Subsurface Combustion in Mali: Refutation of the Active Volcanism Hypothesis in West Africa

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ABSTRACT

Surface heat anomalies have been known in the Timbuktu region in northern Mali for more than a century. Since about 1960, several authors have argued that that these heat anomalies are caused by incipient volcanic and hydrothermal activity. Surface temperatures as high as 765 °C were measured locally in January 2002, and smoke emanated from holes and fractures in the ground. We demonstrate that subsurface combustion of organic material is the source of the heat and the gases. Several square kilometers are currently active or have been affected by subsurface fires since 2001. Self-ignition during biological degradation of organic-rich layers in the lacustrine deposits is the most likely mechanism that started the subsurface combustion that caused the heat anomalies in the area. An important consequence of this conclusion is that west Africa should still be regarded as volcanologically inactive, and that possible reactivations of the major EW-trending Guinean-Nubian lineament is not associated with volcanism. We suggest that the subsurface combustion in the Timbuktu region today represents a phenomenon with a very long record in the Trans-Saharan region.

Introduction

West Africa is regarded as a stable craton. It is therefore quite surprising that incipient volcanism near Timbuktu in Mali has been proposed by several authors since the early 1960's (Monod and Palausi, 1961; Sauvage and Sauvage, 1992; El Abbass et al., 1993). Observations of magmatic rocks and hot fumaroles, supposedly forming the uppermost part of a hydrothermal system, has been taken as evidence for incipient volcanic activity. Based on these field observations and on geophysical modeling, a magmatic intrusion has been interpreted at shallow levels in the region (El Abbass et al., 1993). It has been proposed that the magmatic activity is linked to pull-apart tectonics along a major EW-trending lineament in the region (Sauvage and Sauvage, 1991; El Abbass et al., 1993).

A fieldtrip to Lac Faguibine in the Timbuktu region was organized after receiving reports of increased thermal activity in April 2001. The local community feared that the increased thermal activity would be followed by a volcanic eruption. In this paper, we argue that the phenomena previously attributed to incipient volcanism are caused by subsurface combustion of lacustrine organic material, and that there is no incipient volcanism in this part of west Africa. We document the evolution of the subsurface combustion and its surface characteristics and emphasize the importance of subsurface fire as a geologic process. The fires are also relevant for understanding peat fires and coal seam fires – related phenomena with substantial CO_2 emissions (e.g., Voigt et al., 2003).

Subsurface fires

Deposits influenced by both local and regional fires are preserved in the geologic record from various places around the world (e.g., Smith et al., 1973; Leprun, 1986; Wolbach et al., 1988; Killops and Massoud, 1992; Bird and Cali, 1998). Generally, fires can be divided into surface, ground, and subsurface fires. Surface fires are most widespread, occurring in a range of ecological habitats, usually without destroying the subsurface biota. Ground fires (also called smoldering fires) have a more destructive effect on the biological

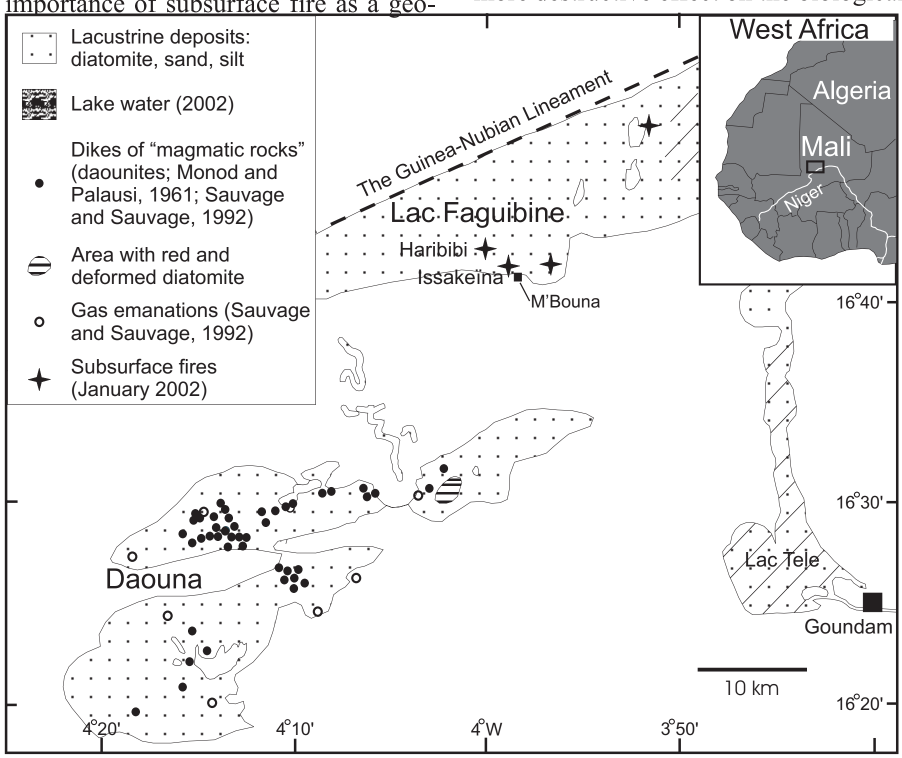

Figure 1. Simplified map of Lac Faguibine and Daouna areas located west of Timbuktu, Mali. Most of Lac Faguibine was dry in January 2002, whereas Lac Tele was filled with water. During flooding, water used to flood from Lac Tele to Lac Faguibine, then south to Daouna area. The latter has been dry since the 1880s. Several areas with red and deformed diatomite were encountered during field work, but only one was mapped.

communities, but are still considered important for maintaining local ecological diversity (Ellery et al., 1989). Ground fires are common in forests with abundant organic litter (e.g., Hungerford et al., 1993) and in wetlands (Ellery et al., 1989; Grundling and Blackmore, 1998) and can be ignited either by surface fires or spontaneous ignition (e.g., Hungerford et al., 1993; Chateauneuf et al., 1986). Subsurface fires are well known as a phenomenon, but are poorly documented in the literature (cf. Ellery et al., 1989; Chateauneuf et al., 1986; Leprun, 1986). Fires in the Trans-Saharan area have both natural and anthropogenic causes (e.g., Phillips, 1968; Chateauneuf et al., 1986; Bird and Cali, 1998) and are a common mechanism for peat destruction (Chateauneuf et al., 1986).

Geology of the Lac Faguibine area

Lac Faguibine is situated in the semiarid Sahel zone of northern Mali in west Africa (Fig. 1). The water level in Lac Faguibine changes periodically, with cycles of flooding and evaporation (Krings, 1985). When the Niger River floods in November–December, water flows through natural channels, successively filling the lakes to the north. The last complete flooding in Lac Faguibine was in 1977 (Sauvage and Sauvage, 1992), and the entire lake was dry during a drought in 1983 (Krings, 1985).

The northern shoreline of Lac Faguibine is aligned along a Mesozoic lineament, the Guinea-Nubian lineament (Guiraud et al., 1985). Recent seismic activity, elevated shorelines in Lac Faguibine (Guiraud et al., 1985; El Abbass et al., 1993), and changes in the course of the River Niger have led to the proposal that this lineament was recently reactivated (Blanck and Tricart, 1990).

The Lac Faguibine area is dominated by lacustrine sediments with diatomitic siltstone, sand layers, and peat horizons (Sauvage and Sauvage, 1992), and are comparable to other lacustrine deposits in the Sahel of northern Africa (e.g., Faure, 1966; Petit-Maire and Riser, 1981). Organic-rich layers within the lacustrine sediments are common, especially in Lac Faguibine, and contain up to 12 wt% organic carbon (Sauvage and Sauvage, 1992; Leino and Vitikka, 2001).

Burning grounds and release of gases through holes in the ground ("fumaroles") have been observed in the Lac Faguibine area during dry periods since the late 1800s, but these features have disappeared during flood periods (cf. Monod and Palausi, 1961). The heat anomalies, burning ground with "fumaroles," have been mapped in numerous places in the Lac Faguibine and Daouna areas (Sauvage and Sauvage, 1992). The local ecology and agricultural areas (Krings, 1985) have been affected.

Thin (2–5 cm) dikes of supposedly volcanic rocks (termed "daounites") have been reported within lacustrine sediments from the Daouna area south of Lac Faguibine (Fig. 1) (Monod and Palausi, 1961; Sauvage and Sauvage, 1992). The petrographic methods leading to the conclusion that the daounites contain small amounts of nepheline lava are highly questionable, and a later study of the original samples concluded that what was taken for nepheline was actually cristobalite (see reference to Marinelli in Sauvage and Sauvage, 1992). The cristobalite found by Sauvage and Sauvage (1992) was reported to be recrystallized from glass formed by melting of diatomite. This process may be induced by high temperature smoldering fire. The geometrical characteristics of the dike networks and of burnt diatomite, as described by Monod and Palausi (1961) and Sauvage and Sauvage (1992), conforms with filling of fracture networks and holes produced by subsurface fires with a mixture of sand and baked diatomite. It has also formerly been suggested that the so-called daounites are formed from subsurface peat fires (see discussion in El Abbass et al., 1993) and that the fumaroles are related to this process as well (Leprun, 1986).

Reactivation of the Guinea-Nubian Lineament and the presence of "magmatic" dikes (daounite), heat anomalies, and "fumaroles" have all been coupled to a hypothesis of incipient volcanism in the Lac Faguibine area (Monod and Palausi, 1961; Sauvage and Sauvage, 1992; El Abbass et al., 1993). In addition, the most recent publication on this issue, that by El Abbass et al. (1993), suggests the presence of an intrusive body 100 km long and almost 4 km thick on the basis of a gravimetric study of the area. They located this "intrusive body" just 2 km below the surface in the Lac Faguibine area. They furthermore suggested the apparent volcanic activity is associated with the intrusion and connects it to a major geodynamic event in the region. One of the consequences of these studies is that the Lac Faguibine area has been incorporated into reviews of active volcanism in Africa (Wilson et al., 1998).

Subsurface combustion in the Lac Faguibine area

Four areas were burning in Lac Faguibine during field work in January 2002 (Fig. 1). Two of these (Haribibi and Issakeïna) are located close to the former nearshore areas in the central parts of Lac Faguibine and were selected for detailed studies.

The two study areas were mapped by using a Garmin Etrex Summit GPS (Global Positioning System), with an accuracy of 4 m. Gases, sediments, and sublimates were collected for analyses at these two localities. Combustion-derived gases were collected by using a metal bucket covering the emanation, with a silicone tube connected to aluminized gas-sampling bags. The gases were analyzed for CO_2, CH_4, and higher hydrocarbon gases on a Carlo Erba HRGC (high-resolution gas chromatograph) 5300 within 10 days of collection.

Temperatures were measured with a thermocouple thermometer, calibrated to 1100 °C. Total organic carbon contents of sediment samples were measured with a Rock-Eval 6 instrument. Sublimates were carefully collected to avoid contamination from the substrate and were separated according to color and structure in a binocular microscope. Each sample (~1 g) was ground in a mortar with ethanol prior to XRD (X-ray diffraction) analyses on a Siemens 5005 at the University of Oslo.

At Haribibi (Figs. 2 and 3A), a relatively large area has been affected by extreme heat since about 1999. A heat front is slowly moving laterally through the lacustrine sediments. Smoke ema-

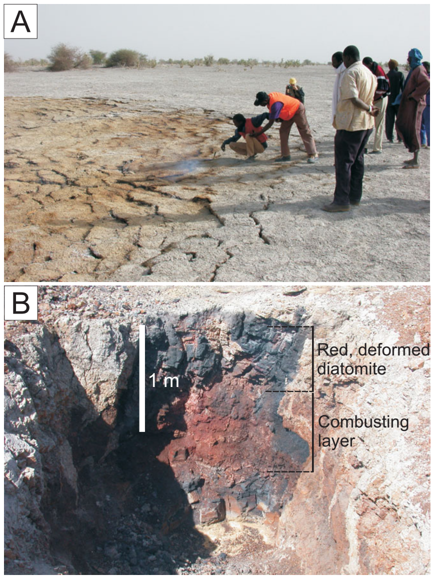

Figure 2. A: Surface expression of subsurface combustion at Haribibi. Slowly migrating heat front is defined by fracturing and a color change of surface. A trench dug into this heat front verified presence of a combusting peat layer ~60 cm below surface. B: Trench 2 m deep dug into combustion front at Haribibi.

nates from cracks in the heat front, and temperatures were locally as high as 530 °C at the surface. No temperature anomalies were present 15–20 m behind the front.

A 2.5-m-deep trench was dug into the heat front. We located a combusting organic rich layer at 60 cm depth (Figs. 2B and 3B) where temperatures reached 830 °C. Visible flames emerged from the organic-rich layer. In contrast, flameless combustion (smoldering fire) normally results in temperatures of 375–625 °C (Hungerford et al., 1993). Below the combusting layer was a layer of claystone and siltstone, in which temperatures dropped considerably (Fig. 3B). Open fractures were found in the siltstone; these are related to desiccation during heating. The temperature was as low as 40 °C in a sand layer 0.75 m below the combusting layer (Fig. 3B). A temperature profile perpendicular to the front gave background temperatures 2 m ahead of the front.

Fractures at the surface in the migrating heat-front are caused by volumetric reduction during combustion and are associated with a 10–15 cm lowering of the surface. The combusting peat layer has a relatively low content of organic carbon (8 wt%). H_2O, CO_2, and traces of CH_4 are released during combustion. Samples from the combusting layer (collected at 830 °C) showed complete combustion of organic material, leaving a residue of elemental carbon and trace amounts of iron oxide and mullite. The latter mineral characteristically forms during coal burning (Smith et al., 1973). Thermal metamorphism of the diatomite above the peat layer is manifested by oxidation (formation of Fe_2O_3) and a color change from gray to red. Traces of diaspore were also found in the baked diatomite. However, the clay minerals are not altered by the heat.

The other study area, Issakeïna[1], was reported to be active in April 2001 and was still active in January 2002. During these 10 months, ~2 km^2 of richly vegetated land was burned. The subsurface fire has migrated 2-300 m during this period, resulting in a speed of about 3–4.5 cm per hour. This agrees well with laboratory experiments on smoldering peat fire propagation (Frandsen, 1991). The subsurface combustion destroys the vegetation, and the circular shape of the combusted area is easily identified in the field as a transition from green bush to smoke emanations and fallen dead trees with combusted roots. The most active areas are along the margins of this area, whereas the central parts were the sites of subsurface combustion prior to January 2002. The subsurface combustion is spreading radially. At Issakeïna, gases emanate from circular holes and occasionally from fractures up to 4–5 m long and 10 cm wide. As at Haribibi, the sampled gases were dominated by H_2O and CO_2, with traces of CH_4. Some of the holes were glowing with temperatures above 750 °C along the rims. These observations, together with the loose and partially caved and subsided surface, is unambiguous evidence for near-surface combustion of organic material (cf. Ellery et al., 1989). However, the surface temperatures in the vicinity of the smoke-emanating holes were similar to background values in unaffected areas. The different surface manifestations of the combustion at the two studied localities could reflect different depths of combustion or different thicknesses of the organic layers.

Vapor released through the holes and fractures commonly precipitates salts at the surface. XRD analysis of these salts verified the presence of salammoniac (NH_4Cl), ammonium hydrogen sulfate ($(NH_4)_3H(SO_4)_2$), native sulfur, amorphous silica, and sodium alum ($NaAl(SO_4)_2(H_2O)_{12}$). Salammoniac is a common product of coal combustion and is also found in volcanic fumaroles (e.g., Oftedal, 1922; Coradossi et al., 1996) and as a product

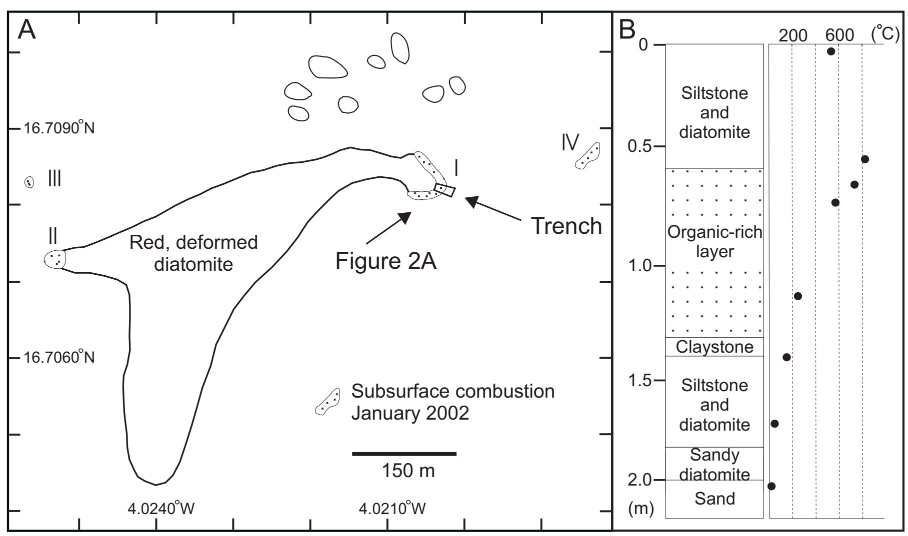

Figure 3. A: Four areas with subsurface fires were found at Haribibi. Combustion probably started in one area and then migrated with different velocities in various directions. Areas previously combusted are easily identified in field by red and deformed (tilted and fractured) diatomite. B: Trench dug into heat front at site I revealed a combusting layer (with 8 wt% organic carbon) and is direct evidence for a causal relationship between surface heat anomalies and subsurface combustion of organic material. Temperatures of >800 °C were measured in upper parts of combusting layer. This high temperature measurement reflects an increased combustion rate as oxygen was supplied directly to the peat by the trench and the fire evolved from smoldering to open flames.

of subsurface peat combustion (Leprun, 1986).

Discussion

Digging of a trench across the heat front at Haribibi verified the hypothesis of a combustion source for this heat anomaly and showed a direct relationship between combusting organic material and gas and heat emanations. We propose that the processes causing subsurface combustion at Haribibi are representative of the processes causing all heat anomalies in the entire Lac Faguibine region.

Further field evidence against the volcanism hypothesis include the following: (1) *Dynamics of the heat front*—the active fronts at each location have in the course of 1 yr propagated outwards from a central starting point through what is now an affected, but not active, area. The pattern and speed is typical for the propagation of a smoldering fire front. Although volcanic fumaroles may migrate as well, their pattern and speed are not as regular (Harris and Maciejewski, 2000). (2) *Absence of rocks of proven volcanic origin*—we hold the documentation of the volcanic origin of the daounites as insufficient. Some of the minerals claimed to be characteristically magmatic are also found in the heat-affected sediments (e.g., mullite). Local production of melt can be caused by subsurface combustion and has been documented from other geologic settings and processes as well, e.g., fires associated with mud-volcano eruptions (Hovland et al., 1997). (3) *Temporal cycles of "fumarole" activity*—there has been reported recurring "fumarole" activity in the region during the entire twentieth century. Reports state that "fumaroles" are suppressed during the rainy season or flooding of the lake and that they recur at the same general locations after drying of the lake. This recurrence is hard to explain by volcanic activity, but is consistent with wetting-drying cycles affecting combustion and ignition of organic matter. On the basis of these arguments, we find the large-scale active volcanism hypothesis of Monod and Palausi (1961), Sauvage and Sauvage (1992), and El Abbass et al. (1993) highly implausible.

Although the subsurface combustion in the studied areas could have had an anthropogenic initiation, we find it most probable that a process of spontaneous self-ignition is responsible. Exothermal microbial decomposition of organic matter in an environment with good thermal isolation causes local accumulation of the heat produced (even by slow decomposition) until an activation threshold is reached. Self-ignition has been described, e.g., from sawdust piles and in forest soils (Frandsen, 1993; Hungerford et al., 1993) and in peat deposits from west Africa (Leprun, 1986; Chateauneuf et al., 1986).

Observations in the Lac Faguibine area have led us to propose the following initiation and evolution of the subsurface combustion of peat: (1) lowering of the water level in the lake, followed by lowering of the water table; (2) drying and microbial decomposition of organic material, accompanied by heat accumulation; (3) self-ignition of the decomposing organic material; (4) slow combustion of organic material and propagation of the heat fronts, and (5) alteration of diatomite above the subsurface combustion owing to contact metamorphism.

Oxygen for the combustion is supplied through the surrounding porous sediments. Volatiles are released from the organic layer in front of the combustion front, resulting in high soil humidity and temperatures of 40–60 °C in the vicinity of the burning areas. Volume reduction in the combusting organic-rich layer results in surface-collapse features like fractures and holes. Gases produced during the combustion (mostly H_2O and CO_2) are released through these fractures and holes ("fumaroles") and through destroyed root systems. Water-soluble elements precipitate at the surface via sublimation.

We suggest that the presence of red altered diatomite can be used as an indicator of areas affected by previous subsurface combustion. At least one relatively large area with red and deformed diatomite was identified in the Daouna area (Fig. 1). Shallow lakes, similar to Lac Faguibine, were abundant in the Trans-Saharan region during the Holocene, but evaporated during global climate changes at ca. 4000–3000 B.P. (e.g., Faure, 1966; Petit-Maire and Riser, 1981; Gasse et al., 1990). Considering that red diatomite is commonly encountered in the Trans-Saharan region (cf. Leprun, 1986), the subsurface combustion in the Lac Faguibine area may represent a phenomenon with a very long record. Thus, the stratigraphic record from the Holocene lakes should be investigated to determine the importance of former fire regimes and their possible contribution to the anthropogenic signature in the fire record in sub-Saharan Africa (see Bird and Cali, 1998).

Considering the widespread lacustrine deposits in the Lac Faguibine and Daouna areas (~1000 km^2) and the presence of near-surface organic-rich sediments, subsurface combustion will likely occur as long as the lacustrine sediments are not permanently flooded and organic-rich sediments remain.

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