Explosive eruption of coal and basalt and the end-Permian mass extinction

Darcy E. Ogden[a] and Norman H. Sleep[b,1]

[a]Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, University of California, San Diego, 1156 Gilman Drive, La Jolla, CA 92093-0225; and [b]Department of Geophysics, Mitchell Building, 397 Panama Mall, Stanford University, Stanford CA 94305

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The end-Permian extinction decimated up to 95% of carbonate shell-bearing marine species and 80% of land animals. Isotopic excursions, dissolution of shallow marine carbonates, and the demise of carbonate shell-bearing organisms suggest global warming and ocean acidification. The temporal association of the extinction with the Siberia flood basalts at approximately 250 Ma is well known, and recent evidence suggests these flood basalts may have mobilized carbon in thick deposits of organic-rich sediments. Large isotopic excursions recorded in this period are potentially explained by rapid venting of coal-derived methane, which has primarily been attributed to metamorphism of coal by basaltic intrusion. However, recently discovered contemporaneous deposits of fly ash in northern Canada suggest large-scale combustion of coal as an additional mechanism for rapid release of carbon. This massive coal combustion may have resulted from explosive interaction with basalt sills of the Siberian Traps. Here we present physical analysis of explosive eruption of coal and basalt, demonstrating that it is a viable mechanism for global extinction. We describe and constrain the physics of this process including necessary magnitudes of basaltic intrusion, mixing and mobilization of coal and basalt, ascent to the surface, explosive combustion, and the atmospheric rise necessary for global distribution.

Recent studies have brought the Great Dying at the end of the Permian Period into focus. Up to 95% of shell-bearing marine species and 80% of land animals perished (1, 2). The temporal association of the extinction with the Siberia flood basalts at approximately 250 Ma is well known (1–7), but a causal mechanism connecting the flood basalts to global extinction is not evident. The flows directly killed only those biota in their path, and basalt is not a massive source of greenhouse gases such as CO_2 (8). Recent studies suggest flood basalts may have mobilized carbon in thick deposits of organic-rich sediments, resulting in global climate change and extinction (4, 5, 7, 9–13). New work also suggests magmatic release of CO_2 from mantle-derived eclogite as a potential extinction mechanism (14).

Svensen et al. (15) were the first to discuss the mechanism by which basaltic interaction with organic sediments may cause mass extinction through explosive release of methane. McElwain et al. (16) expanded on this idea by linking the intrusion of Karoo–Ferrar magmas into coal with the 183 Ma Toarcian oceanic anoxic event. In this model, basaltic intrusions metamorphosed sediments driving off hydrocarbons, including methane, which quickly oxidized to carbon dioxide (CO_2) and water. This sudden release of organic carbon acidified the ocean and caused a $\partial^{13}C$ excursion in the sedimentary record.

Retallack and Jahren (5) applied a similar idea linking basaltic intrusion of coal seams in Siberia to the late Permian extinction. Their study focused on this mechanism as an explanation for the large, short-term carbon isotopic excursions observed during this time. In their model, basaltic dikes feeding flood basalts repeatedly intrude and heat coal seams, causing mobilization and release of methane into the atmosphere. The low carbon isotopic value of coal-derived methane makes it a plausible source for the large isotopic excursions. Other carbon sources have much higher isotopic ratios and would require much larger releases in order to cause the observed excursions (5).

In addition to these mechanisms for carbon release, fly ash recently documented in contemporaneous sediments in northern Canada suggest explosive combustion of coal by mafic intrusion (17). This paper explores the physical mechanism by which coal and basalt may have erupted and contributed to the end-Permian mass extinction along with other previously proposed mechanisms.

The process begins with a massive mafic sill preferentially intruding, heating, and mixing with thick coal seams in Siberia (Fig. 1). This mechanism is far more efficient than dikes in quickly delivering heat to coal. The hot coal–basalt mixture extrudes at numerous surface locations. The physical mechanism behind this process of pipe initiation and fracturing would be similar to that described by Jamtveit et al. (18). The coal in the mixture ignites on contact with the air, causing pyroclastic fly ash, soot, sulfate, and basaltic dust to ascend into the stratosphere.

Acceleration of extinction by massive coal–basalt eruption is particularly attractive because it has the virtue of changing the environment within a generation time of many of the organisms that became extinct. Detailed ecology, ocean, and climate modeling are beyond the scope of this paper, but we note potential adverse effects on biota. Large injections of dust, CO_2 and methane into the atmosphere may have generated a highly unstable climate, driving extinctions of land biota. Ocean acidification may have resulted from the sudden addition of CO_2 to the shallow mixed layer on the scale of months to years, driving extinction of marine organisms and formation of the observed dissolution horizon (2).

Coal–Basalt Volcanism

Retallack and Jahren (5) computed the necessary amount of sudden carbon (C) release as 0.23×10^{18} moles in three events, or approximately 1 trillion tonnes C per event based on isotopic excursion data. We provide example calculations to constrain the necessary mass of coal and its areal extent. Although small outcrops of metamorphosed coal have been observed in Siberia, large-scale remnants from the mechanism described here would be buried deeply beneath Siberian lavas and not accessible for study. We follow Retallack and Jahren (5) and use coals in the accessible Tunguska region on the edge of the Siberian basaltic province as proxies.

Coal has a variable density and wt % C depending on rank and purity. Rank was presumably low; Siberian coal bearing strata were young and shallow at the end of the Permian. For an example mass-balance calculation, we assume a density of $1{,}200\ \mathrm{kg\,m^{-3}}$ and a composition of about 80–90 wt % C. Based on these values, all of the carbon in approximately $1{,}000\ \mathrm{km^3}$ of coal would need to be fully liberated and injected into the atmosphere in order to cause the observed isotopic excursion.

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[1]To whom correspondence should be addressed. E-mail: norm@stanford.edu.

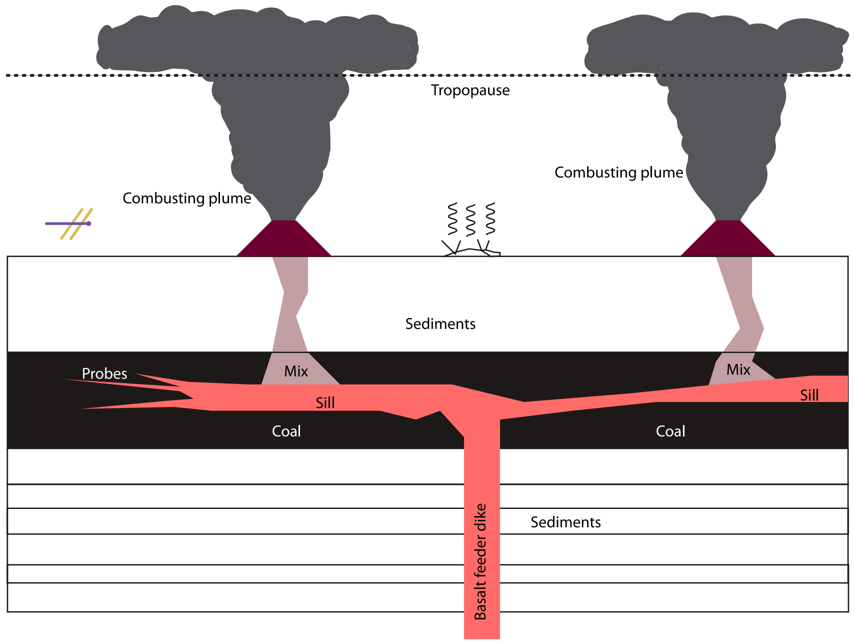

Fig. 1. Schematic of coal–basalt volcanism leading to mass extinction.

The deformable rheology and low density of coal beds tend to confine basaltic magma into sills. Geometrically, an intrusion must have occurred over a surface area of 11,000 km^2 (i.e., approximately 105 km square on a side) if the cumulative thickness of coal in the Siberian basin is 92 m (5). A typical moderately thick coal bed of 20–30 m (19) may be more realistic and would increase the affected region to an approximately 200-km square. Single intrusions large enough to mobilize this amount of coal are well documented in flood basalt provinces (20).

Alternatively, intrusion of basalt sills into coal may have resulted in devolatilization of the coal at depth and incorporation of those volatiles into erupting basalt, leaving behind natural coke (21–23). For this scenario, a larger coal bed is needed and can be calculated based on coke production data. The specific heat per mass for basalt and coal are comparable (approximately 1.25 and approximately 1.4×10^3 J kg^{-1} K^{-1}, respectively). Therefore, a 50:50 by mass mixture of basalt at approximately 1,000 °C and coal at approximately 20 °C can be estimated at approximately 500 °C. The Fischer analyses for volatile gases components in coal run at this temperature produce gas yields of about 20% (24). Therefore, if carbon mixes with basalt purely through volatilization, the volume of affected coal needs to be increased by a factor of 3 to 5, which is in line with estimates by Retallack and Jahren (5). The area of our example bed goes from 200 km^2 to 400 km^2 if we retain a bed thickness of 25 m. The computed surface area is reduced some if several sills simultaneously intruded several thick coal beds from one feeder dike. A volatile-only hypothesis therefore remains conceivable for a very rare event. However, the presence of fly ash in Canadian deposits (17) suggests at least partial mobilization of coal to the surface.

Delivery of the bulk of thick coal beds to the surface requires basaltic intrusion, mixing between the basalt and coal, and transport of the mixture to the surface. Each of these processes is physically reasonable. Coal is mechanically weak and less dense than basalt, making it a rheological trap to form sills (25). Observationally, several thin protosills extend in front of a major propagating sill (26), preferentially intruding weak coal beds and shales. This network allows sills to intrude multiple thick coal beds or to jump between them. Field evidence in the Raton basin shows mafic sills will preferentially intrude even thin coal beds (22).

Coal has a tendency to flow suddenly once started (27). Coking industry experience indicates that hot coal behaves as a fluid until the gas and tar have escaped. Coal heated to about 500 °C and quenched clearly shows evidence of gas exsolution and fluidization of the matrix (28). Díaz et al. (29) measured the rheology of coals at 400–500 °C at durations and strain rates relevant to its behavior as an igneous rock. They obtain viscosities between $3 \times 10^5 - 3 \times 10^2$ Pa s at strain rates from 0.1–10 s^1. The higher viscosities at lower strain rates are partly the result of tar leaking out. Hot coal is strain-rate softening because flow prevents formation of the lattice of hard coke. Tar and volatiles are less likely to quickly lead out of a thick coal bed than a laboratory scale experiment.

Hot coal and basalt will have a tendency to mingle as the effective viscosity of cooling basalt approaches that of the warming coal. We assume that the heated coal is a heterogeneous mixture of liquid and solid depending on temperature and mixes accordingly. This process is analogous to the mingling of cooling basalt with barely solidified and then melted granitic rock (30). Field examples support coal mobility by igneous intrusion. McClintock and White (27) describe viscous mingling of coal and basalt on a scale of 10 mm in Antarctica. Podwysocki and Dutcher (21) report coal dikes mobilized by lamprophyre intrusions in Colorado. Partially mobilized coal called "jhama" and "ball coal" has been documented in India (31). These rocks are a significant hindrance to mining; there is no economic reason to chase a thin stringer of natural intrusive coke into the country rock. We therefore suspect that such incidences are underreported.

The coal–magma–volatile mixture behaves as a volatile–rich explosive magma with a viscosity similar to andesite or dacite but a much lower density. The hot mixture of basalt and coal is buoyant with respect common sedimentary rocks and will tend to ascend. The typical thermal conductivity for coal (0.33 W m^{-1} K^{-1}) (32) is well below the conductivities of common sedimentary and basaltic rocks, trapping heat (22) and further favoring its ascent with entrained domains of weakly heated coal. The transport process to the surface can be considered analogous to basaltic fire fountains or the explosive escape of chloride-rich fluids (13).

The hot (approximately 500 C) mixture of basalt, volatiles, coke, and solid coal would combust as it is exposed to oxygen at the surface, rapidly releasing fly ash, CO_2, sulfate, basaltic ash, and other potentially harmful products into the atmosphere. These products must be injected into the stratosphere in order to have the observed global catastrophic effects, including fly ash deposits in Canada (17). The theory of eruptive columns by Wilson et al. (33) suffices to estimate the eruption rate of coal–basalt mixture that is necessary for plume heights of this magnitude. The column height (H) depends on the rate at which energy is supplied to the plume ($\dot{Q}$),

$$H = 8.2(\dot{Q})^{1/4} \quad [1]$$

In the case of a combusting mixture of basalt and coal, $\dot{Q}$ is supplied by the thermal energy of the initially hot basalt ($\dot{Q}_B$) and the chemical energy supplied by the coal ($\dot{Q}_C$). $\dot{Q}_B$ is estimated by $\dot{Q}_B = \dot{m}_B C_B \Delta T$, where $\dot{m}_B$, C_B, and ΔT are the mass flux and specific heat of the basalt, and the temperature contrast between basalt and the ambient air, respectively. $C_B \Delta T$ is approximately $10^6\ \mathrm{J\,kg^{-1}}$. When the mixture ignites upon mixing with air, chemical energy from the coal is released such that, $\dot{Q}_C = \dot{m}_C E_C$, where E_C is approximately $24 \times 10^6\ \mathrm{J\,kg^{-1}}$ and $\dot{m}_C$ is the mass flux of coal. Any significant addition of coal makes the eruption much more vigorous.

We calculate column height as a function of total mass flow of the basalt–coal mixture for different mass fractions of coal (x_c) for eruption rates typical of basaltic fire fountains (Fig. 2). For simplicity, we assume the tropopause was located at an altitude of approximately 10 km. These results show that the extra energy from combustion of coal is necessary for the plume to reach the stratosphere and suggest a minimum basalt–coal eruption rate of $10^5\ \mathrm{kg\,s^{-1}}$.

These calculations represent an approximate maximum height that could be attained by a plume with the given eruption rate. To do so, we assume all available thermal and chemical energy is converted into potential energy and omits complications including vapor condensation, fragmentation energy, and efficiency of heat exchange with air. We assume that the coal ignites, which is reasonable considering the ample supply of hot basaltic wicks and the huge surface area available for interaction with oxygen in a vigorous fountain. In addition to providing energy for buoyant rise, we also expect the combustion process to further fragment the molten basalt–coal mixture. This increase in fragmentation helps to improve the chances of eruption products reaching the stratosphere by producing finer, more easily entrained particulates.

The lifetime of an individual vent is easily obtained. For example, a circular area with a radius of 1 km and a thickness of 25 m (i.e., a mass of 1.2×10^{11} kg) would be drained in 14 days by an eruption with an approximate mass flux of $10^5\ \mathrm{kg\,s^{-1}}$. Vigorous activity at each individual vent was likely short lived, followed by low-level effusive eruption of basalt or hot coal sluggishly leaking out. The latter case would resemble accidental fires in large coal tailings piles (34).

As a simple test of the feasibility of this mechanism, we compute this viscosity needed for a mass flux of $10^5\ \mathrm{kg\,s^{-1}}$ for comparison with data on the viscosity of hot coal. The relevant physical parameters are well enough constrained for an order of magnitude viscosity estimate using analytical calculations for pipe flow. The model 1:1 coal–basalt mixture has a density ρ of approximately $1{,}500\ \mathrm{kg\,m^{-3}}$ and a density contrast with the surrounding rock $\Delta\rho$ of approximately $1{,}000\ \mathrm{kg\,m^{-3}}$. The thickness approximately 30 m of a major coal bed provides a scale of the radius R of the conduit, here 15 m. We use the analytical formula for pipe flow with the caveat that it yields an apparent viscosity in a nonlinear substance:

$$\dot{m} = \frac{\rho \pi \Delta\rho g R^4}{8\eta} \quad [2]$$

Solving a viscosity of 9×10^5 Pa s produces the necessary mass flux of $10^5\ \mathrm{kg\,s^{-1}}$. This is at the top of the range for viscosities of hot coal and basalt so there is no difficulty for the mixture to ascend through a reasonably sized conduit.

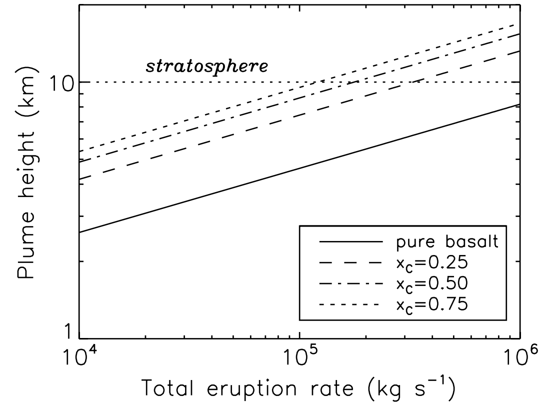

Fig. 2. Estimated plume heights for coal–basalt eruptions. Additional chemical energy from coal increases plume heights, transporting eruption and combustion products into the stratosphere (approximately >10 Km). Larger mass fractions of coal (x_c) result in higher plumes.

Conclusions

Our hypothesis attempts to explain the sudden release of approximately 1 trillion tonnes of carbon into the surface environment inferred from the carbon isotopic record (5) and to associate one of these events with the end-Permian mass extinction. The analysis presented here coupled with the depositional evidence of fly ash (17) strongly suggest that explosive interaction of basalt and coal in the Siberian traps may have played a role in the end-Permian mass extinction. This process may also be a contributing mechanism for other extinctions involving large carbon isotopic excursions.

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