The final issue is the origin of local variability. It may have little to do with sediment fluxes. Volcanic data from other tectonic settings has shown us that different processes may be responsible for geochemical variations at different length scales. For example, local geochemical trends on the Mid-Atlantic ridge and some ocean islands are actually orthogonal to global trends, and appear to derive from different magmatic phenomena[11,12]. Similarly, we can imagine many processes that could effect local, intra-arc variability: mantle heterogeneity, sediment heterogeneity, variable sediment or fluid delivery, temporal variations, etc. The origins of this local variability are an important and on-going topic of research. We hope that with expanded data sets, the patterns and origins of local variability in subduction zones will be revealed.

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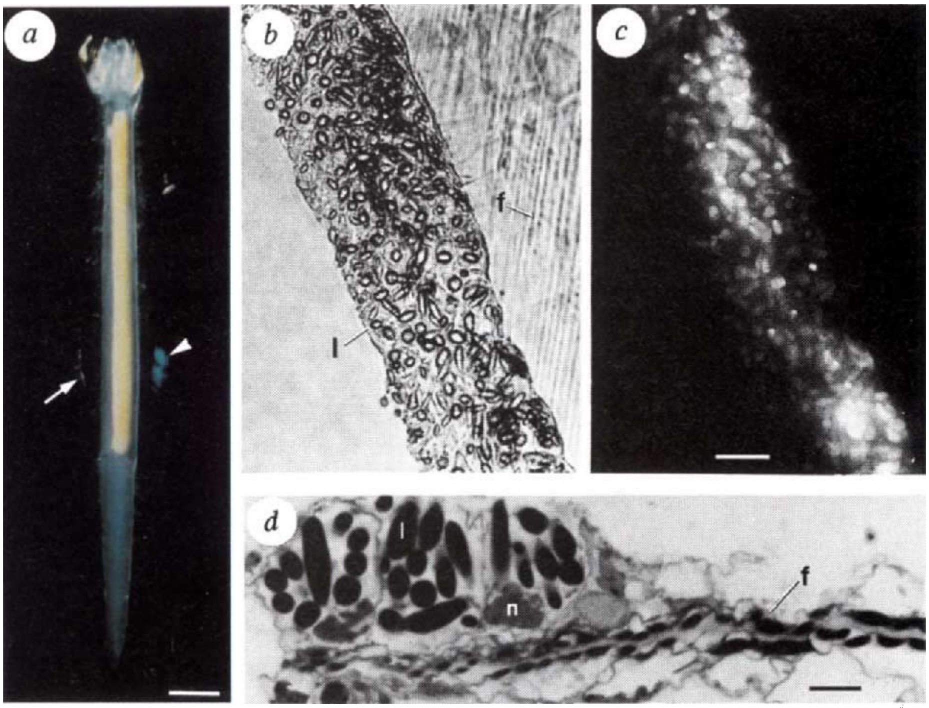

Sources of luminescence in the chaetognath *C. macrocephala*. *a*, Composite image showing the yellow luminous bodies (arrow) on the edge of the transparent anterior fins (not visible) and their blue emitted light (arrowhead). *b*, Light and *c*, fluorescence microscopy of the region indicated by the arrow in *a*. *d*, Cross section through the edge of the fin showing three large cells, each with several luminous organelles, attached above the supportive fin rays. l, Light-emitting organelle; n, nucleus; f, fin ray. Scale bars: *a*, 2 mm; *b*, *c*, 40 μm; *d*, 10 μm.

A bioluminescent chaetognath

SIR — The ability to produce light is especially widespread among marine zooplankton, where the only major phylum without a luminous species has been thought to be the Chaetognatha[1].

These carnivorous arrow worms are found throughout the world's oceans, where their abundance approaches that of copepods[2]. We have discovered bioluminescence in a well-known bathypelagic chaetognath. This is the first addition to the roster of luminescent phyla in more than 50 years[3].

Chaetognath bioluminescence was first noted from the *Johnson-Sea-Link* submersible on cruises with E. A. Widder near the Bahamas Islands. On three dives, at 870, 850 and 760 m, a chaetognath with an orange-pigmented gut darted away, leaving a plume of luminescence.

We subsequently examined chaetognaths collected from the North Pacific Ocean on cruises with J. J. Childress and E. V. Thuesen. Luminescence was repeatedly evoked in specimens of *Caecosagitta macrocephala* (Fowler, 1905), a cosmopolitan species generally found at depths greater than 700 m (ref. 4) (*a* in the figure). Luminescence was not produced by *Eukrohnia fowleri*, the other common species with an orange gut, nor by nine other chaetognath species examined (identified by E. V. Thuesen).

In marine invertebrates luminescence is produced via bacterial symbionts, or through the oxidation of a light-producing compound (luciferin), mediated by a calcium-activated photoprotein or by an enzyme (luciferase). Methanolic extracts of *C. macrocephala* contained coelenterazine, the luciferin of cnidarians, ctenophores, radiolarians, and some squid, fish, and crustaceans[5]. Aqueous extracts added to coelenterazine showed high levels of luciferase activity. (Substrates for the assays were provided by O. Shimomura and S. Inoue.) No calcium-activated photoprotein was detected, and an assay for bacterial luciferase performed by M. G. Haygood and G. Mowlds was also negative. These results indicate that light is produced by a coelenterazine–luciferase reaction, making Chaetognatha the seventh phylum known to use coelenterazine for its luminescence.

Light is produced at the midpoint of the body by large vacuolar cells on the edges of the anterior fins (*a* in the figure). Ovoid or fusiform membrane-bound inclusions within these cells (*b*, *d*) are autofluorescent to varying degrees (*c*), a trait that has been correlated with the location of luminescent sources in many taxa[6,7]. The fluorescent subcellular bodies are likely sites for storage of the components of the luminescent reaction. Electron microscopy (not shown) indicates that most contain a dense paracrystalline matrix with small spherical inclusions. Others, even within the same cell, lack internal organization, possibly indicating organelles in which the luminescent compounds have reacted.

Although the luminous bodies are visible to the naked eye and may even be visible in a published micrograph[8], they have not been included in previous descriptions of this species[8–11]. These omissions, as well as the failure to note bioluminescence, may be due in part to the poor condition of specimens examined in the past; the insulated closing cod end of the 10 m^2 Tucker trawl[12] used in this study recovers animals in excellent condition.

Chaetognaths are commonly allied with pseudocoelomates (=Aschelminthes) and with deuterostomes, but recent molecular work supports the view that they diverged near the roots of the Metazoa[13]. Based on this early divergence and on the uniqueness of the light-producing cells, it appears

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that luminescence evolved independently in *C. macrocephala*, although in some organisms luciferin can be obtained from food.

Because luminescence is normally produced in conjunction with an escape response, the cloud of light appears to function as a diversionary display. This adaptation highlights the importance of bioluminescence in the interactions among marine organisms and demonstrates the value of *in situ* observations for understanding life in the sea.

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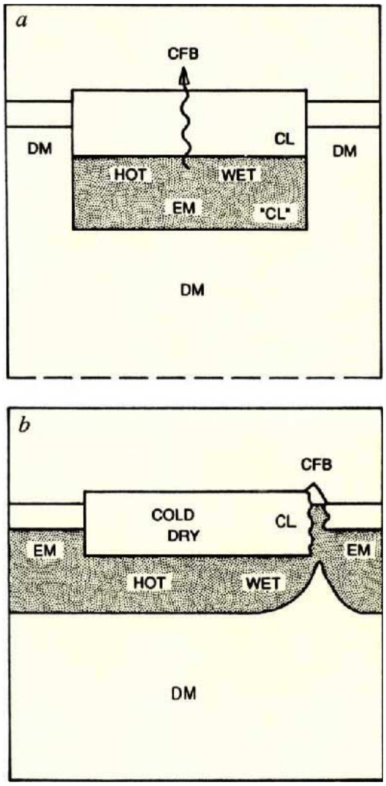
Lithosphere and flood basalts

SIR — So-called hotspot magmas, including ocean island basalts and continental flood basalts, differ isotopically from mid-ocean-ridge basalts (MORB) and require a reservoir, or a component, that has been isolated from the MORB source for more than 2 billion years. It has been widely assumed that a suitable isolated reservoir might be the continent lithosphere.

Most authors refer to 'lithosphere' as the strong outer shell of the Earth. Geophysics[1] and rock physics[2] show that the silicates of the mantle have little strength at temperatures greater than 650±100 °C or about half the absolute melting temperature. Some authors, however, refer to the thermal boundary layer as 'lithosphere' even though it extends to about 1,300 °C, near or above the silicate solidus[3]. The thermal boundary layer has a close to critical Rayleigh number and cannot remain attached to the plate or accumulate long-term isotope anomalies[3] unless it is also isolated from the 'convecting mantle' by buoyancy[4,5]. Only the shallow colder part of the thermal boundary layer can be considered rigid, or can maintain a long-term attachment to the plate or to an overlying continent. The use of the term 'lithosphere' for the thermal boundary layer is unfortunate, as it has led geochemists to believe that it is strong and can remain attached to ancient crust and its associated mantle (the rheological or real lithosphere) for long periods.

Both the lithosphere and the thermal boundary layer are colder than the rest of the mantle and are relatively thin. This makes it hard to see how large amounts of melt can be produced in a short period of time, as is characteristic of continental flood basalt provinces[6]. Gallagher and Hawkesworth[7] therefore propose a "wet continental lithosphere" reservoir with a melting temperature ∼500 °C lower than that of dry silicates. The lower part of this proposed 'lithospheric' source has temperatures ranging from 1,000 to 1,500 °C. Such mantle has low viscosity and low seismic velocities. The presence of even trace amounts of water results in significantly lower creep strength than under strictly dry conditions. The strain rate of wet olivine[2] at 1,200 °C for a typical lithospheric deviatoric stress of 500 MPa is 10^{-8} s^{-1}. Lithosphere straining uniformly at this rate will experience a strain of unity in 3 years. Such high stresses cannot be maintained in hot mantle, which is thus better described as 'asthenosphere' (weak layer). The lower part of the thermal boundary layer cannot support even its own weight for long periods of time. It will also delaminate or deform irreversibly when subjected to compression or extension. It does not contribute to the strength of the lithosphere and deforms independently of it.



a, The continental lithosphere (CL) hypothesis attributes continental flood basalts (CFB) to the lower part of the thermal boundary layer under continents, called by some the "lithosphere". This material has asthenosphere-like seismic velocity and viscosity and cannot be isolated from depleted mantle (DM) by its strength. It will flow laterally. *b*, The perisphere model attributes enriched components of hotshot magmas to a weak enriched mantle (EM) tapped at continental rifts or in the initial stages of DM upwelling. The strong lithosphere or plate is limited to regions colder than 650±100 °C. Basalts from DM are not evident in the initial stages of rifting but become dominant at mature or rapidly spreading ridges.

Observed seismic velocities in cratonic lithosphere require a refractory oblivine-rich composition[8]. Seismic shear velocities at 1,200 °C and 150 km depth in olivine-rich mantle are 4.6 km s^{-1}, and they will be even lower in wet mantle. Observed shear-wave velocities at this depth under ancient cratons are 4.78 km s^{-1}, which imply temperatures of ∼600 °C (ref. 8). Non-cratonic mantle has lower velocities.

Thus, the physical properties calculated for wet lithosphere are asthenosphere-like. The conditions envisaged for continental 'lithosphere' will not be long maintained and the material will flow readily. Metasomatized or hydrous mantle is buoyant, particularly if it is basalt-depleted harzburgite, and therefore is likely to spread across the top of sub-lithospheric mantle (see figure). Fossil plume heads, another proposed source for flood basalts[9], are even hotter than continental lithosphere and will suffer the same fate. In either case an enriched sub-lithospheric layer will result. Such a layer, which I have called the 'perisphere'[10], will isolate the deeper MORB reservoir from recycling and fluids resulting from slab dehydration. In addition to these components it may also be rich in residual, small-melt fraction fluids[4,11,12]. A global shallow enriched or metasomatized layer is intrinsic in some mantle evolutionary models[4,8,11]. The enriched perisphere can eventually be pushed aside or depleted, just as has been proposed for continental lithosphere and 'fossil plume heads', to allow egress of depleted mantle or MORB melts therefrom. Attributing the source of flood basalts to continental lithosphere rather than the hot and weak sub-lithospheric mantle results from a semantic confusion between 'lithosphere' and 'thermal boundary layer'. A recent reappraisal of the geochemistry of flood basalts and continental lithosphere also favours a sub-lithospheric origin[13].

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