼3.5 m of sediment deposited before 4.3 Myr and 5 m was eroded and/or not deposited from 4.3 to 2.6 Myr. The total erosional effect of the bottom currents in this area, therefore, is nearly 10 m of sediment. Areas of more intense erosion have occurred in the southeastern Indian Ocean as much older sediment is exposed by other disconformities[1,2] which must have been nearer the axis of flow.

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