environmental conditions favoring the evolution of this fog-collecting behavior appear to be the vegetationless sand environment and the occurrence of advective fogs.

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Combustion Metamorphism in Southern California

Abstract. *In several places in Southern California bituminous sediments of the Monterey Formation—siliceous shales, phosphatic rocks, dolomites, and arkoses—were affected during the Pleistocene and as late as the 19th century by spontaneous subsurface combustion of organic matter, during which temperatures up to 1600°C were reached. This oxidative heating (combustion metamorphism) affected rock complexes over areas of tens of square kilometers that tend to occur in clusters. As a result of these processes, the rocks recrystallized and partially melted to form pseudomagmas which intruded the country rocks. The chemical compositions of these melts differ from those of igneous magmas. Acid and intermediate siliceous melts as well as phosphatic melts have formed. These two types are generally immiscible. The following high-temperature minerals were determined: α- and β-cristobalite, quartz, calcic plagioclase, diopsidic pyroxene, wollastonite, cordierite, graphite, fluorapatite, and fluorite; at lower temperature pyrite, gypsum, aragonite, calcite, jarosite, and hexahydrite crystallized.*

During the last few years, several investigators have described the formation or mentioned the occurrence of rocks which burned spontaneously (*1*) and were, in consequence, affected by what might be termed combustion metamorphism. These rocks were originally sediments rich in organic matter, mainly bituminous carbonates, shales, or siliceous rocks, for example, diatomites. Under suitable conditions, the uppermost few hundred meters of these rocks undergo spontaneous combustion. The very high temperatures developed during this process frequently lead to partial melting of the mother rocks and the formation of pseudomagmas; the latter behave in a way very similar to the behavior of ordinary magmas and form small-scale intrusions such as dikes, sills, and laccoliths. In contrast to most magmatic occurrences, stages in the formation of the melts produced by combustion metamorphism can actually be studied in outcrops in situ. Almost any form of naturally occurring organic substance—bituminous matter, coal, or oil—can serve as fuel, but the most effective of these seems to be bituminous matter because of its intimate association with the inorganic constituents of the rocks. Occurrences of combustion metamorphic rocks are now known from Israel (*2*), Jordan, the U.S.S.R. (*3*), Iran (*4*), India (*5*), Australia (*6*), and Canada (*7*). The occurrence studied in most detail is that of the Hatrurim Basin in Israel (*2, 8*), where not less than 130 minerals have been produced by this process (*9*). Combustion metamorphism in action was observed in the Kimmeridgean oil shales of Dorset by Cole in 1973 (*10*), and Cretaceous oil shales along a 65-km stretch on the northern coast of Canada ("Smoking Hills") are known to have undergone burning for at least the last 150 years (*11*). In contrast, combustion metamorphic rocks in the United States have rarely been studied, with the exception of the Clinker beds of Montana (*12*).

Recently we have undertaken an investigation of combustion metamorphic rocks at several places in California: the Grimes Canyon and Virgines Canyon areas, Ventura County, and three separate localities near Santa Maria, Santa Barbara County (*13*). In all these localities, combustion metamorphism has affected rocks of the Miocene Monterey Formation, where it is particularly rich in organic matter. Some of these places are located within producing oil fields; the participation of oil in the combustion process can therefore not be excluded. The rocks of the Monterey Formation represent a broad lithological spectrum, and those affected by combustion metamorphism are correspondingly varied; they include diatomites, siliceous shales, dolomites, phosphatic rocks, and even arkoses.

The only locality we have thus far studied in some detail is Grimes Canyon (*14*), 5 km south of Fillmore. Here, the combustion metamorphic rocks form an almost uninterrupted belt 20 km long and 1 to 3 km wide. Within this belt, patches a few hundred meters long have occasionally escaped burning. Along some of the canyon walls, metamorphic rocks crop out over a vertical distance of about 400 m. Burning took place very recently, probably in the late 19th century, under the present topographical conditions; the depth below the surface affected by combustion is therefore not known. In the Hatrurim Basin, where burning occurred in the late Miocene, the metamorphic rock sequence is 260 m thick.

About 30 percent of the Grimes Canyon rocks are glasses, some vesicular and slaggy and others dense and closely resembling obsidian. The original melts were formed by selective melting of the parent rocks. Many Monterey rocks are finely laminated, phosphatic laminae alternating with others poor in P_2O_5. During the combustion process, the phosphatic laminae became molten, whereas the more refractory ones recrystallized only by sintering. The result is a strongly laminated rock in which stony layers alternate with glassy ones (Fig. 1). Wherever only small amounts of melt were formed, the material solidified in situ, but, as the quantity of melt increased, it was mobilized and formed small intrusive bodies. Sills several hundred meters in length are abundant (Fig. 2). Veins and dikes, small stocks, and occasionally a laccolith also occur, very similar to those formed by igneous magmas. The central part of the sills and dikes is frequently highly vesicular, the vesicles being strongly elongated in the direction of flow. Chilled zones, dense and darker in color, occur on both sides. Melts, forming stocks, frequently continued moving after initial solidification and broke up into a blocky breccia, reminiscent of an *aa* lava field (lava with a blocky structure). They contain numerous metamorphosed xenoliths of the country rock. The country rock frequently collapsed, owing to volume contraction because of the dissociation of carbonates, the oxidation of organic matter, and the loss of much volatiles. Therefore, both collapse breccias and intrusion breccias occur (Fig. 3). The structure of the original rock sequence is generally preserved, however, and beds of the country rock can frequently be followed well into the metamorphic zone.

The boundary between metamorphosed and unaffected mother rocks is usually sharp but sometimes highly irregular. Two cases can be distinguished:

1) The contact follows a stratigraphic horizon, usually the formational boundary between the bituminous Monterey rocks and the overlying nonbituminous sandstones of the Pliocene Pico Formation. In this case, burning stopped for lack of fuel.

2) The contact is irregular, cutting steeply through the bituminous layers of the Monterey Formation. Outcrops of burnt rocks within the country rock and vice versa are common (Fig. 4). In the Airox Mine area, near Santa Maria, pockets and veins of asphaltic residue accompanied by abundant jarosite are found on the metamorphic side near the contact. In this case, burning stopped for lack of oxygen.

The metamorphic rocks produced by combustion range from very soft to extremely hard and splintery; they are very colorful, red and yellow being most common. Texturally, three groups of rocks can be distinguished: (i) glasses, (ii) fine-grained stony rocks, and (iii) those rocks in which both stony and glassy parts are present, either as a breccia, in which stony pieces are cemented by glass or slag, or built of alternating stony and glassy laminae. All types of transitions from stony to sintered to fused rocks can be observed, and many rocks show textures very reminiscent of migmatites (Fig. 5), in which the granitic portions of the rock are replaced by glass.

The minerals composing the stony rocks measure a few micrometers at most and can be determined only by x-ray diffraction and occasionally by microprobe analysis. Among the high-temperature minerals so far determined are α- and β-cristobalite, quartz, calcic plagioclase, diopsidic pyroxene, wollastonite, cordierite, graphite, fluorapatite, spinel, and fluorite. During cooling, pyrite, abundant fibrous gypsum, aragonite, and calcite were formed.

The glasses are highly variable. Some are holohyaline; their x-ray diffraction pattern is indistinguishable from that of obsidians. Some are structureless, and others show a pronounced fluidal texture. These melts were highly gas-charged but viscous, and were emplaced by turbulent flow (Fig. 6). A widespread type of glass is composed entirely of tiny, sometimes welded shards in subparallel arrangement; the texture of these rocks is closely akin to that of welded tuffs. Glasses composed of shards frequently form sills or dikes. Gas pressure must have shattered the cooling glass and forcefully intruded it, a mechanism similar to that which leads to the formation of tuffisites.

Other melts crystallized partly or entirely during cooling into tiny, usually needlelike crystals. Their mineralogy is similar to that of the stony metamorphic rocks. These glasses are still undergoing reactions, and on their surface a caliche consisting mostly of gypsum, but locally of zinc-bearing hexahydrite, is at present being formed.

We determined the highly variable chemical composition of the glasses by microprobe analysis. Some are acid, and others are intermediate silicate melts. These glasses are chemically heterogeneous, confirming the evidence of the mineral assemblages that, because of the short duration of the thermal process, equilibrium was rarely reached. The siliceous glasses differ in composition from igneous magmas but some approach the composition of engadinitic granite. A third group consists of almost pure phosphatic melts with a P_2O_5 content of as much as 39.25 percent. Siliceous and phosphatic glasses frequently appear side by side with sharp boundaries between them, even on a microscopic scale. Moreover, droplike bodies of phosphatic glass occur within siliceous glass. Obviously, the two types of melts were immiscible.

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1. The term "spontaneous" implies at least that, in contrast to all other forms of metamorphism in which the energy is supplied from the outside, combustion metamorphism is sustained by energy contained in the rock itself. We believe, moreover, on the basis of evidence from the combustion metamorphic occurrence at Hatrurim, Israel (2), that in this case the ignition was also spontaneous, that is, the result of the heat of oxidation. In some of the other occurrences, however, burning might have been trig-

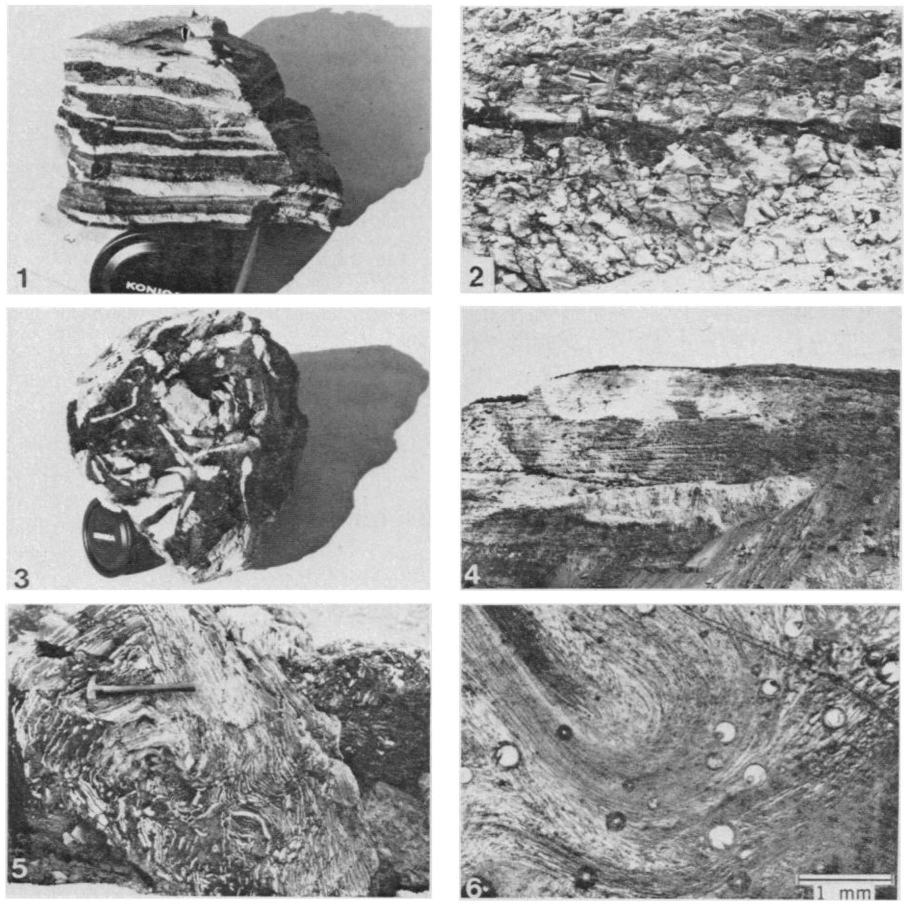

Fig. 1. Grimes Canyon rock composed of alternating stony (light) and glassy (dark) laminae. Fig. 2. Sill of black glass, 20 cm thick, with apophyses intrusive into burnt rocks (Grimes Canyon); an arrow points to the rock pick. Fig. 3. Intrusion breccia: light stony pieces cemented by dark glass (Grimes Canyon). Fig. 4. Residual band of bituminous shales (dark) surrounded by burnt rock (light), Airox Mine; the height of outcrop is about 90 m. Fig. 5. Burnt rock with migmatitic texture; the stony component is light, and the glass is dark (Grimes Canyon). Fig. 6. Flow texture in siliceous glass (Grimes Canyon).

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Plutonium Hazard in Respirable Dust on the Surface of Soil

Abstract. *Plutonium-239 in the fine particulate soil fraction of surface dust is subject to suspension by air currents and is a potential health hazard to humans who may inhale it. This respirable particulate fraction is defined as particles ≤ 5 micrometers. The respirable fraction of surface dust was separated by ultrasonic dispersion and a standard water-sedimentation procedure. Plutonium concentrations in this fraction of off-site soils located downwind from the Rocky Flats Nuclear Weapons Plant (Jefferson County, Colorado) were as much as 380 times the background concentration. It is proposed that this method of evaluation defines more precisely the potential health hazard from the respirable fraction of plutonium-contaminated soils.*

Methods of evaluating Pu inventories in soils are important because of the possibility of soil contamination near Pu processing plants and nuclear generating stations and areas where Pu has been accidentally released—for example, at Palomares, Spain, and Thule, Greenland, where Pu was released in airplane accidents in January 1966 and January 1968, respectively. Evaluation of Pu (*1*) in the soil is of special importance in contaminated areas that are now considered for residential development. One such area is in the vicinity of the Rocky Flats Nuclear Weapons Plant (Jefferson County, Colorado), which is currently operated by Rockwell International for the Energy Research and Development Administration (ERDA). Activities at the plant include processing radioactive chemicals and making weapons from radioactive metals (*2*).

The Colorado State Health Department in 1973 proposed an interim standard for soil contaminated with Pu, setting the maximum allowable concentration at 2 disintegrations per minute per gram (dpm/g) (*3*). Land with Pu concentrations in excess of the standard would require ameliorative treatment before residential development could be approved. However, the standard fails to define "soil." Either single or composite samples of the soil at a depth of 0 to 0.5 cm from numerous locations in a development area are required. Because such samples include soil particles much too large to be resuspended or inhaled, the possible risk to health cannot be properly evaluated (*4*). Further, no provision is made to prevent the treated soil from being recontaminated by redeposition of Pu from more highly contaminated soils upwind. This redeposition mechanism potentially exists because winds in the area exceed 30 km/hour for 500 to 600 hours yearly. Wind speeds commonly reach 130 km/hour or more, with winds blowing predominantly to the east and southeast toward the Denver metropolitan area (Figs. 1 and 2).

The plant is located about 16 km northwest of Denver and about 8 km from the cities of Boulder, Westminster, and Arvada. Approximately 200,000 people live within 16 km and 600,000 people within 32 km of the plant. Residential development is now proposed within about 5 km of the plant (Fig. 1), involving as many as 3000 homes or a potential population of about 10,000 persons (*5*).

Since the plant began operation in 1953, there have been two major fires (1957 and 1969), a large release of Pu to off-site soils from a spill of metal-laden cutting oil, and an accidental release of Pu to the air in 1974. The major sources of off-site contamination are considered to be emissions from the 1957 fire and the oil leakage from corroded barrels of contaminated cutting oil that were stored

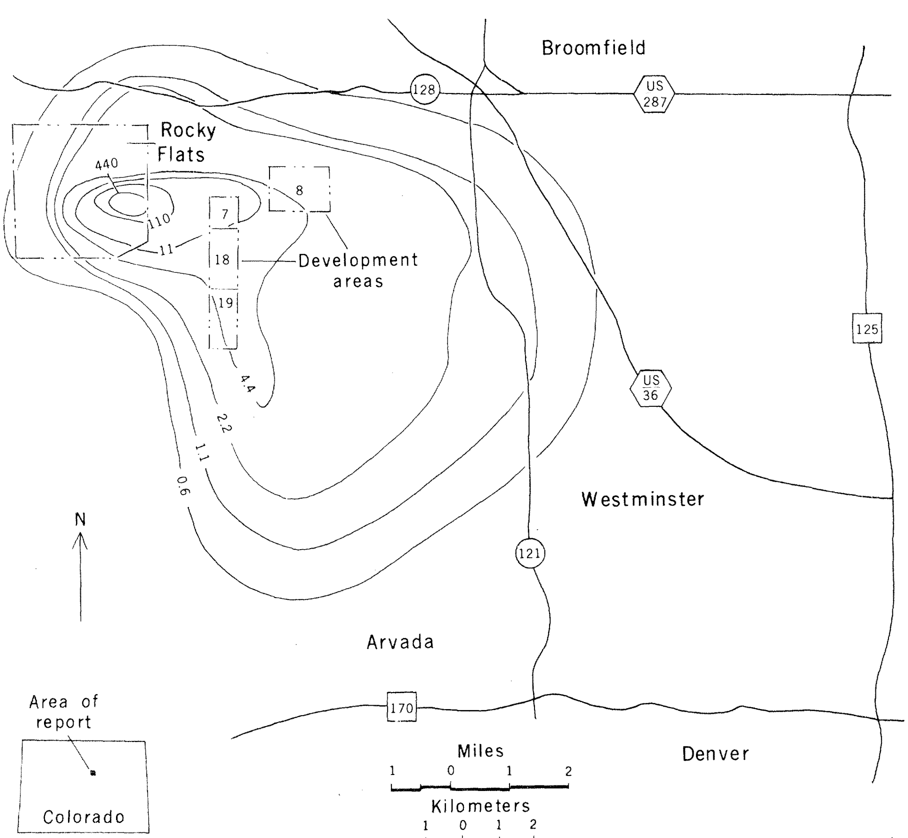

Fig. 1. Rocky Flats Nuclear Weapons Plant and proposed housing development area. Isopleths are labeled in disintegrations per minute per gram of whole soil, calculated from values in (*2*).