RESEARCH: GEOPHYSICS

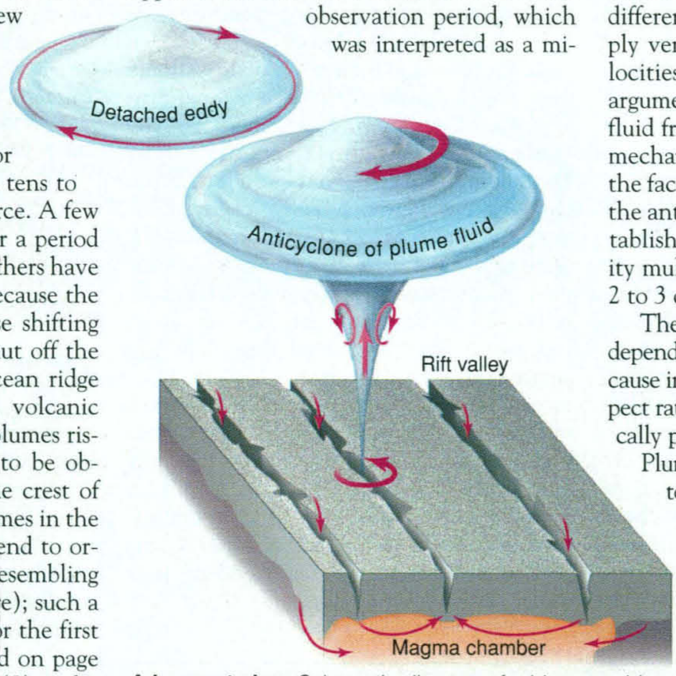
A New Spin on Hydrothermal Plumes

Kevin G. Speer

Mid-ocean ridges are undersea boundaries between Earth's crustal plates where new crust is formed. During crust formation, upwelling magma cools from temperatures of about 1200°C to ambient values, releasing heat to the overlying ocean. Energy conservation suggests, and subsequent observations have confirmed, that a large fraction of the heat is carried by the circulation of seawater within the permeable new crust. Some of this hot, chemically enriched seawater exits the sea floor in a broad, diffuse flow, and some exits in highly focused flow through chimneys or vents, producing plumes that rise tens to hundreds of meters above the source. A few plumes have been monitored over a period of years and appear to be steady; others have been found to be extinguished, because the rock has finally cooled or because shifting fracture zones within the crust shut off the flow. Certain parts of the mid-ocean ridge are very active, and occasional volcanic eruptions generate large "event" plumes rising, in the case of the first one to be observed, roughly 1000 m above the crest of the ridge (*1*). Unlike volcanic plumes in the atmosphere, those in the ocean tend to organize themselves into an object resembling a rotating lens or vortex (see figure); such a flow has been observed directly for the first time with measurements described on page 1052 of this issue by Lupton *et al.* (*2*) at the Gorda Ridge in the Pacific Ocean.

The experiment combined hydrographic surveys of physical characteristics such as temperature and salinity and chemical properties peculiar to plumes with the deployment of a drifting buoy, ballasted to sink to a depth of about 2 km, where it "floats" at its equilibrium level. The float is tracked acoustically by measuring the distance between it and several sound sources moored in the region and by triangulating. The observed trajectory is difficult to interpret in detail, because the flow near the source on the crest of the ridge is complex and includes higher frequency components that can alias the signal but clearly shows an anticyclonic motion as expected in an organized hydrothermal plume. The inferred dimension of this anticyclone corresponds roughly to the size of the plume as determined by tracers, and the speed is in accord with previous indirect estimates.

Curiously, the anticyclonic motion disappeared for some time in the middle of the observation period, which was interpreted as a migration relative to the center of motion. It is not obvious how secondary, radial flow could bring the float inward and then outward at the same depth, but Lupton *et al.* note that the float was not drifting at the core of the plume but below it, and it is likely that the formation and detachment process could result in complex behavior. The net motion of the float, although weak, suggests that the plume as a whole drifted northwest above the western crest of the ridge, following the 2500-m isobath. This result would be in accord with a passive advection of the plume in a larger scale, northward mean flow west of the crest found at other sites.



A buoyant view. Schematic diagram of mid-ocean ridge, showing the seawater being heated by a magma chamber. The heated water is emitted from the rift floor and rises to form an anticyclonic hydrothermal plume. Ocean flow instability can cause eddies to be shed from the anticyclone.

ILLUSTRATION: K. SUTLIFF

Several different mechanisms have been proposed to explain the generation of event plumes by volcanic eruptions, ranging from the sudden release of a large volume of hot seawater trapped within the new crust to the intense heating by the intrusion of a sheet of magma. Recent studies suggest that the cooling of lava flows associated with the eruptions on the crest may be the principal cause (*3*, *4*). The question of the generation mechanism is pertinent here because the physics of the fluid motion in the case of a sudden release of a large volume of hot fluid differs substantially from the heating of ambient fluid by lava. In the first case, a thermal is formed as a volume of hot fluid rises and mixes with its surroundings; in the second case, the mixing is much greater, because the fluid is not isolated from the surroundings by its own mass and the scales for vertical penetration, size, and so forth are different (*5*, *6*). Thermal scales tend to imply vertical penetration and horizontal velocities that are too large, so physical scaling arguments favor a constrained release of hot fluid from a reservoir or the heating by lava mechanism. The latter can be illustrated by the fact that the horizontal velocity scale for the anticyclone is, after the plume is well established, about twice Earth's angular velocity multiplied by the penetration height, or 2 to 3 cm s^{-1}, similar to observations.

The lifetime or stability of the plume also depends on the formation mechanism, because incompletely formed plumes have an aspect ratio somewhat larger than that theoretically possible and as a result are more stable. Plumes formed by steady sources continue to fill with hydrothermal fluid until they reach a size that depends on stratification and rotation, at which point they become unstable and break apart into two separate eddies or plumes. So the combination of an intense heat source with the rapid transfer of heat to the surrounding seawater is best to produce a large, stable hydrothermal eddy. On the basis of chemical and particulate measurements, Lupton *et al.* were able to predict a long lifetime for the observed plume and infer as a result the long-range transport of hydrothermal properties.

Plume physics predicts the existence of a counterrotating cyclonic motion underneath the anticyclone, but this "invisible" part of the hydrothermal circulation is much less known, because it involves the motion of ambient seawater and has no dramatic chemical anomalies to act as tracers. Moreover, the rough topography at the crest of the ridge probably acts to brake or disperse this component of flow. Complementary observations on the Juan de Fuca Ridge, a hydrothermally active ridge several hun-

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dred kilometers north of the float experiment, do indicate the presence of cyclonic motion below the steady plume level (*7*), suggesting that a similar situation may occur at the Gorda Ridge. Thus, very different float trajectory behavior can be expected near the formation site of an event plume at different depths, and a float may drift from one type of circulation regime to another if multiple plumes are forming.

In a larger context, ridge-related oceanography has experienced a renaissance as the effect of fracture zones and passages on the control of deep and bottom water, the evidence for enhanced mixing above the flanks of the ridge, and the possible role of this mixing as well as geothermal heating on deep upwelling all occupy the attention of researchers. The propagation of event plumes adds another element to the impact of the ridge on deep circulation and the transport of volcanically enriched seawater and hydrothermal organisms. Much remains to be done to quantify this transport, and floats will clearly be of help because they mark water parcels approximately and in principle reflect the net effect of all transport processes from mean and fluctuating currents. Transport in the across-ridge direction by event plumes is of special interest; flow along the ridge may be dominated by the combined effects of many weaker, nearly steady sources of heat, as well as nonhydrothermal effects. Future experiments are likely to be cross-disciplinary, already a notable aspect of hydrothermal research, involving a diverse set of measurements to address mixing and transport issues related to geothermal heating, internal-gravity wave breaking, and the role of topographic waves on the ridge flank and crest. These physical processes all exert some control on circulation and, in turn, water column chemistry is helping to provide information about the circulation not only with tracers but also with quantitative constraints on residence times, turbulent suspension velocities, and the nature of heat and chemical transfer at the source.

References

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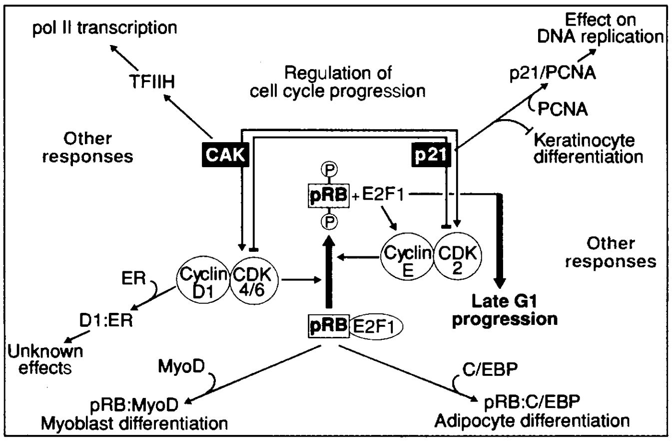
CELL CYCLE

The Expanding Role of Cell Cycle Regulators

Tyler Jacks and Robert A. Weinberg

The cell cycle clock orchestrates the progression of eukaryotic cells through their growth and division cycles. Much of its importance derives from its job as the master controller of a cell's decision to continue proliferating or to withdraw from the cycle and enter a state of quiescence. But recent work—including that of Di Cunto *et al.* on page 1069 of this issue (*1*)—points to a wider role for components of the clock apparatus, some of which extend their reach as far as cellular differentiation.

The core clock machinery is assembled from modular components—cyclins and cyclin-dependent kinases (CDKs). The CDKs control various cellular responses through their ability to phosphorylate appropriate substrates within the cell. The cyclins, acting like guide dogs, bind to and direct CDKs to appropriate substrates during specific phases of the cell cycle, thereby dictating when and where these substrates will become phosphorylated.



The cell cycle machinery extends its influence. ER, estrogen receptor; pRB, retinoblastoma protein; p21, cyclin-dependent kinase inhibitor; E2F1, transcription factor active in late G_1 phase; MyoD, transcription factor controlling muscle differentiation; CAK, CDK-activating kinase; C/EBP, transcription factor controlling adipocyte differentiation.

The retinoblastoma protein, pRB, and related family members are critical targets for cyclins and CDKs. During the mid-G_1 phase of the growth cycle, their phosphorylation by certain cyclin D–CDK4 and cyclin D–CDK6 complexes enables the activation of yet other cyclin-CDK complexes and the transcription of genes required for S phase entry and progression. All these events permit the cell to advance into the late G_1 and S phases (see the figure).

Equally important components of this core machinery are two groups of CDK inhibitors (CKIs) that block the actions of specific cyclin-CDK complexes (green squares in the figure). In so doing, they may prevent cell cycle progression or induce cells to exit the active proliferative cycle and enter the quiescent G_0 phase. For example, CKIs of the INK4 group (p15, p16, p18, p19) are specialized to block the cyclin-CDK4 and cyclin-CDK6 complexes that are essential to pRB phosphorylation and the associated advance into the late G_1 phase of the cell cycle.

But some of the components of the cell cycle clock have other functions besides direct control of proliferation. The Di Cunto *et al.* report indicates that the p21 CKI, which is capable of inhibiting a wide spectrum of CDKs operating throughout the cell cycle, also participates in the development of differentiated phenotypes of keratinocytes of the skin. These authors demonstrate that the amount of p21 protein decreases as keratinocytes initiate end-stage differentiation, and that forced expression of p21 can inhibit the differentiation process. Biochemical and mutational evidence indicates that this differentiation-inhibiting function of p21 can be

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