PERSPECTIVES: PALEOENVIRONMENT

Clues from Fluid Inclusions

Robert H. Goldstein

The reconstruction of Earth's environmental conditions in the geologic past is a challenging task involving many disciplines. Attempts at such reconstruction require knowledge of climatic conditions, such as moisture budgets and temperature, composition of ocean and atmosphere, water depth in lakes and seas, and biological parameters such as the organisms living at the time and their ecology.

Several approaches have been used to reconstruct paleoenvironmental conditions. Observations from the rock and fossil record are commonly interpreted on the basis of knowledge of modern processes. The chemical and isotopic composition of minerals formed in surface environments may be converted to paleoenvironmental parameters on the basis of other assumptions. Many paleoenvironmental parameters are derived from calculations that are based on quantitative reconstructions of tectonic, physical, chemical, and biological processes.

All these approaches involve substantial assumptions and uncertainties, and it is essential that reliable tests of paleoenvironmental interpretations are developed. As Lowenstein *et al.* (*1*) show on page 1086 of this issue, tiny fluid inclusions trapped during the growth of minerals near Earth's surface are beginning to provide such tests (see the figure). Studies of fluid inclusions are challenging: The inclusions are so small, normally micrometers in size, that their analysis can be difficult, and the fluids may be modified before or after their entrapment as inclusions in a host crystal. But despite these difficulties, fluid inclusions represent some of our best opportunities for straightforward determination of past environmental conditions.

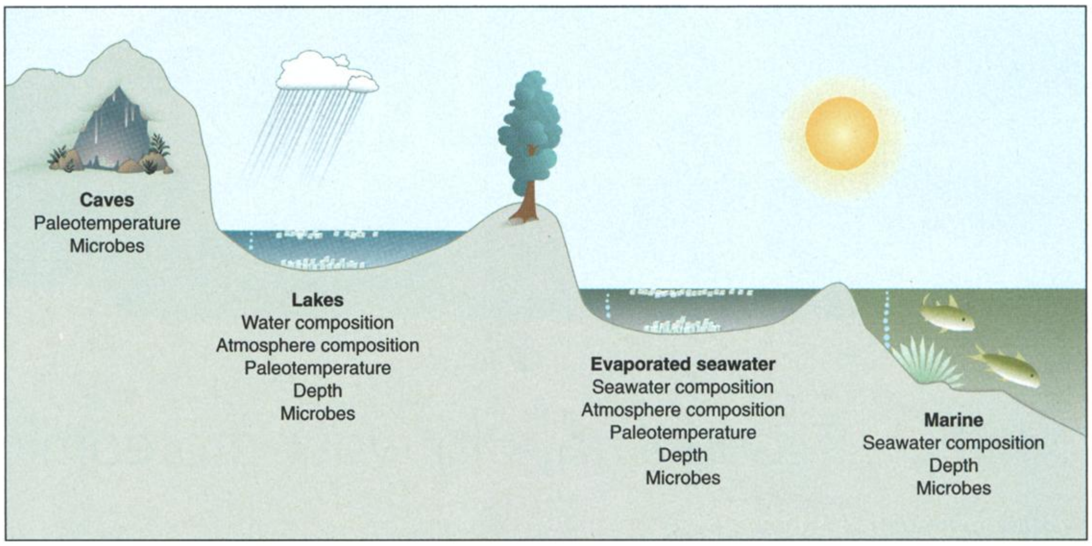
Lowenstein *et al.* (*1*) have analyzed samples of modified seawater from rocks as old as 544 to 543 million years. Their samples were trapped as fluid inclusions in halite crystals formed during the evaporation of seawater and have remained isolated since their entrapment within their crystal hosts. Because the inclusions are samples of seawater modified by evaporation, some assumptions must be made before they can be used to reconstruct ancient seawater chemistry (*2*). The results can nevertheless be regarded as reliable tests of calculated changes in seawater chemistry (*3*) and should improve the accuracy of future models. The results show that the chemical composition of ancient seawater was different from that of modern seawater and that plate tectonics probably controlled much of this variation.

To improve the record of ancient seawater chemistry, a wider range of elements and isotopic compositions must be characterized, and seawater inclusions that have not been modified by evaporation and mineral precipitation must be analyzed. Such inclusions are preserved in calcite crystals that formed in seawater as old as the Cambrian (*4*). They preserve fluids whose salinity is essentially the same as that of modern seawater but whose composition has not been analyzed. Inclusions in calcite have lower concentrations and are smaller and less abundant than in halite; also, the matrix may interfere with measurements. To use these tiny samples as detailed records of ancient seawater chemistry, new techniques will have to be developed for their chemical and isotopic analysis.

Insights into ancient seawater chemistry are not the only use of fluid inclusions. Fluid inclusions of atmospheric gas in glacial ice provide excellent samples of atmospheric chemistry of the recent geologic past (*5*). But atmospheric samples from the deepest reaches of geologic time still await our analysis. Initial attempts at such analysis were controversial, involving the extraction of gas bubbles from fossil amber (*6*). The least altered samples of ancient atmosphere may still remain trapped in samples of halite that formed as floating crystals at the air-water interface of ancient lakes and marine evaporite basins (*7*).

Fluid inclusions can also be used to reconstruct past climates. As liquid inclusions are cooled below their formation temperature, they may generate a tiny bubble. Reheating to the temperature at which the bubble disappears reveals information on the temperature of entrapment. For minerals formed at Earth's surface, fluid inclusions can yield direct measures of paleotemperature and can even reflect the ancient temperature variation from day to night (*8*, *9*). Until now, the most successful studies of this kind have been based on evaporite minerals, but fluid inclusions in ancient cave minerals may hold a record of mean annual surface temperature. Fluid inclusions can preserve data on ancient temperature so precisely that it is surprising that fluid inclusions are not widely used in paleoclimate reconstructions.

Fluid inclusions trapped in minerals precipitated in ancient lakes provide samples of the chemical composition of the lake water. Chemical analysis of these in-



Cross section of environments, illustrating uses of fluid inclusions in paleoenvironmental reconstructions.

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clusions can be used to calculate past moisture budgets (*7*, *10*). Recent analyses of fluid inclusions in halite from Permian lakes have even shown that pH dropped below 1 partly as a result of aridity and low buffering capacity (*11*).

Fluid inclusions may also provide information about water table elevation, lake level, or sea level. As minerals precipitate near Earth's surface, they may entrap bubbles of immiscible gas. Those gases may preserve information on the pressure at the time of entrapment and may be used to reconstruct water depth (*12*, *13*).

When minerals grow in Earth-surface environments, microbes and organic material may be sealed within fluid inclusions. Recently, researchers have revived dormant microbes believed to have been entrapped in fluid inclusions in 250-million-year-old halite (*14*). The potential for preservation and the timing of entrapment of these microbes have been questioned (*15*), but the possibility of finding degraded or even viable organisms in fluid inclusions opens up many exciting (and likely controversial) possibilities in paleobiology.

Lowenstein *et al.*'s study exemplifies the potential of fluid inclusions to elucidate environmental conditions in the geologic past. Studies of fluid inclusions are likely to play an important role in future reconstructions of Earth's paleoenvironment, from the composition of sea and atmosphere to biology and climate.

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PERSPECTIVES: NEUROBIOLOGY

Neurocreationism—Making New Cortical Maps

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The brain can be thought of as a map in which the position of its constituent neurons indicates what they do. Nowhere is this more evident than in a brain region called the cerebral cortex, which consists of structurally distinct cellular (cytoarchitectonic) areas responsible for functions as diverse as sensory perception, motor control, and cognition.

As the cerebral cortex evolved, the number of cytoarchitectonic areas increased and the number of sensory representations was duplicated (*1*). Interest in how the map of the cerebral cortex develops in the embryo has been sustained by the belief that it can explain the emergence of human mental capacity during evolution. The research article by Fukuchi-Shimogori and Grove on page 1071 of this issue (*2*) now identifies a molecule that is involved in defining areas within the telencephalon of the developing mouse brain.

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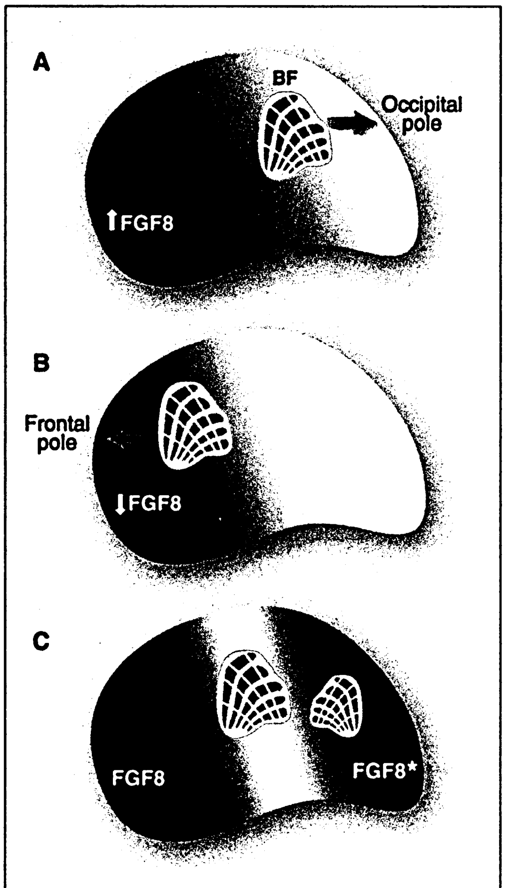
Traditionally, it has been presumed that the embryonic telencephalon first forms an equipotential sheet of cells that then becomes specified by input from subcortical centers (tabula rasa model) (*3*). An alternative view—derived from experimental manipulations of cortical input in primate embryos—is that cells of the embryonic cerebral vesicle themselves carry intrinsic programs for species-specific cortical regionalization (protomap model) (*4*). According to this hypothesis, some region-specific cytoarchitectonic features can develop independently of input (*5*, *6*). Indeed, the word "proto" emphasizes the malleable nature of this primordial map. Within this primordial map, it is envisaged that cues generated within cortical neurons attract appropriate input and cooperatively create a final area-specific, three-dimensional organization. Support for the intrinsic specification of cortical maps has accumulated steadily with reports that a number of genes whose products regulate development are expressed in discrete gradients within cortical regions before (or independently of) the incoming input (*7*–*11*). The protomap hypothesis has been bolstered by evidence that abolition of thalamic input by genetic manipulation does not prevent cortical compartmentalization (*12*–*14*). These dramatic findings prompt the question of how a well-defined cortical area can be established by proteins secreted far from their targets. Fukuchi-Shimogori and Grove (*2*) now reveal that a change in the concentration gradient of a single growth factor across the cerebral wall may have a dramatic effect on the organization of the cortical map in developing mouse embryos.



Developmental cartography. A concentration gradient of FGF8 (blue) with the source situated in the frontal pole affects the position of the whisker barrel field (BF) in the cerebral cortex of developing mouse embryos. An increase (**A**) or decrease (**B**) in the production of FGF8 causes a shift of the BF toward the frontal or occipital pole, respectively. (**C**) Insertion of another source of FGF8 at the occipital pole (*) induces formation of an extra BF with mirror-image whisker representation.

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