Reports

Paleocurrent Indicators in Deep-Sea Sediment

Abstract. *The fabric and texture of deep-sea sediments have been used to detect periods of high-velocity bottom-water flow through the Vema Channel in the southwest Atlantic Ocean. In addition, the alignment of the long axis of magnetic grains has been used to indicate the direction of bottom-water flow.*

Erosion of abyssal sediment by high-velocity bottom currents has resulted in widespread regional hiatuses in the sedimentary record that may span millions of years (*1*). These disconformities are recognized in deep-sea piston cores and drilled cores by the absence of biostratigraphic zones and may be associated with sedimentary features such as manganese nodules or coarse lag deposits. These erosional zones represent one extreme of the spectrum of deep-sea paleocirculation events. Hiatuses of short duration are commonly identified, but are more difficult to detect because biostratigraphic or sedimentological changes are less conspicuous.

To determine the timing and direction of an erosional bottom-water event, it is necessary to examine areas with continued but slow sedimentation along the margins of scour zones (*2*). We have developed a technique for determining the relative magnitude and azimuth of bottom currents, based on an examination of the fabric in deep-sea sedimentary cores (*3*). Magnetic particle orientation and silt particle size data provide powerful paleoceanographic tools that are independent of sedimentation rate variability resulting from dissolution, decreased sediment input, or slumping.

The Vema Channel in the southwest Atlantic Ocean (Fig. 1) is the principal passage in the Rio Grande Rise through which Antarctic Bottom Water (AABW) passes from the Argentine Basin northward into the Brazil Basin (*4, 5*). In the channel, northward-flowing high-velocity AABW is overlain by lower-velocity southward-flowing North Atlantic Deep Water (NADW) (*4–6*). The transition zone between the two water masses (*5, 7*) makes it difficult to place the boundary on the basis of water-mass properties. Geologic parameters, which are sensitive to variations in bottom-water velocity, suggest that the boundary is at about 4200 m (*3, 7, 8*), which approximately corresponds to the position of the maximum gradient of the benthic thermocline (*5*) and to the calcite compensation depth (*6, 7*). The Vema Channel provides an ideal setting for studying velocity changes of AABW through geologic time, since the direction and, to some extent, the net transport are constrained by the bathymetry of the channel (*7*). The availability of current meter data from the axis of the channel (*9*) makes it possible to compare the modern current flow direction with the time-averaged values determined from sedimentary analysis.

The sedimentary fabric was determined by using the efficiency of alignment of long magnetic grains. This alignment was detected by determining the anisotropy of magnetic susceptibility (AMS) for these grains. The AMS method has been established as a means of determining grain alignment in both natural and experimentally deposited sediments (*10*). Measurement of several sets of California beach sand, for example, showed that magnetic particle orientations, determined by the AMS method (*11*), reflected the alignment of grains that had previously been independently determined by standard sedimentologic methods (*12*). We have shown that the standardized AMS parameter F_s is sensitive to the efficiency of alignment of the long axis of magnetic particles (*3*) caused by fluctuations in bottom-water velocity.

To compare the AMS method with a totally independent parameter, we used particle size analysis of the sediment fine fraction (*3*). The particle size distribution of deep-sea sediment is a sensitive monitor of paleovelocity fluctuations, since winnowing of the finer, lighter component by active bottom currents changes the size distribution of the sediment deposited (*8*). Several methods have been devised to determine which characteristic of the particle size distribution is most sensitive to bottom-water velocity fluctuations. Analysis of component modes within the total size distribution has been used to determine the size ranges that are most sensitive to paleovelocity fluctuations and current dispersal patterns (*13*). Further, the mean particle size and skewness of the total size distribution (*2*) and the mean size of the silt fraction have been used to indicate bottom-water velocity fluctuations (*7, 8*). To eliminate effects resulting from calcium carbonate dissolution, we analyzed the noncarbonate portion of the sediment. The size analysis was also restricted to the silt fraction in order to eliminate the effects on the grain size distribution produced by large grains, which are not sensitive to fluctuations in AABW velocity in the Vema Channel (*3, 7, 8*).

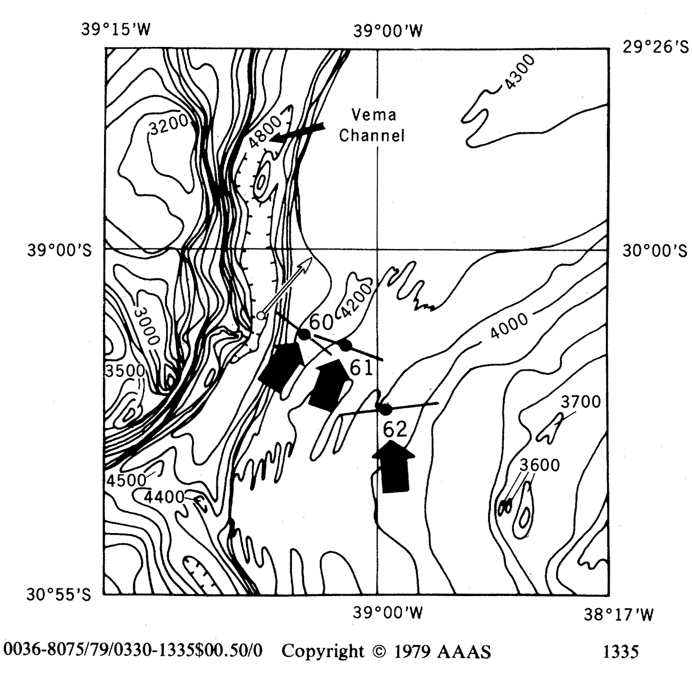


Fig. 1. Proposed current directions recorded in cores CH-115-60PG, CH115-61, and CH115-62. Filled circles represent core locations and bars represent the alignment of the long axis of magnetic grains (see text). Alignments normal to the inferred current flow direction (filled arrows) are attributed to a traction transport mode of sedimentation. The open arrow represents the AABW flow direction recorded by a current meter located close to the site of core CH115-60PG (*9*).

0036-8075/79/0330-1335$00.50/0

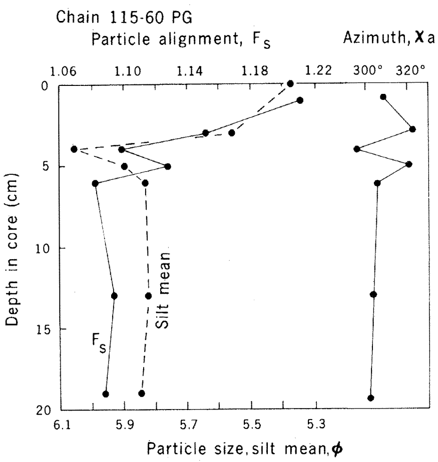
A total of 155 samples (*14*) were removed from three piston cores recovered from the east flank of the Vema Channel (Fig. 1). Figures 2 to 4 show data from down-core measurements of the remanent magnetism, grain alignment (F_s), and grain size (silt mean) for cores CH115-60PG, CH115-61, and CH115-62 (henceforth referred to as 60PG, 61, and 62).

The age of the sediment recovered from cores 61 and 62 was established by using magnetostratigraphy and biostratigraphy (*15*). No age estimate is available for 60PG because of lack of microfossils. Core 61 is normally magnetized (Fig. 3) and falls entirely within the Brunhes normal epoch, 0 to 730,000 years before present (B.P.). Foraminiferal biostratigraphy indicates that the bottom of the core is approximately 400,000 years old (*15*). Only a very small segment of Brunhes sediment was recovered at the top of 62 (Fig. 4), indicating that the top portion of this core was lost during piston coring (*15*). The Matuyama reversed epoch is recorded in the top 3.7 m, with sediments of Gauss age at 376 cm and a manganese crust at 576 cm in the core (*15, 16*). The age below this level is unknown.

The manganese crust in core 62, dated at 3 million years B.P. (Fig. 4), is associated with a hiatus in sedimentation resulting from erosion by bottom currents (*15, 16*). Immediately above and below this hiatus, values of particle alignment and particle size are particularly high, reflecting high bottom current velocities before and after the erosional event that caused the hiatus and manganese crust development. The high velocities resulted in zero sedimentation during the time when the manganese crust formed. After the bottom current slowed, sedimentation resumed above the manganese crust; the particle alignment and particle size values indicate a general trend of decreasing velocity interspersed with brief periods of higher velocity. For most of the Gauss epoch and the early part of the Matuyama the sediment fabric and texture are highly variable, indicating relatively large changes in bottom current velocity. This variability decreased during the middle Matuyama but increased again during the latest Matuyama.

Particle alignment and particle sizes in core 60PG, recovered near the present axis of high-velocity AABW in the Vema Channel (*5, 7*), decrease below the sediment-water interface (Fig. 2), as do values below the manganese crust in core 62 (Fig. 4). We infer that the bottom-water velocity has increased sufficiently in modern times to cause zero sedimentation or erosion on the sea floor at the site of core 60PG.

Core 61 lies within the zone of transition between AABW and NADW, and we infer that the increases in particle alignment and particle size in the core resulted from higher bottom current velocities as the top of the AABW shallowed during periods of increased AABW production. Most of the variability of particle alignment and particle size occurs in the upper 2 m, covering approximately the last 130,000 years (*3*), with decreasing magnitudes and variability deeper in the core (Fig. 3). Therefore, we infer that bottom current velocity was generally higher during the late Brunhes (0 to 130,000 years B.P.) than during the period 130,000 to 400,000 years B.P. The bottom-water velocity record for the period 400,000 to 1 million years B.P. is not known because there is no sedimentary record for that period in cores near the margin of the AABW.



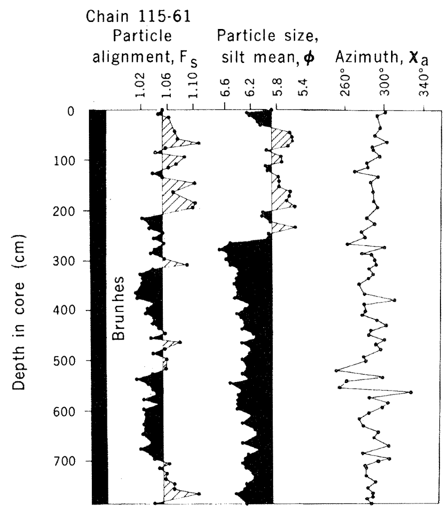


Fig. 2 (left). Variations in the efficiency of long-axis alignment of magnetic grains (F_s), silt mean particle size (in ϕ units), and azimuth of magnetic grain alignment as a function of depth in core CH115-60PG. The more efficient alignment and coarser particle sizes near the present sea floor are interpreted as indicating an increase in bottom-water velocity at this site, which is near the axis of present-day high-velocity Antarctic Bottom Water. Fig. 3 (right). Variations in F_s, silt mean particle size (in ϕ units), and azimuth of magnetic grain alignment as a function of depth in core CH115-61. Vertical lines separate values of F_s and silt mean that are higher (hachured) and lower (filled) than values for the present sea floor. Remanent magnetic polarity log (all samples are normally magnetized) is plotted to the left. The greatest fluctuations in inferred current velocity occur in the upper 250 cm, and the alignment azimuth is consistently normal to the expected bottom current flow direction.

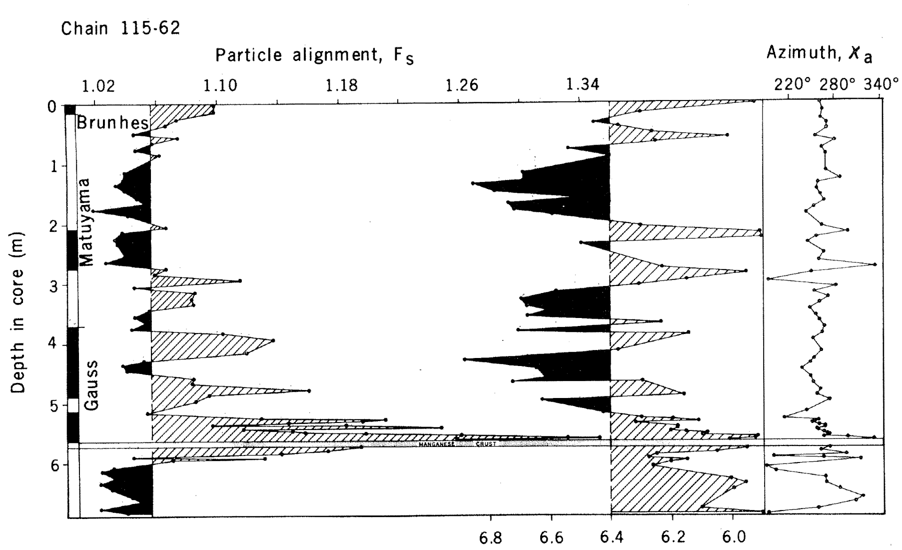


Fig. 4. Variations in F_s, silt mean particle size (in ϕ units), and magnetic grain long-axis alignment as a function of depth in core CH115-62. Vertical dashed lines separate values of F_s and silt mean that are higher (hachured) or lower (filled) than values for the present sea floor. The paleomagnetic polarity log is plotted to the left: normal (filled) and reversed (open). The period of highest inferred bottom current velocity is associated with the formation of a manganese crust recovered at a depth of 576 cm in the core.

Particle alignment analyses provide additional information on long-term bottom-water activity. The net alignment direction of all magnetic particles is represented in the AMS analysis by the χ_a direction, corresponding to the orientation of the long axis of the magnetic grains. This orientation is meaningless, however, unless the cores can be realigned within geographic coordinates. We accomplished this by using the stable remanent magnetic declination measured in the cores (*3*). It is assumed that the mean remanent magnetic declination recorded in the cores represents an axial dipole magnetic field with secular variation averaged out. After the core is rotated until the remanent magnetic declination is coincident with geographic direction 0° (due north), the χ_a declination represents the geographically realigned orientation of the long axis of the magnetic grains.

Realignment values for cores 60PG and 61 are reported elsewhere (*3*). Because of the lack of Brunhes age sediments, the stable but reversed remanent magnetic direction obtained within reversed polarity segments (0.2 to 3.7 m in depth; Fig. 4) in core 62 was used to realign the core. Current directions for the three cores are shown in Fig. 1, along with the mean AABW direction determined from current meter data obtained near the core 60PG site (*9*).

The long axes of the magnetic grains from all three cores are aligned within a few degrees of an east-west azimuth, and there is excellent agreement between the inferred AMS current azimuth for core 60PG and the mean current meter direction near the site. Since the flow direction of bottom water is constrained by the bathymetry of the Vema Channel to be northerly, the long axes of the magnetic grains are aligned normal to the flow direction; this was a surprising result since we expected the long axis of the magnetic grains to be aligned parallel to the bottom current flow direction. This unexpected alignment is, however, consistent with a traction transport mechanism of sedimentation. If elongated grains are moved along the sea floor by high-velocity bottom currents, the long axes may align normal to the flow (*17*). (By analogy, the long axis of a barrel rolling down a hill aligns normal to the direction in which the barrel is rolling; a parallel alignment would produce a tumbling pattern.) The consistency of the alignment data in all three cores and the excellent agreement with modern flow directions determined by current meter (Fig. 1) suggest that grain movement by traction transport best explains our results.

Combined particle alignment and particle size data may be used to determine fluctuations in both relative magnitude and azimuth of bottom current flow recorded by abyssal sedimentary fabric. The alignment efficiency of long magnetic grains together with the mean silt particle size of abyssal sediment may be used to infer relative current speed. The method may be applied to sedimentary sections with a suspected hiatus to delineate zones of high bottom current activity. Since both relative speed and azimuth of bottom currents may be inferred from our measurements, we suggest that abyssal sedimentary fabric may be considered as a long-term fossil bottom current indicator. Although it is not possible at present to determine absolute paleocurrent speeds by any method, temporal changes in the relative speed may be determined. The excellent agreement between our magnetically determined current azimuth and current meter data supports the reliability of paleocurrent direction analysis.

BROOKS B. ELLWOOD
MICHAEL T. LEDBETTER
Department of Geology,
University of Georgia, Athens 30602

References and Notes

1. N. D. Watkins and J. P. Kennett, *Science* **173**, 813 (1971); *Antarct. Res. Ser.* **19**, 272 (1972); *Mar. Geol.* **23**, 103 (1977); T. A. Davies, O. E. Weser, B. P. Luyendyk, R. B. Kidd, *Nature (London)* **253**, 15 (1975); D. A. Johnson, *Geol. Soc. Am. Bull.* **83**, 3121 (1972); *Mar. Geol.* **17**, 71 (1974); Tj. H. van Andel, G. R. Heath, T. C. Moore, *Geol. Soc. Am. Mem. 143* (1975); J. P. Kennett and N. D. Watkins, *Geol. Soc. Am. Bull.* **87**, 321 (1976); J. P. Kennett *et al.*, *Nature (London)* **239**, 51 (1972); J. P. Kennett *et al.*, *Science* **186**, 144 (1974).
2. T. C. Huang and N. D. Watkins, *Mar. Geol.* **23**, 113 (1977).
3. B. B. Ellwood and M. T. Ledbetter, *Earth Planet. Sci. Lett.* **35**, 189 (1977).
4. X. Le Pichon, M. Ewing, M. Truchan, *Phys. Chem. Earth* **8**, 31 (1971).
5. D. A. Johnson, S. E. McDowell, L. G. Sullivan, P. E. Biscaye, *J. Geophys. Res.* **81**, 5771 (1976).
6. M. Melguen and J. Thiede, *Mar. Geol.* **17**, 341 (1974).
7. D. A. Johnson, M. T. Ledbetter, L. H. Burckle, *ibid.* **23**, 1 (1977).
8. M. T. Ledbetter and D. A. Johnson, *Science* **194**, 837 (1976).
9. J. L. Reid, W. D. Nowlin, Jr., W. C. Patzert, *J. Phys. Oceanogr.* **7**, 62 (1977).
10. G. Ising, *Ark. Mat. Astron. Fys. A* **29**, 1 (1942); N. D. Hamilton and A. I. Rees, *Paleogeophysics* (Academic Press, New York, 1970), pp. 445–463; D. V. Kent and W. Lowrie, *Earth Planet. Sci. Lett.* **28**, 1 (1975).
11. A. I. Rees, *Sedimentology* **6**, 257 (1966).
12. J. R. Curray, *Bull. Am. Assoc. Pet. Geol.* **40**, 2440 (1956).
13. R. K. Oser, *J. Sediment. Petrol.* **42**, 461 (1972); Tj. H. van Andel, *J. Geol.* **81**, 434 (1973).
14. The sample holders have a diameter of 2.5 cm and a length-to-diameter ratio of 0.86. This ratio was shown to be optimum for magnetic measurements by S. K. Banerjee and F. D. Stacy [*Methods of Paleomagnetism* (Elsevier, Amsterdam, 1967), pp. 470–476] and optimum for AMS measurements by H. C. Noltimier [*J. Geophys. Res.* **76**, 4849 (1971)]. Closely spaced samples were taken to a depth of 20 cm in core 60PG, and 50 cm above and below a manganese crust in core 62. The remainder of core 62 and all of core 61 were sampled at approximately 10-cm intervals.
15. D. F. Williams and M. T. Ledbetter, *Mar. Micropaleontol.*, in press.
16. M. T. Ledbetter, D. F. Williams, B. B. Ellwood, *Nature (London)* **272**, 237 (1978).
17. G. A. Rusnak, *J. Geol.* **65**, 384 (1957); A. H. Bouma, *Sedimentology of Some Flysch Deposits* (Elsevier, Amsterdam, 1962); H. Blatt *et al.*, *Origin of Sedimentary Rocks* (Prentice-Hall, Englewood Cliffs, N.J., 1972).
18. We thank D. A. Johnson for providing samples and much encouragement. Cores were collected by D.A.J. under NSF grant OCE74-01744. M.T.L. received support from NSF grants DES72-01568 and DPP77-09491. We are very indebted to N. D. Watkins, who, before his death in 1977, instilled in us a sense of excitement about research in bottom current processes.

27 September 1978; revised 18 December 1978

Geologic Migration Potentials of Technetium-99 and Neptunium-237

Abstract. *Relatively mobile TcO_4^- and NpO_2^+ can be chemically reduced to less soluble oxidation states in the presence of igneous rocks, as predicted by oxidation-reduction measurements. Current risk assessments, which consider technetium and neptunium as potentially capable of migrating from high-level radioactive waste repositories, may be overestimating their potential hazard to the public since the Fe(II) content of many subsurface waters may maintain these elements in less soluble oxidation states.*

The permanent disposal of high-level radioactive wastes in geologic media is under active consideration by many nations facing the problem of isolating long-lived radionuclides from the biosphere. Geologic disposal is attractive for many reasons, one of which is the retardation of radionuclide migration if water enters the disposal formation. In assessing the risks of geologic disposal, one must have a thorough understanding of the interactions between the geologic media and the long-lived radionuclides which might migrate.

We believe that the migration potentials of at least two of the longest lived radionuclides, ^{99}Tc and ^{237}Np, are possibly being overestimated. Technetium has been considered to be poorly "sorbed" by deep geologic media (*1*), apparently on the basis of experimental data obtained with the pertechnetate oxyanion (TcO_4^-) under oxidizing conditions (*2*). The migration potential of Tc

0036-8075/79/0330-1337$00.50/0