Carbon dioxide is produced by metamorphic reactions in orogenic belts and high-heat-flow systems. Part of this carbon is ultimately released to the atmosphere, but the long timescale of regional metamorphism implies that the short-term effects on the environment are minor. However, contact metamorphism around igneous sill intrusions in organic-rich sedimentary basins has the potential to generate huge volumes of CH$_4$ and CO$_2$, and these gases are rapidly released to the atmosphere through vertical pipe structures. The high flux and volume of greenhouse gases produced in this way suggest that contact metamorphic processes could have a first-order influence on global warming and mass extinctions.

**INTRODUCTION**

Carbon-bearing fluids are constantly seeping from the lithosphere to the Earth’s surface and into the atmosphere (e.g. Kerrick 2001; Morner and Eliope 2002). In some places, such as young mountain ranges and high-heat-flow zones, the seepage is more intense than in others. In these settings, fluid expulsion at the Earth’s surface is a reflection of metamorphism taking place many kilometers below the surface. Hot springs and mud pots are familiar surface manifestations of metamorphic fluid production. The processes behind the production of C-rich volatiles include reactions that transform carbonates, feldspar, and quartz into amphibole, epidote, pyroxene, garnet, and CO$_2$ (e.g. Kerrick et al. 1991). Key questions include: How much CO$_2$ can be generated and released by metamorphic processes? And how fast? Can the degassing trigger rapid global warming and make an impact on life on Earth?

Pioneering work by Derrill M. Kerrick and coworkers in the 1990s attempted to link Cenozoic greenhouse events (see Zachos et al. 2001) to large-scale CO$_2$ degassing caused by prograde metamorphism of carbonate-bearing rocks (Kerrick et al. 1995; Nesbitt et al. 1995). It was proposed that contact metamorphism of limestone around plutons in western North America in the Eocene released large amounts of metamorphic CO$_2$ (0.167 gigatons [Gt] per square kilometer per million years) and that this degassing could have contributed to Eocene greenhouse conditions if more than 10$^8$ km$^2$ were metamorphosed (Nesbitt et al. 1995; Kerrick and Caldeira 1998). Such abundant CO$_2$ degassing would have exceeded CO$_2$ consumption by silicate weathering (Kerrick and Caldeira 1993). An Early Cenozoic climatic effect of CO$_2$ degassing by Himalayan regional metamorphism was however discarded (Kerrick and Caldeira 1999), but new data suggest that present-day regional metamorphism is a net supplier of CO$_2$ to the atmosphere (Becker et al. 2008; Evans et al. 2008).

The relatively short duration of Cenozoic greenhouse gas–driven events, which lasted less than 200,000 years, relative to the long duration of orogenesis is a major challenge for the hypothesis that metamorphic CO$_2$ has affected climate. Several rapid global warming events and mass extinctions are known from the geological record, including the Paleocene-Eocene thermal maximum (PETM; 55 million years [Ma]), the Toarcian (183 Ma), the end-Permian (252 Ma), and the Triassic-Jurassic (200 Ma) (e.g. Wignall 2001; Courtillot and Renne 2003). The triggering mechanisms of these events are poorly understood. Gas hydrate dissociation, sluggish ocean circulation and anoxia, CO$_2$ degassing of lava, and CH$_4$ degassing during metamorphism are among the hypotheses that have been proposed (e.g. Wignall 2001; Cohen et al. 2007; Knoll et al. 2007). However, the temporal correlations among these environmental events, the formation of large igneous provinces (LIPs), and contact metamorphism in sedimentary basins intruded by LIP magmas (Table 1) suggest a causal relationship.

**VOLCANIC BASINS AND LIPS**

Contact metamorphism in sedimentary basins occurs when hot and partly molten igneous intrusions heat the country rocks. These sedimentary basins are called volcanic basins. The igneous intrusions are often basaltic and emplaced during LIP formation. Volcanic basins are common along volcanic rifted margins and on cratons (Fig. 1). The intrusions commonly form sheet-like sills and dikes. Sills are commonly sandwiched between sedimentary sequences and can be more than 350 m thick. Because sedimentary basins are among the main crustal reservoirs of organic and inorganic carbon (e.g. IPCC 2001), they have a huge potential for CH$_4$ and CO$_2$ generation. A link between contact metamorphism and the PETM was proposed in 2004, based on detailed seismic imaging and borehole studies in the Voring and Møre basins, offshore Norway (Svensen et al. 2004). This hypothesis provided a new framework for investigating the environmental consequences of metamorphism. The cornerstone of the theory is that gas is rapidly generated from heated organic material in metamorphic aureoles and is subsequently released to the atmosphere as greenhouse gas. Recent results have provided strong evidence that a similar explanation applies...
to other climate events, including the Toarcian (Lower Jurassic), the Triassic-Jurassic, the end-Permian, and the end-Guadalupian (e.g. McElwain et al. 2005; Beerling et al. 2007; Svensen et al. 2007, 2009; Retallack and Jahren 2008; Ganino and Arndt 2009). This hypothesis is supported by geological constraints (e.g. observed contact aureoles, sill intrusions, and vertical pipe structures) as well as the fact that metamorphism of organic carbon leads to generation of \(^{13}C\)-enriched CH\(_4\), which better explains the available geochemical data than the emission of \(^{12}C\)-depleted mantle CO\(_2\) as a result of the degassing of LIP lava.

**CONTACT METAMORPHISM AND CARBON DEGASSING**

Vast volumes of sedimentary rocks are heated in volcanic basins following sill emplacement (Fig. 1; Table 2). Sill intrusions can extend laterally over several hundred kilometers, with thicknesses commonly in the 50–200-meter range, and they can dominate the geology of sedimentary basins (Fig. 2a). A single sill could fill a volume of 5,000 to 20,000 km\(^3\). Considering that the thickness of the metamorphic aureole on each side of the sill is commonly about the same as the sill thickness, the volume of heated sediments could be as much as 40,000 km\(^3\). Because the contact aureoles reach peak metamorphic conditions (typically 400–500°C) shortly after sill emplacement (tens to hundreds of years), the metamorphic reactions and associated fluid production are also very fast. If only 1 wt% of the organic carbon in shale or siltstone is transformed into gaseous carbon compounds, the gas production potential associated with a 5,000–20,000 km\(^3\) sill is 230–920 Gt C (corresponding to a greenhouse gas equivalent of 310–1200 Gt methane, CH\(_4\)). This means that a single melt batch injected into an organic-rich sedimentary basin can generate sufficient methane to cause global warming (Svensen et al. 2004, 2007).

In volcanic basins, there is abundant evidence for rapid injection of the aureole-generated gases into the atmosphere. When sedimentary rocks are heated by magma, decomposition of organic matter, mineral dehydration (generating H\(_2\)O and CO\(_2\)), and pore fluid expansion or boiling occur on a timescale of years. The resulting over-pressure can lead to hydrofracturing and the formation of breccia pipes and hydrothermal vent complexes (e.g. Jamtveit et al. 2004). In the Karoo Basin, South Africa, hydrothermal vent complexes commonly formed in the uppermost 400–500 meters of the basin (Fig. 2). In addition, numerous breccia pipes are rooted in contact aureoles in black shale at deeper levels in the basin (Svensen et al. 2007). Baked grey shales that have lost their organic carbon remain in the pipes (Fig. 3). Vent structures and breccia pipes are characteristic features of many volcanic basins, including the Voring and More basins, the Faroe-Shetland
In the Siberian Tunguska Basin, spectacular pipes with up to 1.6 km wide subaerial explosion craters formed during the latest Permian. A schematic cross section of a volcanic basin with pipe structures is shown in Figure 4. In marine settings, such as the Voring Basin, the craters can be more than 10 km in diameter (Planke et al. 2005).

SEDIMENT COMPOSITION AND ENVIRONMENTAL EFFECTS

The chemical composition of the sedimentary rocks heated by igneous intrusions has a profound influence on the metamorphic fluid composition (e.g. Svensen et al. 2004, 2009; Ganino and Arndt 2009). An overview of the sediment types heated in various volcanic basins is given in Table 2. For example, organic-rich shale generates CH$_4$ during contact metamorphism, whereas coal generates fluids enriched in CO$_2$. Both generate water by dehydration. Because many sedimentary basins contained hydrogen-rich kerogen and oil and gas accumulations at the time of sill emplacement, petroleum-derived gases such as CH$_4$ and C$_2$H$_6$ may dominate the metamorphic fluid. If limestones or dolostones are heated, the generated fluid is dominated by $^{13}$C-enriched CO$_2$, but if organic matter or graphite is present, the fluid contains $^{13}$C-depleted CH$_4$. Evaporites with anhydrite and rock salt can generate SO$_2$ and HCl, and if organic matter or petroleum is present, CH$_4$ and halocarbons such as CH$_3$Cl (methyl chloride) and CH$_3$Br can also form. Halocarbon generation was recently confirmed by experiments in which natural rock salt from the Tunguska Basin in eastern Siberia was heated to 275°C, to simulate contact metamorphism (Svensen et al. 2009).

In eastern Siberia, a major sill-emplacement event took place at the end of the Permian, when thick sills were injected throughout the basin. Mass-balance calculations suggest that 10,000–30,000 Gt C could have been generated during contact metamorphism of organic matter, accompanied by 4,500–13,000 Gt CH$_3$Cl (Svensen et al. 2009). The presence of hundreds of pipe structures rooted in evaporitic rocks suggests that the gases were released to the atmosphere. Thus the end-Permian global warming event could have been triggered by aureole degassing. Recent atmospheric modeling showed that $>$1000 Gt of methyl chloride are required to cause significant stratospheric warming.
ozone depletion over a 100,000-year timescale (Beerling et al. 2007). This may explain the terrestrial end-Perman mass extinctions. Evidence for ozone-layer breakdown and damaging UV-B radiation is found in mutated pollen (Visscher et al. 2004).

**CONTACT VERSUS REGIONAL METAMORPHISM**

Regional metamorphism is unlikely to cause short-term global climate changes for two main reasons: (1) The timescale of orogeny and crustal extension is long, typically >5 million years, whereas the relevant climatic events occur on a timescale of a few hundred thousand years or less. (2) Regional metamorphism of carbonates generates 13C-depleted CO₂ whereas available geological data show that the carbon responsible for Eocene global warming was enriched in 13C (e.g. Dickens et al. 1997; Zachos et al. 2001). Contact metamorphism in volcanic basins is a far more likely mechanism for transferring greenhouse gases to the atmosphere on a short timescale. This scenario provides causal connections between flow processes taking place in the deep interior of the Earth, heat transfer to the shallow crust by rising magma bodies, associated contact metamorphism of carbon-bearing sedimentary rocks, release of massive volumes of greenhouse gases, and associated climate change. In this sequence of events, contact metamorphism represents a critical link that even connects the biosphere to the bowels of the Earth.

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