Discovery of a kimberlite pipe and recognition of a diagnostic botanical indicator in NW Liberia

Article *in* Economic Geology · April 2015

DOI: 10.2113/econgeo.110.4.851

Stephen Haggerty
Florida International University

Economic Geology

BULLETIN OF THE SOCIETY OF ECONOMIC GEOLOGISTS

VOL. 110 June–July NO. 4

EXPRESS LETTER

DISCOVERY OF A KIMBERLITE PIPE AND RECOGNITION OF A DIAGNOSTIC BOTANICAL INDICATOR IN NW LIBERIA

STEPHEN E. HAGGERTY

Earth & Environmental Sciences, Florida International University, Miami, Florida 33155

Abstract

Diamond-bearing kimberlite dikes (fissures) are present in the deeply eroded Man Shield of West Africa. Small kimberlite pipes, generally less than 1 hectare in area, are known in Guinea, Sierra Leone, and Liberia. Exploration for larger bodies has been severely hampered by thick tropical vegetation, and the lack of distinct geophysical contrasts between weathered kimberlite and the nonresponsive nature of country-rock granites and granodioritic gneisses. Following several years of intense exploration in the highly active artisanal diamond district of northwestern Liberia (which was a major source of alluvial "blood diamonds") by several large companies and the present study, we report that an elusive diamond-bearing kimberlite pipe has finally been located. A bonus to the pipe location is that an unusual botanical indicator, *Pandanus candelabrum*, is now recognized exclusively on the pipe and not in eluvium covering the adjacent kimberlite dikes. Plants (*Lychnis alpina*) have been widely used since medieval times for copper in Sweden, and with *Haumaniastrum katangese,* more recently in Africa. Other plants have evolved to physiologically stabilize heavy metals (U, Pb, Zn, Ni, Cr, Ba, Pb, Zn) in leaves and bark. Termite hills have been used in diamond exploration for kimberlitic indicator minerals (ilmenite, chromite, garnet, pyroxene) in Botswana, the United States, and Australia, but the identification of *Pandanus candelabrum,* with stilt-like aerial roots, is the first plant to be described that has a marked affinity for kimberlite pipes. This could dramatically change the exploration dynamics for diamonds in West Africa, as geobotanical mapping and sampling is cost-effective in tough terrain.

Introduction

An exploration program on behalf of the Youssef Diamond Mining Company, in the Camp Alpha area of Cape Mount County, has advanced on several fronts with outstanding results. A paradigm shift in diamond exploration protocol was adopted by changing the focus from an emphasis on kimberlite dikes that pervade the province and extend into neighboring Sierra Leone and Guinea (Haggerty, 1982, 1992) to the possible presence of kimberlite pipes. Large kimberlite pipes (hectares in diameter), were thought to simply not exist in the Man Shield of West Africa, a consequence of deep erosion over the past 100 m.y. (Hawthorne, 1975). Dike targets (~10 m) were successfully discovered in dense vegetation of swampy terrain (Haggerty, 2013) and are shown to be considerably wider than kimberlite dikes elsewhere, some of which are <0.5 m in width (Gurney and Kirkley, 1996; Field et al., 2008). The tectonic control of kimberlites in West Africa is complex (Haggerty, 1982), with dikes filling reactivated fractures dating from the Archean to the Mesozoic. The dikes are Cretaceous, and lithologies are diverse and are equal to or greater than kimberlite dike systems globally (Haggerty, 2013). The new diamond-bearing kimberlite pipe was suspected during reconnaissance in brief field trips between 1977 and 1980 (Haggerty, 1982) but was only confirmed in 2013 following a renewed entry to the property after the civil war. The highly unusual *Pendanus candelabrum,* known locally as *Pamaya*, first recognized in 1978 in the artisanal diamond diggings as an exotic plant, is now also confirmed as being diagnostic of coarsely brecciated kimberlite pipe eluvium. Extensive coverage of northwestern Liberia by road, foot, and air shows that *Pandanus* has a restricted distribution with the promising observation that groves are only present in areas of artisanal alluvial diamond mining.

Methods

Ilmenite was used as a critical kimberlite-indicator mineral (KIM). The mineral is rounded (by gas abrasion in the erupting kimberlite and by alluvial transport), and grains are larger (up to 10 cm in diam) in size and more abundant as the parent kimberlite is approached. Delicate, cryptocrystalline *leucoxene* (anatase + magnetite-hematite) in white to gray alteration rims, magnetic and clearly visible in the field, is only

E-mail: haggerty@fiu.edu

0361-0128/15/4309/851-6

Submitted: January 15, 2015
Accepted: March 26, 2015

present in eluvium and in alluvial deposits some 50 to 100 m from a kimberlite; at greater distances the *leucoxcene* skin has been removed by stream abrasion. From selected ilmenite compositional parameters (Wyatt et al., 2004, and references therein) such as Mg vs. Ti (which distinguishes kimberlitic from nonkimberlitic ilmenite), Mg vs. Cr (which is an indicator of diamond prospectivity), and Mg vs. Fe^{3+} (which serves as a proxy for diamond preservation), and ternary variables of ilmenite-geikielite-hematite (which reflect mantle oxidation states), it is concluded that the kimberlites examined to date have significant diamond reserves.

Kimberlite Dikes

Our discoveries include a well-defined regional trend for kimberlite dikes along reactivated fracture zones, Archean in age (Liberia trend ~N 26° E), coupled with kimberlite dikes of Mesozoic oceanic transform age (Sierra Leone trend ~N 56° E), as shown in Figure 1. Absolute ages correspond to the global Mesozoic intrusion event for kimberlites between 120 and 80 Ma (Haggerty, 1994, and references therein). Cross-cutting relationships confirm that the Liberia dike trend is indeed older than dikes along the Sierra Leone trend (Haggerty, 2013). The former are in reactivated fractures that opened during the initial "rifting" of Gondwana, whereas the latter are contemporaneous with "drifting" of the fragmented supercontinent (Haggerty, 1992). Both intrusion events are considered to be driven by plumes from the core-mantle boundary at ~2,900 km (Haggerty, 1994).

Overburden of brown, organic-rich soil on the dikes is up to 1 m thick. This is underlain by a soft, in situ, eluvial horizon of kimberlite (1–2 m thick), followed by solid unaltered kimberlite. Chilled margins at the country-rock granitic gneisses are glassy, grading to aphanitic, and to coarsely crystalline textures at dike interiors. Explosive blows on the dikes are brecciated and have marked, dislocation-sheared contacts. There are few polycrystalline xenoliths in the dikes and blows but ilmenite, garnet (discrete, eclogitic, and peridotitic), clinopyroxene, and zircon are abundant.

New Kimberlite Pipe

Microdiamond data on the dikes are consistent with the artisanal recovery of diamonds over the past 70 years at Camp Alpha in Cape Mount County, and with the fact that West Africa produced an astounding 10% of the world's diamonds in 1977 (Haggerty, 1992); these included some of the largest diamonds (>300 ct) ever reported. With this in mind, from observations made between 1977 and 1980 (large diamonds but small dikes), as well as the fact that the district was a major source of "blood diamonds" during the internal civil conflict between 1989 and 2003, the question arose: are the diamonds in local alluvial deposits exclusively from kimberlite dikes, or is there an additional source related to undiscovered kimberlite pipes? It was not until very large ilmenites (>10 cm in diam; Haggerty, 2013) were found, comparable to those from the Koidu Kimberlite Complex (pipes and dikes) in Sierra Leone (Tompkins and Haggerty, 1984), that a pipe was seriously

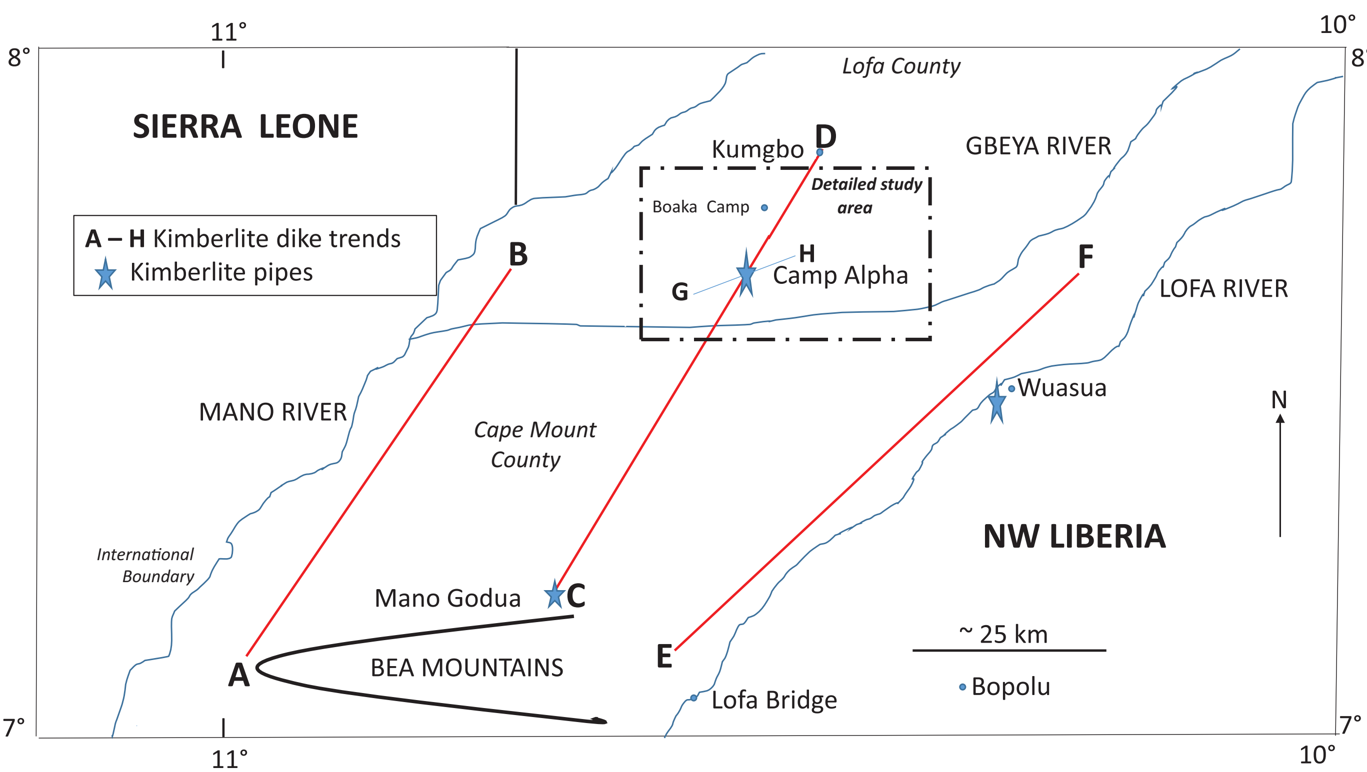

FIG. 1. Sketch map of the Bopolu Quadrangle (Wallace, 1977), Liberia (1:250,000). The Man Shield is dated at 2.7 Ga and the basement is composed of granite-related suites. The three lineaments (A-F) are kimberlite dike trends with sporadic exposures; these are designated as the Liberia trend (Haggerty, 1982) with known kimberlite pipes (stars) along trends C-D and E-F. The newly discovered pipe at Camp Alpha includes the first recognition of the Sierra Leone dike trend (G-H) in Liberia.

considered. Eluvial kimberlite can be recognized from rebar soil tests (a simple substitute for an augur using a crenulated reinforced steel bar, 2.5 m in length × 1.75 cm in diameter, that is screwed into the ground and pulled out vertically with adhering material). From the results of systematic soil testing and selective pitting, a new diamond-bearing kimberlite pipe (~500 m in length × 30–50 m in width), adjacent to the Liberia dike trend [~N 26° E], is now confirmed at Camp Alpha (UTM WGS 29N: Easting 83145; Northing 313998). Preliminary washing by hand of the eluvium has yielded four diamonds: two in the range of ~20 ct, and two of ~1 ct. With a 10:1 aspect ratio, the elongate kimberlite pipe is unusual but not unique: in South Africa, Du Toits Pan at 870 m is 10:1; K1 Venetia at 678 m is 7:1; and pipe 2 in Finland is 10:1 (Field et al., 2008; Kurszlaukis and Barnett, 2003). Two exposed sections (~250 m^2) of the new pipe show that the organic overburden, eluvial horizon, and depth to fresh kimberlite are similar to the stratigraphy found in the dikes. The pipe kimberlite is hypabyssal facies, but polymict breccias and pockets of diatreme-infill are also present; some blocks are distinctly micaceous but typical type 1 kimberlite dominates. The xenolith suite has abundant eclogite with discrete ilmenite and in this respect the assemblage is very similar to the Koidu pipe in neighboring Sierra Leone (Tompkins and Haggerty, 1984).

Bulk Chemistry

Bulk chemical X-ray fluorescence data were obtained on samples from well-exposed kimberlite pavements, in which the organic overburden and the eluvial blankets were removed. Samples of kimberlite were collected by jack-hammering in order to ensure that the effects of surficial weathering are minimized. The central cores of the dikes and the hypabyssal pipe are pristine and correspond to type 1 kimberlites in South Africa and Koidu in major and trace element plots (Taylor et al., 1994). The fine-grained dike contacts surprisingly show minor crustal contamination with higher SiO_2, CaO, Sr, Rb, and lower MgO, Nb, Ni, Cr, and Ti. Overall, MgO is approximately equal to SiO_2 (each with ~30 wt %), and both Cr and Ni exceed 1,000 ppm.

Botanical Indicator

The brecciated pipe, but not the texturally aphanitic dike complex, is delineated by an unusual plant with aerial, stilt-like roots and thorn-encrusted palm fronds, reaching heights of 10 to 15 m, which may be a new species in the genus *Pandanus*. Beentje and Callmander (2014) suggest *Pandanus candelabrum*, but the authors note (p. 318) that "several species are imperfectly known and their taxonomic status is not clear. This difficulty is mainly linked with the fact that all the systematics of the family are often based on fragmentary fruiting and leaf material (especially true for Africa where very few and complete collections are available). Furthermore, taxonomists frequently, almost automatically, regard new collections as representing new species." The authors go on to say (p. 320) that "the lack of good recent fertile collections from *Pandanus* in western Africa, coupled with the very incomplete type material of *P. candelabrum*, are both responsible for the long lasting uncertainty around this species. It is also possible that more than one species is involved in the *Pandanus candelabrum* complex."

Recorded along the coastal margin of West Africa, from Cameroon to Senegal, the plant is typically present along river banks, mangrove edges, and in forests or open swamps. In spite of poor documentation, the Liberia species (Figs. 2–3) has several features in common with the diagnostics described by Beentje and Callander (2014) for *Pandanus candilabrium*. These include plant height (3–20 m), root height (2–2.5 m in mature plants; Fig. 2C), trunk (15–20 cm diam), branches (1–3 cm thick; Fig. 3A-B), candelabra-shaped canopy (Fig. 2A-B), spiny aerial roots (Fig. 2C-D), sympodial stem growth, long, broad, and prickly leaves with spines on the edges and along the midfold (Fig. 2E), and with a vascular system that is spongy to fibrous (Fig. 3A-B). Black and dense, dehydrated seeds were found to be fairly common in the oversize fraction of our field grizzly, which has holes of ~2.5 cm in diameter. The significance of these objects, however, was not appreciated until *Pandanus candelabrum* was later suggested during postseason enquiries. At 2 to 3 cm in length, the seeds bear a vague resemblance to the asymmetric, doubly terminated and pentagonal drupes typical of the *Pendanus* family; fresh drupes in syncarps or cephaliums (Fig. 3C-D), are essential to classification (Beentjes and Callmande, 2014), but have not been observed during the dry season (January-May) of exploration activities. Root-casts (rhizoliths; Klappa, 1980), as shown in Figure 4, are abundant in the kimberlite pipe eluvium, many with firmly attached discrete fragments of ilmenite (Fig. 4A). In detail, the interiors of the tubes (Fig. 4A-B) have a patina in gray, brown, or red with distinct root impressions (Fig. 4C), followed by clusters of bulbous, mammillary aggregates (Fig. 4D-E) that grade into fused beads on the outermost margins. In a comparison with the bulk chemistry of the kimberlite (given above), and from the compositions (determined by energy dispersive X-ray analysis [EDAX]) of the cylindrical walls, the roots have preferentially extracted Mg, K, and P (the kimberlite appears to be a natural nutrient-rich fertilizer), plus SiO_2, leaving a residue of hard, Fe-enriched (89–94 wt % FeO) casts in the soft eluvium. The kimberlite ranges from 8 to 12 wt % FeO so that ionic-Fe translocation, by nutrient diffusion along soil moisture gradients or chelation possibly by organic acids, has taken place (Cramer and Hawkins, 2009; Genise et al., 2011). In either case, the sequestering process has been very effective in the selective adsorption of some ions (e.g., Mg, K, P) by the roots and relegation of Fe, by close to an order of magnitude, to the rhizolith walls. The spheres are zoned with cores of 1 to 4 wt % SiO_2, and 2 to 4 wt % Al_2O_3; rims have less than half these values but are distinctive in elevated contents of Na_2O (2–4 wt %), MnO (2–6 wt %) and Cl (0.5–1.5 wt %), pointing again to effective ionic migration from the kimberlite host to the roots. The spherical bodies have a low reflectivity in reflected light, are optically anisotropic, and are either goethite (α FeO.OH), or lepidocrocite (γ FeO.OH), given that both tabular (Fig. 4D) and flattened (Fig. 4E) crystal habits are present; akaganeite (β FeO.OH, green-rust) is less likely because the clusters are primary precipitates, not alteration products of preexisting Fe-rich minerals; with the presence of Cl, however, the rims may subsequently have been modified to the β-polymorph (e.g., Remazeilles and Rejait, 2007).

FIG. 2. A. Tall *Pandandus candelabrum* in the background, with excavated kimberlite from the new pipe in the foreground. B. A closer view of the *Pandanus* grove, illustrating the dense undergrowth that develops on the kimberlite eluvium. C. Aerial root system to *Pandanus candelabrum*, which is typically 2 to 2.5 m in height. D. A close-up view of the thorn-encrusted aerial roots. E. Long fronds with prickles along the leaf margins and the median fold.

FIG. 3. A. Partially cut section of a *Pandanus candelabrum* branch, illustrating the fibrous nature of the vascular system. B. Cross section of a larger branch, showing the spongy form to the vascular system. C. A spherical cephalium pod (~15 cm in diam) in a species (from Miami, Florida) closely related to *Pandanus candelabrum.* Essential to accurate classification, the fruiting heads have not yet been observed in the Liberia setting; however, hard, black seeds of pentamid symmetry that resemble the drupes in D are found in the upper soil horizon above the kimberlite pipe eluvium.

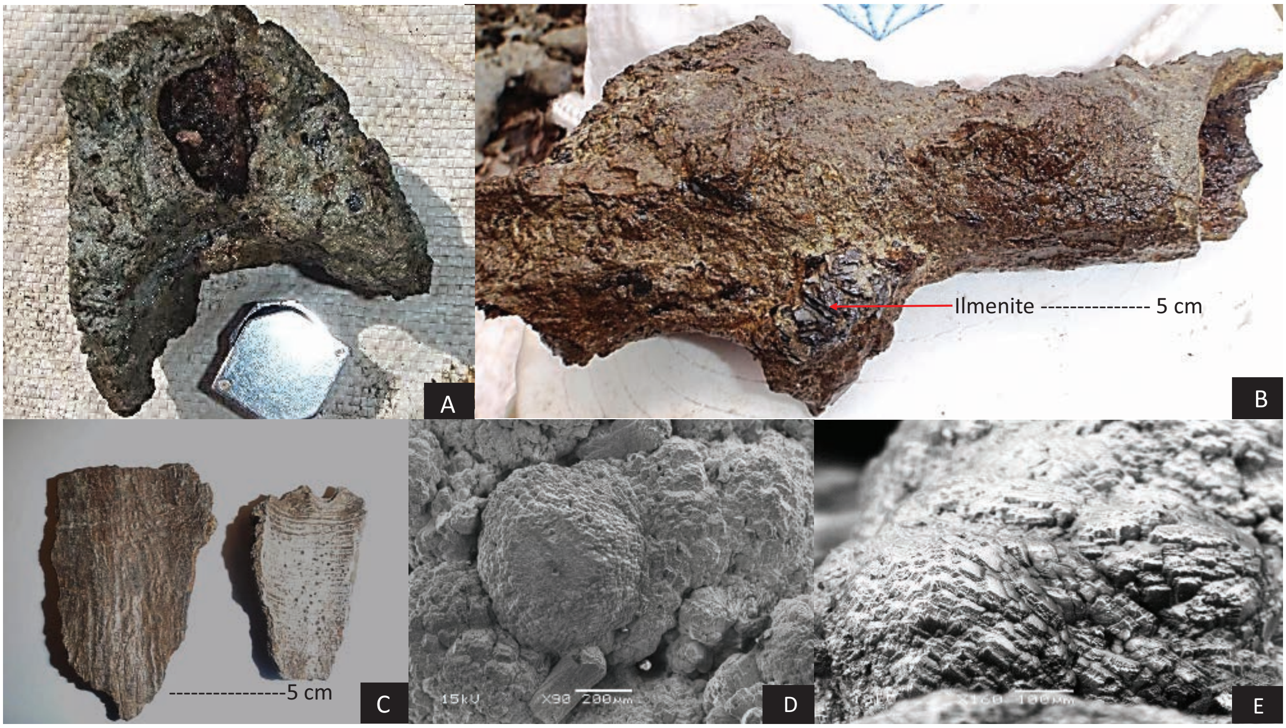

FIG. 4. A Brown decaying root with a thinly (~1 mm) developed rhizolith wall in fresh kimberlite. B. A red to brown, thick-walled (5–10 mm) rhizolith with a large embedded fragment of xenolith ilmenite; the decayed root was removed from the opening on the right-hand side of the cast (mold). C. Curved, thin-walled (2–3 mm) fragments of rhizoliths with smooth surfaces, gray patinas, and root ornamentations; the obverse sides are superficially crusty as in A, but in details have spherical clusters of goethite (D. stubby crystals) or lepidocrocite (E. flat crystals) at SEM magnification.

The unusual *Pandanus candelabrum* is confirmed at two other kimberlite sites in the Camp Alpha area, and at the Mano Godua (Richardson, 1973) kimberlite pipe ~50 km to the south-southwest of Camp Alpha (Fig. 1). A cluster of six Neoproterozoic kimberlites (Skinner et al., 2004) at Wuasua (Fig. 1) has yet to be examined. The kimberlites at Camp Alpha are restricted to a narrow valley, 100 to 300 m in width, and although the en-echelon dikes are only 5 to 10 m from the pipe, rebar soil profiling shows that the botanical boundary between the dike complex and the pipe is remarkably sharp. *Pendanus candelabrum* has evidently taken advantage of root penetration into the explosively brecciated pipe and appears not to be supported by the glassy to aphanitic kimberlite dikes. Secondly, although both kimberlite bodies are clay rich on weathering, the pipe shows more advanced alteration, and an aquiclude to aquitard environment has developed, leaving it distinctly swampier than the eluvium horizons above the adjacent kimberlite dikes. Swamps are expected to develop in strongly contrasting rock terrains, such as the granitic gneisses that envelope the intrusive kimberlites of northwestern Liberia (Fig. 1). Swamps to the north and northeast of Camp Alpha, in particular at Boaka Camp (Fig. 1), have been tested; *Pendanus* is absent and the sites are kimberlite-negative. Swampy conditions but also soil texture appear to be the controlling factors for the selective growth of *Pandanus candelabrum*, but higher levels of nutrient trace elements may also be a contributing factor; chemical tests on the eluvium soils and ash analyses of the leaves are planned for future studies.

Conclusions

Years of intense exploration in the dense bush of northwestern Liberia, a district well known for the artisanal mining of alluvial diamonds, have led to the unexpected discovery of a diamond-bearing kimberlite pipe, 2.5 hectares in area, at Camp Alpha. This is unexpected because deep erosion of 1 to 2 km of model kimberlite intrusions would have removed any pipes, exposing only the root zones of the deep dike feeders. Elongated, with a 10:1 aspect ratio, the pipe parallels an associated kimberlite dike complex. The pipe is a type 1 hypabyssal kimberlite with blocks that are mica rich and enclaves that are polymict breccias. Field observations to date show that the pipe, but not the dikes, support an unusual palmlike growth, 10 to 15 m in height, with characteristic aerial roots, spiny fronds, and an impenetrable undergrowth that evidently left the swampy mangrove entanglement untouched by earlier exploration (including our own) efforts. Now tentatively identified as *Pandanus candelabrum,* the plant is confirmed at two other kimberlite localities in surrounding Camp Alpha, and at the Mano Godua pipe ~50 km to the south-southwest of the new discovery. *Pandanus candelabrum* is the first botanical indicator to be described for kimberlite pipes. The exotic plant may be a new species, and its growing in soil of a very distinctive chemistry holds enormous potential for the cost-effective exploration of kimberlite pipes in Liberia and possibly elsewhere in West Africa. Efforts are underway to determine whether the species has a characteristic spectral signature at aircraft and possibly at satellite altitudes.

Acknowledgments

Between civil wars and now ebola, Youssef Diamond Mining Company is thanked for permission to publish our recent exploration results. Henk Beentje (Royal Botanical Gardens, London) and Martin Callmander (Missouri Botanical Gardens) provided invaluable assistance in identifying *Pandanus candelabrum*. Tom Beasley and Sven Holbik (FIU) provided the EDAX analyses and SEM images. Bulk chemistry was determined by Mike Rhodes (University of Massachusetts, Amherst). Larry Gough and David Cooke suggested editorial comments for clarity. To all, I express my sincere appreciation.

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