Prepared under the auspices of the U.S. Department of State

Reconnaissance Investigation of the Rough Diamond Resource Potential and Production Capacity of Côte d'Ivoire

Scientific Investigations Report 2013–5185

U.S. Department of the Interior
U.S. Geological Survey

Front cover An oblique aerial photograph showing inactive artisanal mine pits which have filled with water along the Legbo River, near the town of Fourouna, Côte d'Ivoire. Photo by Pete Chirico, U.S. Geological Survey.

Inside cover A large granitic outcrop surrounded by woody savanna, typical of the landscape in northern Côte d'Ivoire. Photo by Pete Chirico, U.S. Geological Survey.

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SALLY JEWELL, Secretary

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Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2013

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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	35.31	cubic foot (ft^3)

Acronyms and Initialisms Used in This Report

BRGM	Bureau de Recherches Géologiques et Minières
CARED	African Research and Minerals Exploitation Cooperative
DEM	digital elevation model
FN	Forces Nouvelles
FPI	Front populaire ivoirien
GIS	geographic information systems
GMT	Greenwhich Mean Time
GVC	Groupements à Vocation Coopérative
JRC	European Commission Joint Research Centre
ICC	International Criminal Court
KP	Kimberley Process
KPCS	Kimberley Process Certification Scheme
OPA	Ouagoudougou Political Agreement
SANDRAMINE	Compagnie Minière du Haut-Sassandra
SAREMCI	Société Anonyme de Recherche et d’Exploitation Minières en Côte d’Ivoire
s.a.r.l.	Carnegie Minerals Ivory Coast
SODIAMCI	Société Diamantifère de la Côte d’Ivoire
SMB	Société Minière des Bandamas
SRTM	Shuttle Radar Topography Mission
UN	United Nations
UNGoE	United Nations Group of Experts
UNOCI	United Nations Operation in Côte d’Ivoire
UNSC	United Nations Security Council
USGS	United States Geological Survey
WAST	West African Selection Trust
WGDE	(Kimberley Process) Working Group of Diamond Experts

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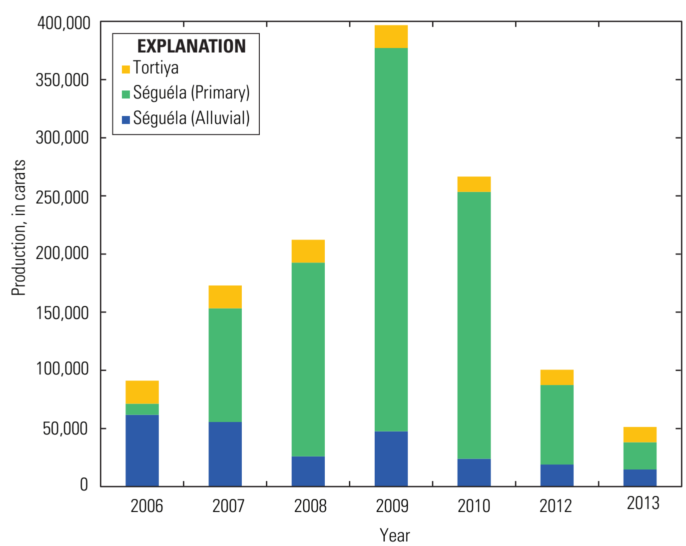
Executive Summary

Ethnic and political conflict developed into open civil war in Côte d’Ivoire in 2002, leading to a de facto partitioning of the country into the government-controlled south and the rebel-controlled north. Côte d’Ivoire’s two main diamond mining areas, Séguéla and Tortiya, are located in the north, under what was, until recently, rebel-controlled territory. In an effort to prevent proceeds from diamond mining from funding the conflict, the United Nations (UN) placed an embargo on the export of rough diamonds from Côte d’Ivoire in 2005. That same year, the Kimberley Process (KP), the international initiative charged with stemming the flow of conflict diamonds, acted to enforce this ban by adopting the Moscow Resolution on Côte d’Ivoire, which contained measures to prevent the infiltration of Ivorian diamonds into the legitimate global rough diamond trade.

Though under scrutiny by the international community, diamond mining activities continued in Côte d’Ivoire, with artisanal miners exploiting both alluvial deposits in fluvial systems and primary kimberlitic dike deposits. However, because of the embargo, there has been no official record of diamond production since the conflict began in 2002. This lack of production statistics represents a significant data gap and hinders efforts by the KP to understand how illicitly produced diamonds may be entering the legitimate trade.

This study presents the results of a multiyear effort to monitor the diamond mining activities of Côte d’Ivoire’s two main diamond mining areas, Séguéla and Tortiya. An innovative approach was developed that integrates data acquired from archival reports and maps, high-resolution satellite imagery, and digital terrain modeling to assess the total diamond endowment of the Séguéla and Tortiya deposits and to calculate annual diamond production from 2006 to 2013. On the basis of currently available data, this study estimates that a total of 10,100,000 carats remain in Séguéla and a total of 1,100,000 carats remain in Tortiya. Production capacity was calculated for the two study areas for the years 2006–2010 and 2012–2013. Production capacity was found to range from between 38,000 carats and 375,000 carats in Séguéla and from 13,000 carats and 20,000 carats in Tortiya (see chart below). Further, this study demonstrates that artisanal mining activities can be successfully monitored by using remote sensing and geologic modeling techniques. The production capacity estimates presented here fill a significant data gap and provide policy makers, the UN, and the KP with important information not otherwise available.



Introduction

The Kimberley Process

In May 2000, a meeting was convened in Kimberley, South Africa, by representatives of the diamond industry and leaders of African governments to develop a certification process intended to ensure that export shipments of rough diamonds were free of conflict concerns. Outcomes of the meeting were formally supported later that year by the United Nations (UN) in a resolution adopted by the General Assembly (A/RES/55/56). By 2002, the Kimberley Process Certification Scheme (KPCS) was ratified and signed by diamond-producing and diamond-importing countries and came into effect on January 1, 2003.

The KPCS is an international activity whose goal is to prevent the trade of "conflict diamonds" while helping to protect legitimate trade through monitoring the production, exportation, and importation of rough diamonds throughout the world. To accomplish this task, the KPCS requires that every country (1) establish a system of internal controls, (2) designate an Importing and Exporting Authority, (3) ensure that rough diamonds are imported and exported in tamper-proof containers, (4) amend or enact appropriate laws or regulations to enforce the KPCS, and (5) collect and maintain relevant diamond-related information.

Countries that are members of the scheme are required to report the official amount of diamond imports and exports, as well as their value, each year to the KP. These data are then made public and provided to other nongovernmental organizations in order to monitor the official statistics reported by all KP members. It is often difficult to obtain independent verification of the diamond-production statistics that are provided by the countries involved in KPCS compliance issues. However, some degree of independent verification can be obtained through an understanding of a country's naturally occurring diamond resources and diamond-production capacity. Studies that integrate these two components can produce a range of estimated values for a country's diamond production, and these estimates can then be compared with the production statistics released by the country.

In 2006, the Bureau de Recherches Géologiques et Minières (BRGM) released the first such assessment for the Republic of the Congo. Two methods, one integrating measurements of the volume of alluvium based on drainage-system models and the other examining historical data, were used to calculate the alluvial diamond resource within four diamond-bearing zones. A method was also implemented for calculating annual production capacity, based on the amount of gravel dug per person per day, the gravel grade, the number of active miners, and the number of days miners work per year (Barthélémy and others, 2006). The U.S. Geological Survey (USGS) collaborated with BRGM scientists to produce subsequent assessments of diamond deposits in the Central African Republic and Mali (Chirico and others, 2010a, b), following the BRGM methodology. The USGS then conducted an assessment of the diamond deposits of Ghana and Guinea, modifying the BRGM methodology by analyzing the deposits at the watershed level and incorporating a geomorphic modeling technique for determining the volume of alluvium (Chirico and others, 2010c, 2012). The goal of this study is to conduct a reconnaissance assessment of alluvial diamond resource potential and production capacity in Côte d'Ivoire's two main diamond producing zones, Séguéla and Tortiya, by using satellite imagery, geographic information systems (GIS) data, fieldwork data, and archival geological information.

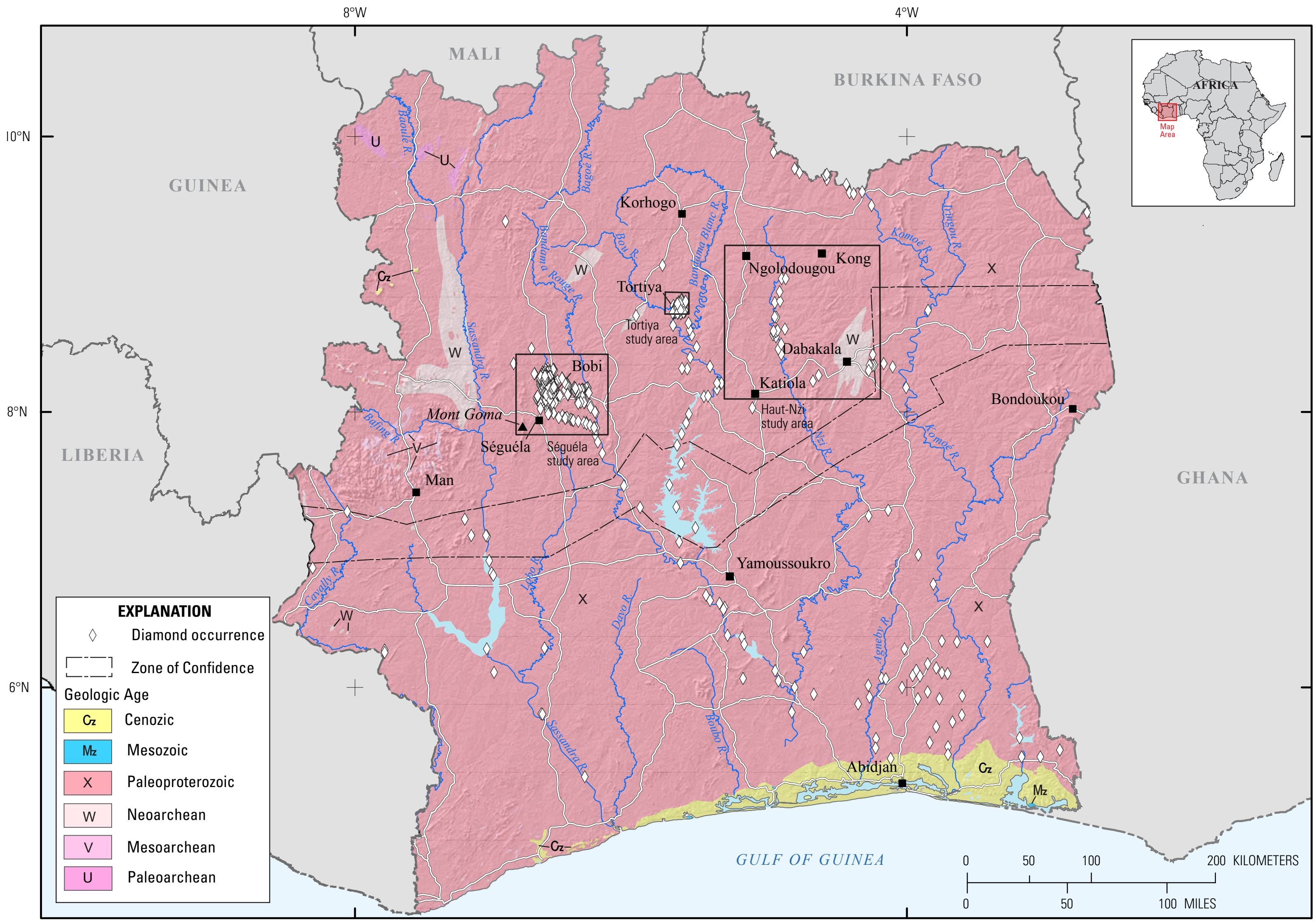
Study Area

Geography of Côte d'Ivoire

Côte d'Ivoire lies between latitudes 11°N. and 5°N. and longitudes 8°W. and 3°W. (fig. 1). It is bordered to the west by Liberia and Guinea, to the north by Mali and Burkina Faso, to the east by Ghana, and to the south by the Gulf of Guinea. The country has two main climate zones, the tropical south and the semiarid north. Côte d'Ivoire is separated into three main geographic regions: the eastern lagoon region, a narrow coastal strip from the Ghana border to the mouth of the Sassandra River; the dense forest region, which covers nearly one-third of the country, extending north from the lagoon region to the western city of Man and the eastern city of Bondoukou; and the northern savanna, a large plateau composed of gently undulating hills, low-lying vegetation, and scattered woodlands. The highest point is Mont Nimba at 1,752 meters (m), which spans the borders of Guinea, Liberia, and Côte d'Ivoire. Côte d'Ivoire is endowed with a variety of natural resources and is the world's leading cocoa producer. Other principal exports include petroleum, coffee, rubber, and timber. Undeveloped resources include bauxite, cobalt, copper, iron ore, nickel, and silica sand (Soto-Viruet, 2010).

Geography of Séguéla and Tortiya

Côte d'Ivoire's two main diamond mining areas are centered around the towns of Séguéla and Tortiya, both in the north (fig. 1). Séguéla is further west, in the region of Worodougou, positioned at 7°57′25″N. and 6°40′5″W. and is just north of the transitional zone between dense humid semideciduous forest and the Sudanian Savanna (Avenard, 1971). The terrain consists of undulating wooded savanna dominated by large granitic domes (Bardet, 1974). Mont Goma, just west of the town of Séguéla, is the highest granitic dome east of the Sassandra River, at 400 m, rising approximately 150 m above base elevation. Tortiya is 140 kilometers (km) northeast of Séguéla, positioned at 8°45′59″N. and 5°41′W. in the region of Vallée du Bandama. Tortiya's climate is semihumid tropical, and the vegetation type is Guinea savanna (Teeuw, 2002).



Shaded relief modified from the Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010)
Diamond occurrences from U.S. Geological Survey digital files
Base layers modified from U.S. Geological Survey Global Geographic Information Systems database
Projection: Geographic Coordinate System (GCS) World Geodetic System (WGS) 1984 Datum

Geology modified from Bagarre and Tagini, 1965

Figure 1. Map of Côte d'Ivoire showing geologic age, diamond occurrences, and the de facto partition between northern and southern Côte d'Ivoire. The Zone of Confidence divided the country between the loyalist south and the rebel-controlled north from 2002 to 2008.

Geography of Haut Nzi

Whereas this study focuses on the diamond deposits of Séguéla and Tortiya, the area of the upper reaches of the Haut Nzi River in northern Côte d'Ivoire is also the location of several known diamond occurrences, though no significant diamond deposit has yet been found in the area.[1] These occurrences are approximately 80 km east of the town of Tortiya, between the towns of Katiola, Dabakala, Ngolodougou, and Kong, in the Vallée du Bandama region (fig. 1). These deposits were explored several times by mining companies, the results of which have located diamond occurrences and a kimberlite, yet no economical deposits have been found thus far. Haut Nzi remains an area of potential future study.

Political Situation and Conflict

In 2002, political instability in Côte d'Ivoire ignited a civil war, which led to the eventual partitioning of the country into the government-held south and the rebel-held north. Tension between northern and southern Côte d'Ivoire dates back to the 1960s, when an influx of immigrants from surrounding former French colonies moved to southern Côte d'Ivoire seeking employment in the nation's booming agricultural sector (fig. 2). During this period, the term *ivoirité* emerged, referring to those of "pure Ivorian" lineage, as opposed to those of foreign descent. In 1993, parliamentary spokesman Henri Konan Bédié was appointed interim president following the death of President Houphouet-Boigny. A competition for power between Bédié and former prime minister Alassane Ouattara evolved and continued up to the planned 1995 presidential elections, which Bédié eventually won. Bédié fueled the *ivoirité* debate in an attempt to discredit and prevent Ouattara, accused of being from Burkina Faso, from taking power, and questioned whether people of northern Ivorian ethnic origins were sufficiently Ivorian. Additionally, each of the three main political parties professed the superiority of either northern or southern ethnic groups and accused each other of working on behalf of ethnic interests rather than in the interests of the nation.

In 1999, a bloodless military coup led by officers of northern origin overthrew Bédié's government. Following the coup, General Robert Guéï became head of the military junta. Guéï was a candidate in the presidential elections the following year, as was Laurent Gbagbo, founder of the Front populaire ivoirien (FPI). Guéï barred the other major opposition candidates (Ouattara and Emile Constant Bombet) from running on the basis that candidates must have two Ivorian parents and never have held citizenship with another country. Guéï then stopped the election during the early polling process, claiming fraud, and declared himself president. Fighting broke out in the commercial capital of Abidjan, Guéï was eventually forced to flee, and Gbagbo was declared president.

In 2002, a failed military coup resulted in rebel forces loyal to Ouattara gaining control of the north. A cease-fire signed one month later led to the division of the country between the loyalist south and the rebel-controlled north, separated by a "Zone of Confidence" (fig. 1). The rebel groups were consolidated into the Forces Nouvelles (FN) under leader Guillaume Soro, and violence continued throughout 2003 and 2004. In support of the UN Operation in Côte d'Ivoire (UNOCI), the French force "Licorne" has been on the ground in Côte d'Ivoire since 2002.

March 2007 saw the signing of the Ouagoudougou Political Agreement (OPA) by President Gbagbo and rebel leader Soro and the appointment of Soro as prime minister. Violence decreased after the signing of the OPA; however, a surge of violence ensued in November 2010 following contention over the results of long-postponed elections between incumbent Gbagbo and former prime minister Ouattara. Although Ouattara was announced the winner by the electoral committee following a runoff election, Gbagbo supporters claimed electoral fraud, and Gbagbo refused to concede. The election dispute escalated into military conflict between forces loyal to Gbagbo and those loyal to Ouattara, sparking renewed postelectoral conflict. In addition to using his own security forces, Gbagbo hired armed militia and mercenaries, some from neighboring Liberia, to assist with the destabilization of Ouattara's government, attacking both civilians and pro-Ouattara forces. The FN hired mercenaries as well, among them members of the Dozo Brotherhood, a group of initiated traditional hunters found in Côte d'Ivoire, Burkina Faso, Guinea, and Mali. Overall, the postelectoral crisis is thought to have killed more than 3,000 people and displaced more than a million citizens.

After several months of violence, Ouattara's forces seized control of most of the country and arrested Gbagbo in April 2011. In May, Ouattara was inaugurated as president. In December 2011, Gbagbo was indicted by the International Criminal Court (ICC) on charges of war crimes against humanity following the 2010 postelectoral crisis, for which he will be tried in The Hague.

The conflict in Côte d'Ivoire has had significant impacts on the country's diamond industry. The diamond mining areas of Séguéla and Tortiya are in northern Côte d'Ivoire and had until recently been under the control of the FN since the country's de facto partitioning. Following the outbreak of violence in 2002, the Ivorian Ministry of Mines placed a ban on the exploration and sale of diamonds. This ban, however, proved ineffective and failed to stop the illicit exploitation of diamonds. In November 2004, the UN Security Council (UNSC) issued an arms embargo on Côte d'Ivoire with Resolution 1572 (S/RES/1572) and in December 2005 issued Resolution 1643 (S/RES/1643), placing an embargo on rough diamonds of Ivorian origin (UNSC, 2004, 2005). This resolution prevented Member States from importing rough diamonds from Côte d'Ivoire.

[1]In this report, distinction is made between an "occurrence" (a concentration of a mineral that is considered valuable by someone somewhere, or that is of scientific and technical interest) and a "deposit" (an occurrence of sufficient size and grade that it might, under the most favorable of circumstances, be considered to have economic potential).

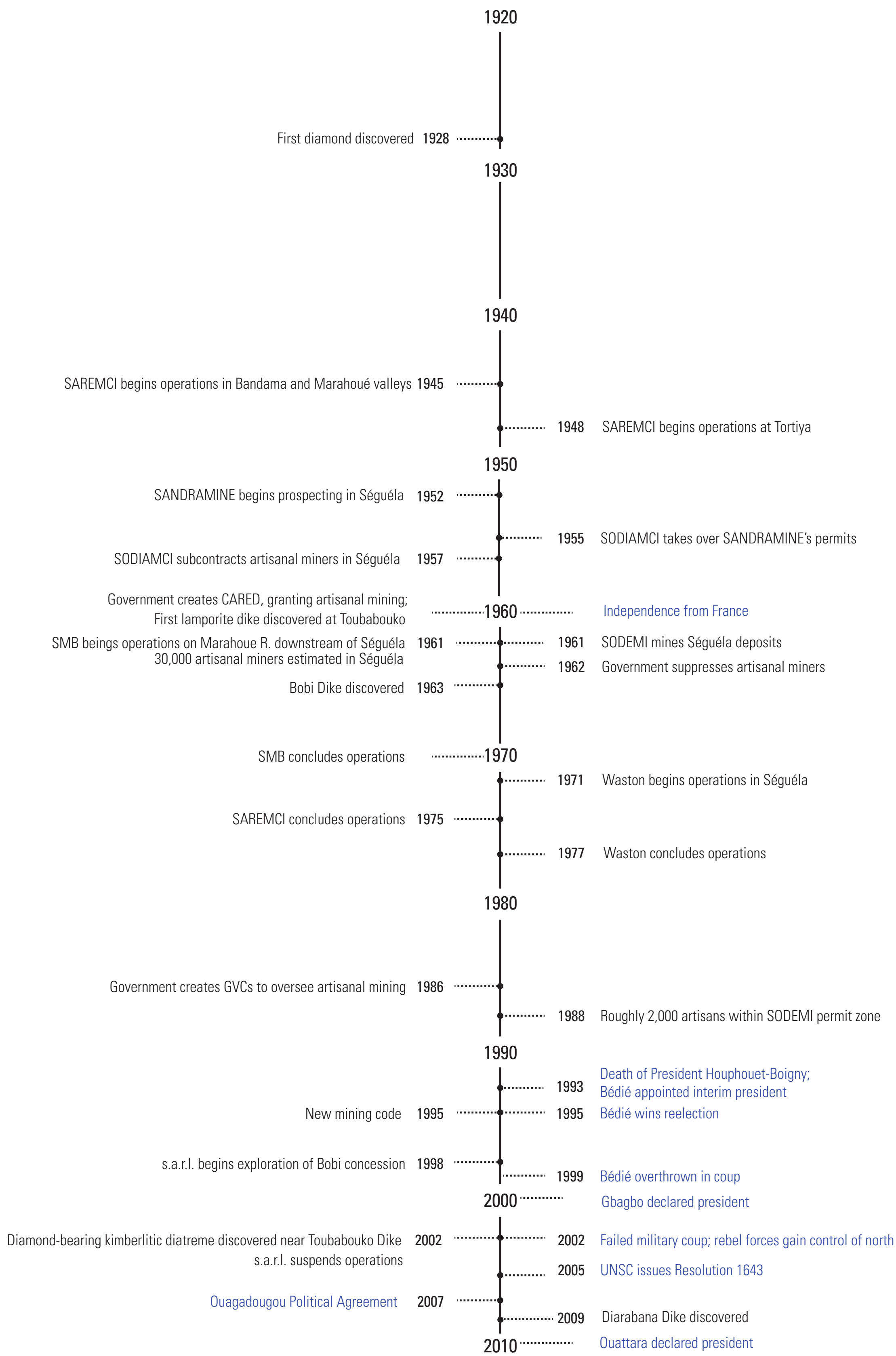


Figure 2. Timeline highlighting key events in the history of mining and politics in Côte d'Ivoire.

The resolution also expanded the mandate of the UN Group of Experts on Côte d'Ivoire (UNGoE), initiated by the UNSC on February 1, 2005, with Resolution 1584 (S/RES/1584) to monitor the arms embargo, to include the monitoring of the diamond embargo. The UNGoE has found that the absence of rule of law in the diamond mining zones, in combination with porous international borders, has led to the continued infiltration of Ivorian rough diamonds into international markets via neighboring countries (UNGoE, 2011a). The UNSC has continued to renew the diamond trade ban, most recently in April 2012, with the adoption of Resolution 2045 (S/RES/2045).

Similarly, the Kimberley Process has acted to enforce the rough diamond trade ban. In 2005, the KP Plenary adopted the Moscow Resolution on Côte d'Ivoire, which contained measures to prevent the infiltration of Ivorian diamonds into the legitimate rough diamond trade (KP, 2005). This was followed by the Brussels Initiative on diamonds from Côte d'Ivoire in 2007, put forth to strengthen past actions by the KP and the UN aimed at preventing the trade of Ivorian diamonds (KP, 2007). Finally, Resolution 2045 urges Ivorian authorities to enforce KPCS regulations in Côte d'Ivoire and to work with the KPCS to conduct an assessment of the country's internal control systems and diamond resources and production capacity (UNSC, 2012).

History of Diamond Mining in Côte d'Ivoire

Mining Company Activity

Diamonds were first discovered in Côte d'Ivoire in 1928, though mining companies did not begin exploitation until the mid-1940s. The first company, the Parisian-based Société Anonyme de Recherche et d'Exploitation Minières en Côte d'Ivoire (SAREMCI), began operations in 1945 in the Bandama and Marahoué River valleys. In 1948, SAREMCI began mining the deposits of Tortiya, at first using only rudimentary tools and methods. During the 1960s, SAREMCI's annual production at Tortiya ranged from 150,000 to 175,000 carats (kt) per year. The company concluded operations in 1975, when costs became too high. Table 1 lists annual diamond production estimates for Séguéla and Tortiya for 1945–2012, where available.

In 1952, the French Compagnie Minière du Haut-Sassandra (SANDRAMINE) began prospecting the Séguéla deposits. Three years later, Société Diamantifère de la Côte d'Ivoire (SODIAMCI) took over SANDRAMINE's permits, which by 1962 covered only 43 square kilometers (km²), with production peaking at 25,000 kt in 1965. The remainder of the Séguéla area was mined by the government-formed Société pour le Développement Minier (SODEMI), in association with Waston Ltd., West African Selection Trust (WAST), and Harry Winston Inc., beginning in the early 1960s. In 1971, Waston opened a separate mine at Séguéla in cooperation with SODEMI. Waston's operation continued until the deposits were deemed exhausted in 1977 (Greenhalgh, 1985).

A subsidiary of SAREMCI, Société Minière des Bandamas (SMB) operated several small production sites on the Marahoué, downstream of the Séguéla diamond field, during 1961–1970. However, the deposits were scattered and not particularly rich, with annual production never exceeding 10,000 kt (Bardet, 1974; Greenhalgh, 1985).

Since the late 1970s, diamond production in Côte d'Ivoire has been primarily artisanal in nature, taking place in the Séguéla and Tortiya diamond fields. In 1995, the government produced a new mining code, listing regulations for both artisanal and industrial mining, and included revisions aimed at encouraging foreign investment (Mobbs, 1996). The most recent company to explore the region was Carnegie Minerals Ivory Coast (s.a.r.l.), a joint venture between African Carnegie Diamonds Plc. (a subsidiary of Carnegie Corp. Ltd. of Australia) and SODEMI, who during 1999–2001 explored Séguéla's Bobi concession, which included the Toubabouko Dike (Bermúdez, 1999; Szczesniak, 2000, 2001). However, the company suspended operations in 2002, because of heightening civil unrest in the region.

Artisanal Diamond Mining

The artisanal mining of diamonds in Côte d'Ivoire began in the mid-1950s. In 1957, SODIAMCI began subcontracting artisanal miners to work low-grade gravels in and around Séguéla (Greenhalgh, 1985). The Ivorian Government also encouraged artisanal mining initially, creating the African Research and Minerals Exploitation Cooperative (CARED) in 1960, which granted miners the right to mine diamondiferous deposits, with the exception of the SANDRAMINE and SAREMCI permit zones (Bardet, 1974). Artisanal mining activities spread rapidly across the Séguéla diamond fields, and by 1961 an estimated 30,000 miners were working the region. With this escalation came an increase in illicit diamond exports, and in 1962 the government used violent military force to suppress artisanal miners, banning the activity and instead promoting commercial, mechanized mining (Greenhalgh, 1985).

In 1986, the Ministry of Industry and Mines created the Groupements à Vocation Coopérative (GVCs) to oversee and control the artisanal mining of diamonds. GVCs were responsible for receiving the diamonds, accounting for their production, and collecting a local tax of 12 percent of the estimated value of the diamonds brought in (UNGoE, 2008). GVCs operated within the SODEMI permit and, by 1988, there were 23 GVCs and roughly 2,000 artisanal miners operating among them within the SODEMI permit zones (SODEMI, 1988). As of 2008, 17 of the total 25 GVC offices were still operational, all located in Séguéla (UNGoE, 2008). The UNGoE reports that in the 1980s, Tortiya supported around 40,000 miners (UNGoE, 2011b). Today, the Ministry of Mines estimates that between 5,000 and 10,000 miners are operating in the Séguéla diamond fields, and between 1,000 and 2,000 are operating in the Tortiya diamond fields (UNGoE, 2008, 2011b). It is important to note, however, that

Table 1. Annual diamond production in Côte d’Ivoire, 1945–2012.

[na, not available]

Year	Production (carats)	Year	Production (carats)	Year	Production (carats)	Year	Production (carats)
1945	na	1962	160,387	1979	na	1996	301,591
1946	na	1963	177,276	1980	40,000	1997	306,665
1947	0	1964	199,200	1981	na	1998	275,000
1948	7,141	1965	197,207	1982	na	1999	400,000
1949	na	1966	182,178	1983	13,132	2000	320,207
1950	52,171	1967	172,654	1984	na	2001	309,000
1951	na	1968	180,169	1985	na	2002	300,000
1952	80,000	1969	196,373	1986	na	2003	230,000
1953	na	1970	212,808	1987	na	2004	300,000
1954	4,385	1971	326,370	1988	na	2005	300,000
1955	107,424	1972	339,719	1989	250,000[a]	2006	300,000
1956	132,225	1973	270,197	1990	350,000[a]	2007	188,500[b]
1957	144,000	1974	242,008	1991	290,000[a]	2008	292,100[b]
1958	164,904	1975	204,826	1992	280,000[a]	2009	na
1959	187,949	1976	na	1993	15,000	2010	na
1960	199,120	1977	na	1994	84,400	2011	na
1961	549,330	1978	na	1995	75,300	2012	na

[a]Exports.

[b]Production estimated by Kimberley Process Working Group of Diamond Experts.

the current and historical figures on the number of artisanal miners are merely estimates, because no official census of this population has been conducted to date to truly capture their numbers and influence. This represents a major data gap in a country whose current production is exclusively artisanal.

Although the exporting of Ivorian rough diamonds is currently banned, artisanal mining of the primary and secondary deposits near Séguéla and the secondary deposits near Tortiya continues. The UNGoE has been monitoring these activities since 2005 and has noted the continuation and, at times, expansion of activities. In 2005, the UNGoE observed the artisanal production of secondary diamond deposits along small streams in and around Séguéla using nonmechanized methods (UNGoE, 2005). The following year, mining activities in Séguéla expanded to the primary deposits of the Bobi Dike, which was mined by use of shovels, picks, and small gasoline-powered water pumps. The mining of alluvial deposits in Séguéla also increased, particularly in riverbed deposits around the Bobi Dike. At Tortiya, only limited mining of alluvial deposits was observed (UNGoE, 2006). In 2007, sustained mining activities were noted at Séguéla and Tortiya, with evidence of well-organized mining of the Bobi Dike (UNSC, 2007). In 2008, the UNGoE again noted considerable mining activity in the Séguéla region, particularly around the Bobi Dike (UNGoE, 2008). That same year, the KP Working Group of Diamond Experts (WGDE) estimated that 104,000–173,000 kt were being produced per year from the Séguéla region, and 10,000–15,000 kt were being produced per year from the Tortiya region (UNGoE, 2010). In 2009, activities increased rapidly in Séguéla, as many artisans abandoned the lower yield secondary deposits to work the newly discovered, higher yield, primary kimberlitic occurrences north of the town of Séguéla. Test-pit excavation was also noted throughout Séguéla and other parts of northern Côte d’Ivoire, though many of these were thought to be alluvial gold mining pits. The WGDE’s annual production figures were revised for Séguéla in 2009, to 135,800–167,000 kt per year. SODEMI, however, estimated an annual diamond production of 1,000,000 kt for that year (UNGoE, 2009a, b). Extensive mining of kimberlitic deposits continued in 2010, with significant expansion noted along the Diarabana Dike and, to a lesser extent, the Bobi Dike (UNGoE, 2010). In 2011, newly mined deposits were observed in the Séguéla and Tortiya diamond fields. Although only a moderate number of miners were observed in and around Séguéla, there was an increase in the number of areas being mined. Meanwhile, in Tortiya, mining activities consisted mainly of the rewashing of unconsolidated material remaining from the previous exploitation of the deposits by industrial-scale mining operations. In general, the higher yielding primary deposits of Séguéla appear to attract larger groups of miners, whereas the lower yielding Tortiya deposits are mined by small, isolated groups of artisans. The UNGoE speculates that a significant increase in revenues from diamond mining in Séguéla is likely due to the growth of mining activities and the increased price of rough diamonds. However, it remains unclear which groups benefit from the revenues (UNGoE, 2011a, b). In 2012, the UNGoE observed through aerial reconnaissance exercises that although mining activities in Séguéla were continuing, there was a reduction in the level of activity, particularly at the Bobi and Diarabana Dikes. As a result, the group estimated that 2012 production was between 100,000 and 150,000 kt (UNGoE, 2012). A continued reduction in activity was noted in 2013, and production was estimated to be between 50,000 and 100,000 kt (UNGoE, 2013). The UNGoE continues to monitor and assess the diamond deposits of northern Côte d'Ivoire, at times working in collaboration with the WGDE on joint review missions.

Geology

General Geology of Côte d'Ivoire

The majority of Côte d'Ivoire is underlain by Archean and Lower Proterozoic rocks belonging to the West African Craton, with the exception of a narrow southeastern coastal strip of Cenozoic sediments (fig. 1). The Precambrian rocks can be divided into the Archean Kenema-Man domain in western Côte d'Ivoire and the Paleoproterozoic Baoulé-Mossi domain in central and eastern Côte d'Ivoire. The two domains are separated by the north-south trending Sassandra mylonitic zone. The Archean rocks consist mainly of granulitic and migmatitic gneisses, whereas the Paleoproterozoic rocks consist mainly of subparallel volcanic belts and sedimentary basins (Schlüter, 2006) (fig. 3). The Baoulé-Mossi domain is underlain by Lower Proterozoic Birimian supracrustal and basement rocks. The Birimian rocks are thought to be the secondary host of diamond deposits in Ghana and parts of Côte d'Ivoire (Tortiya) (Wright and others, 1985).

The Séguéla Deposits

The Séguéla Diamonds

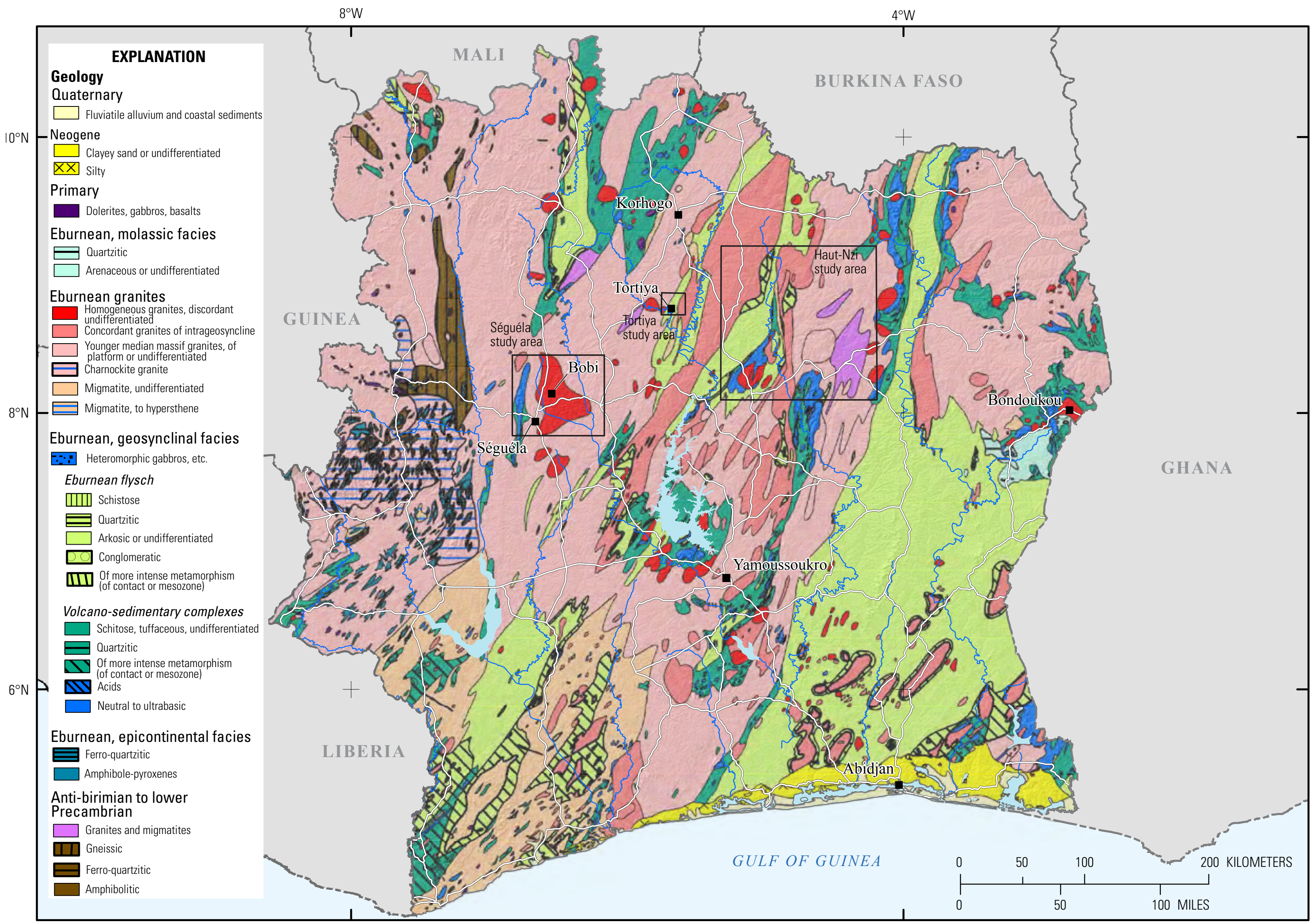
Original estimates of the quality of the Séguéla diamonds state that they are 33 percent gem quality, 33 percent industrial quality, and 33 percent boart (very low quality) (Bardet, 1974). The stones are generally translucent white, sometimes yellow to brown, and, rarely, pale green. The stones produced in the region are small, at about 0.3 kt on average, with the smallest stones being 0.02 kt and the larger stones around 4 kt. The largest stone found to date in the region was 27 kt (Pouclet and others, 2004). The richest deposits are found in the eluvium (in situ weathered rock) of the kimberlitic dikes, whereas the smaller gem-quality stones are found in the downstream alluvial flat deposits. The average grade of the alluvial deposits exploited by SODEMI during 1963–1988 was approximately 0.3 carat per cubic meter (kt/m^3).

Sources of the Séguéla Diamonds

To date, there are 14 known kimberlites, kimberlitic dikes, lamproites, and lamprophyres in the Séguéla region (fig. 4) (Faure, 2010). Figure 5 shows a model of the kimberlite magmatic system and illustrates the components that may be present and exposed at the dikes in Séguéla. The Toubabouko and Bobi Dikes are the two main kimberlitic bodies in the region (fig. 6). The Bobi Dike, located 25 km north-northeast of the town of Séguéla, is 2.5 km long and ranges from 0.25 to 0.50 m in width (Pouclet and others, 2004). It has several veins, three of which have been distinguished and are known as the Prince Dike, the Intermediate Dike, and the Princess Dike (the principal body) (Bardet, 1974). The Toubabouko Dike, located 30 km north of Séguéla, is 4.5 km long and 0.80 to 1 m wide. In 2002, Pouclet and others (2004) reported discovery of a small diatreme in the northern part of the Toubabouko vein, which had been exposed by artisanal digging.

The Bobi and Toubabouko Dikes trend N. 170° and crosscut the Paleoproterozoic Birimian formations of the West African Craton. The kimberlitic structures are covered by several meters of eluvium and colluvium, which have been excavated by artisanal miners, revealing the kimberlitic rocks. Diamonds have eroded from the dikes and are now found in the eluvial, colluvial, and alluvial flat deposits of river valleys (Pouclet and others, 2004). The eluvial diamond deposits occur at the surface and are developed in situ from the weathering of the primary kimberlitic host rocks. Diamonds are also found in ancient alluvial horizons beneath the present low and high terraces, as well as within colluvial deposits on expansive slopes (Knopf, 1970).

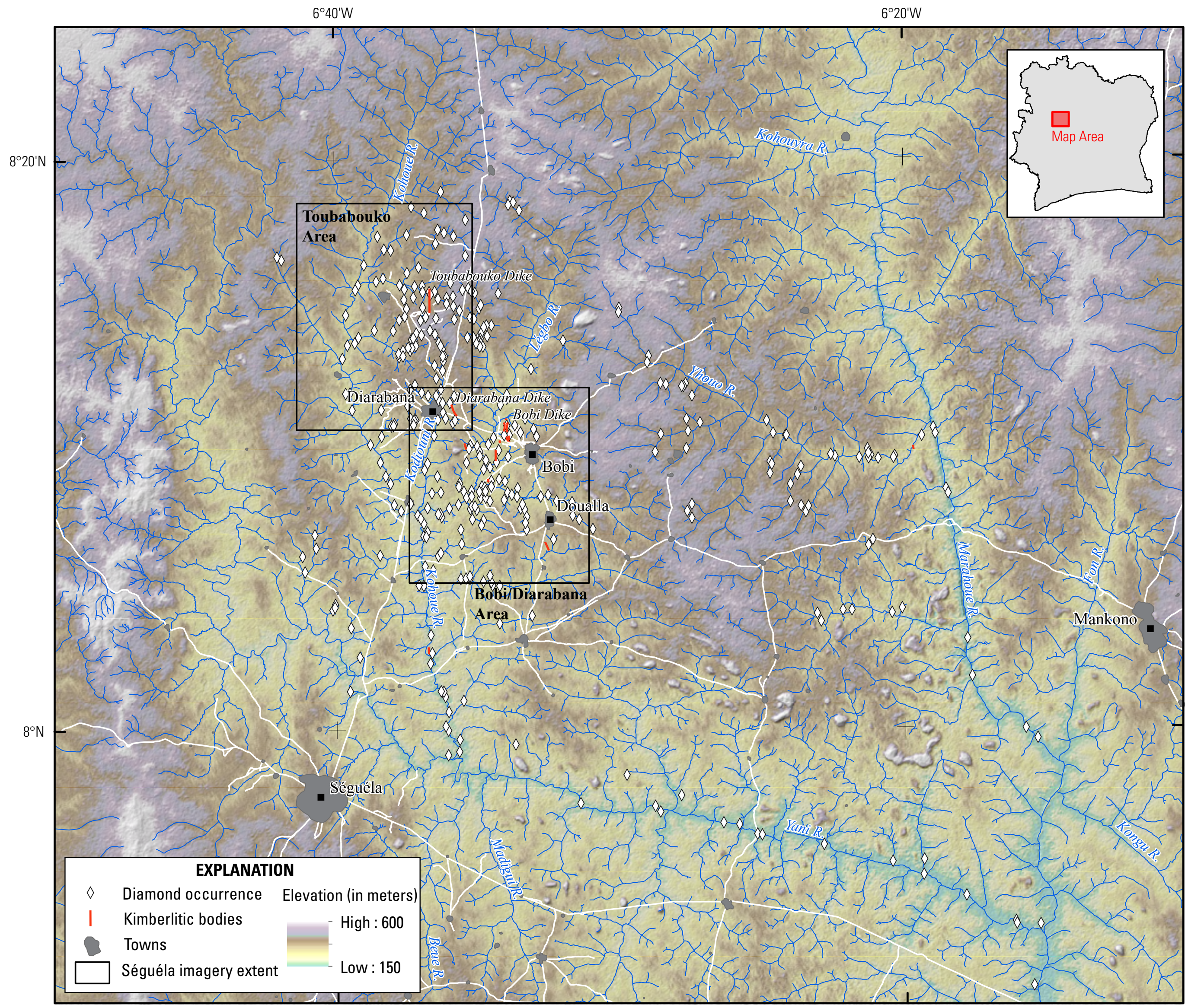
The question of the age of the Séguéla kimberlites has not yet been resolved. Early estimates of their age, based on strontium isotope data, indicated that the kimberlites were between 1,429 and 1,145 mega annum (Ma), or Mesoproterozoic (Bardet and Vachette, 1966). Pouclet and others (2004) challenge this estimate. On the basis of their own chemical and petrographic analysis of the kimberlites, they argue that an age of 1,429–1,145 Ma is unrealistic and suspect that a contamination effect caused incorrect results in the Bardet and Vachette study. Although there are diamondiferous fields in West Africa that are of Precambrian age (4,600–542 Ma), Mesozoic (251–65.5 Ma) pipes and dikes are also found in the region. Pouclet and others (2004) argue that kimberlitic activity in West Africa can be related to the tectono-magmatic events of the region during the Mesozoic era. There were two important phases of tectono-magmatic activity during the Mesozoic. The first occurred at the beginning of the Jurassic period (199.6–145.5 Ma), during which basaltic magmatism with numerous doleritic dikes were put in place. The second event took place during the Early Cretaceous period (99.6–65.5 Ma) and corresponded to the formation of new basic manifestations and alkaline intrusions. In Côte d'Ivoire, the Jurassic event resulted in the intrusion of several doleritic dikes oriented N. 130°.



Shaded relief modified from the Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010)
Base layers modified from U.S. Geological Survey Global Geographic Information Systems database
Projection: Geographic Coordinate System (GCS) World Geodetic System (WGS) 1984 Datum

Geology modified from Bagarre and Tagini, 1965

Figure 3. Lithologic map of Côte d'Ivoire.



Shaded relief modified from ASTER Global Digital Elevation Model version 2
Diamond occurrences and kimberlitic bodies from U.S. Geological Survey digital files
Base layers interpreted from DigitalGlobe's WorldView-1, May 4, 2010
and Corona KH-4A images, 1967 and 1968
Projection: Universal Transverse Mercator (UTM) Zone 29
World Geodetic System (WGS) Datum

Figure 4. Topographic map of the Séguéla, Côte d'Ivoire, study area showing diamond occurrences and kimberlitic bodies.

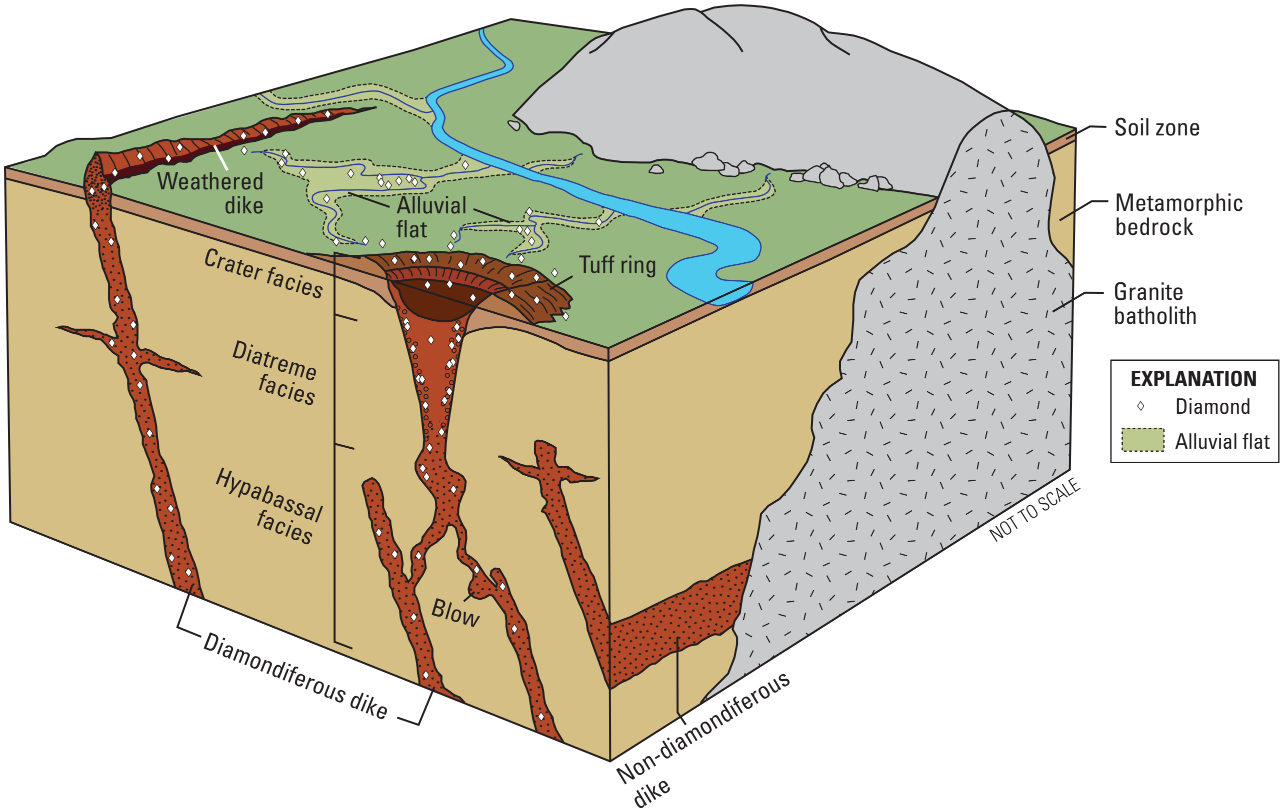
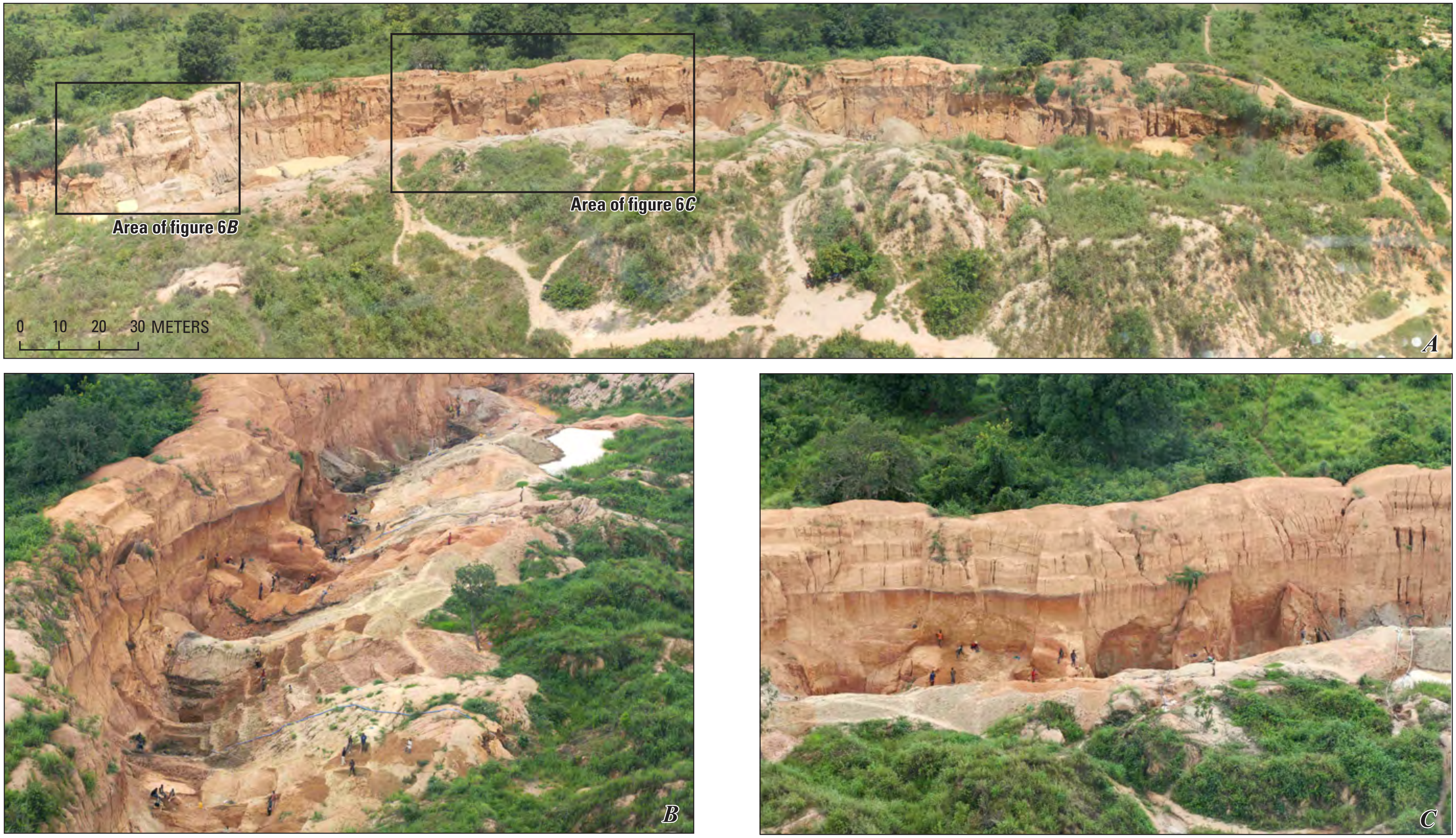


Figure 5. Diagram illustrating the crater facies, diatreme facies, and hypabassal facies of a diamondiferous kimberlitic system; a weathered diamondiferous dike; and a non-diamondiferous dike.

A miner sorting through gravel and sand, as he recycles old diamond mine tailings in search of small diamonds, Tortiya, Côte d'Ivoire. Photo by Pete Chirico, U.S. Geologicial Survey.



Photos B and C courtesy of Simon Gilbert, UNGoE.

Figure 6. Aerial overflight photographs showing exploitation of the Bobi Dike by artisanal miners in 2012. Photos courtesy of Pete Chirico, USGS, and Simon Gilbert, UNGoE.

The Cretaceous tectono-magmatic events resulted in the opening of deep lithospheric fractures, which allowed for the drainage of kimberlitic liquids, notably of the Late Cretaceous (145.5–99.6 Ma). Pouclet and others (2004) maintain that the Séguéla kimberlites were formed during this period, as dikes trending N. 170°, parallel to the Sassandra fault and bordering the Eburnean group. This direction is controlled by a major structural contact between the Archean lithosphere to the west and the Paleoproterozoic lithosphere to the east. The discovery of a well-preserved diatreme with vertical fissures and the lacustrine deposit within an intact maar, devoid of any diagenetic processes, beneath the current colluvium attests to the recent geologic age of the kimberlites, as do the Cretaceous tectono-magmatic events which resulted in the opening of deep lithospheric fractures (Pouclet and others, 2004).

A third major dike, located 1 km east of the town of Diarabana and approximately 3 km northwest of the Bobi Dike, was recently discovered by artisanal miners and has not yet been the subject of any detailed scientific investigations (figs. 7 and 8). The discovery and exploitation of the dike has, however, been monitored remotely by the USGS using high-resolution satellite imagery. On May 2, 2008, a 1-m-resolution panchromatic IKONOS image showed small artisanal exploration pits 1 km east of Diarabana. A second image (1-m-resolution panchromatic IKONOS) acquired on May 21, 2009, revealed the exposure of two segments of a newly discovered dike. The southern segment is the larger of the two at roughly 390 m in length, whereas the northern segment, located approximately 270 m north of the southern segment, is 160 m long. A third image (0.5-m-resolution panchromatic WorldView) acquired on May 4, 2010, showed the continuing excavation of the dike by artisans as well as new artisanal mining pits to the north and east. A fourth image (0.5-m-resolution panchromatic WorldView) from January 10, 2011, showed that the dike was still being exploited and that additional pits had appeared to the north and northwest of the northern segment. The Diarabana Dike has a trend similar to that of the Bobi Dike and is estimated to be between 0.6 and 1 m wide. Although there are some alluvial mining activities close to the dike, the focus of artisanal mining activity has been on the primary deposits of the dike itself.

Geomorphology of Séguéla

The alluvial system and regolith deposits of Séguéla were modeled and mapped as part of this study to analyze the depositional patterns of the placer diamond deposits. The geomorphology of the Séguéla region is composed of recent alluvial materials overlying a series of regolith layers derived from the underlying granitic bedrock (Avenard, 1971). The alluvial system of the region may be divided into (1) the recent alluvium of first-order tributary streams in the upper parts of the watershed subbasins, (2) the alluvial flat deposits of the higher order rivers and streams, and (3) low and high terrace deposits of the former flood plain bordering the alluvial flats.

The regolith zones were modeled by utilizing a basic framework of the history of erosional and weathering events in the region. During the Quaternary in northern Côte d'Ivoire, periods of dry climate alternating with long periods of humid climate led to the development of ferricrete deposits throughout the landscape. The ferricrete caps which formed as a result of these climatic oscillations have been termed "*cuirasse*" by French geologists, whereas the reworked and eroded ferricrete pediment deposits have been termed "*glacis*." The *haut* (upper), *moyen* (middle), and *bas* (lower) *glacis* surfaces correlate with the upper, middle, and lower Quaternary (Peltre, 1978; Teeuw, 2002). In general, the *glacis* deposits form long, gently inclined slopes. Such a landscape is dominated by weakly inclined hills, large plateaus, and buttes or inselbergs. The *cuirasse* zones form at the top of plateaus, whereas the *glacis* form at the base of plateaus or slopes (Avenard, 1971). Although ferricrete caps are no longer apparent within the Séguéla region, dismantled and reworked ferricrete debris, or *glacis*, are evident. Specifically, five distinct regolith zones were developed in the geomorphic model framework (fig. 9):

1. A gravelly sand layer found along the base of hillside slopes and extending to midslope.
2. A dismantled *haut-glacis* zone, consisting of gravelly clay from an entirely dismantled *cuirasse*. This zone formed during the Late Quaternary period.
3. A colluvium zone, consisting of angular gravels transported downslope by gravity.
4. A zone of reworked *haut-glacis*, consisting of a dismantled gravelly clay *cuirasse* material, which has been locally recemented.
5. Granite outcrops or inselbergs of Paleoproterozoic age.

The three alluvial zones and the five regolith zones were combined into a comprehensive geomorphic map to model the region's depositional zones.

A large active mining pit near the town of Fourouna in the Séguéla region of Côte d'Ivoire. Photo by Pete Chirico, U.S. Geologicial Survey.

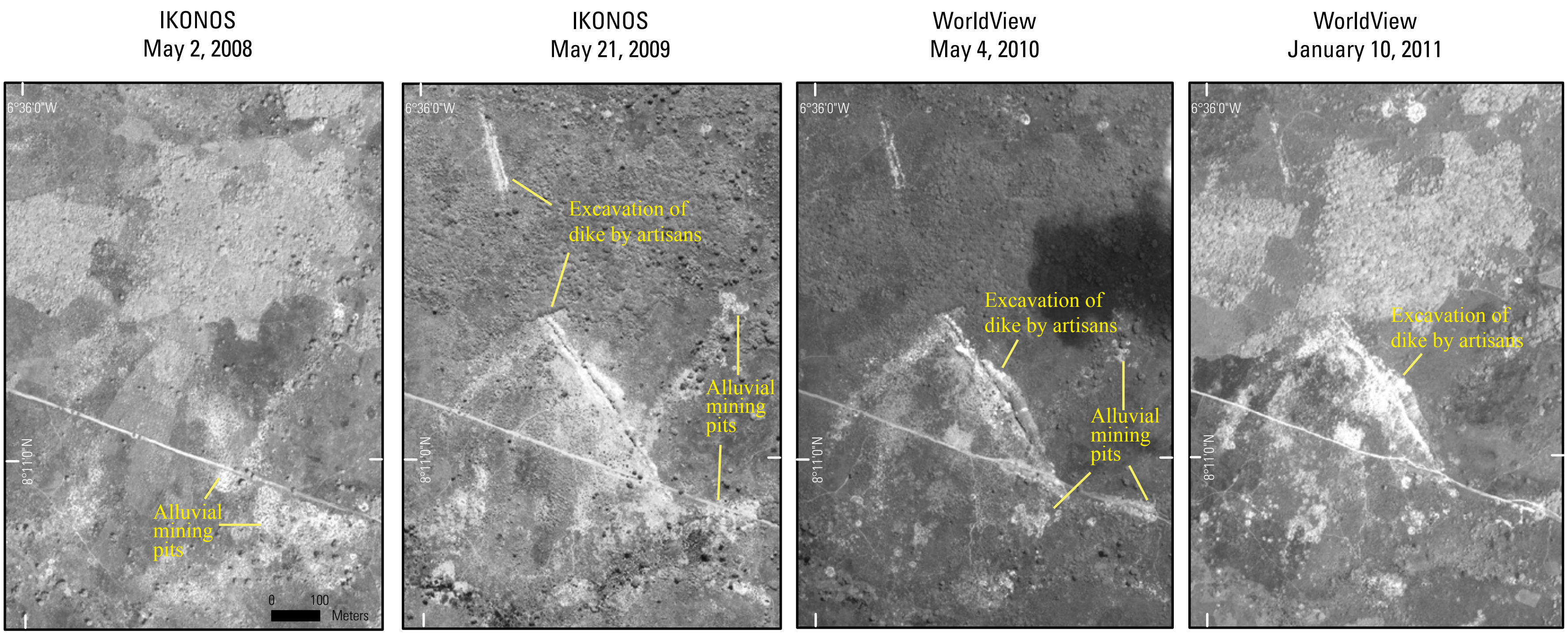


Figure 7. Satellite-image change detection of the Diarabana Dike. Satellite images courtesy of DigitalGlobe's IKONOS and WorldView satellites.

Figure 8. Aerial overflight photographs showing exploitation of the Diarabana Dike by artisanal miners in 2009. Photos courtesy of Noora Jamsheer, UNGoE.

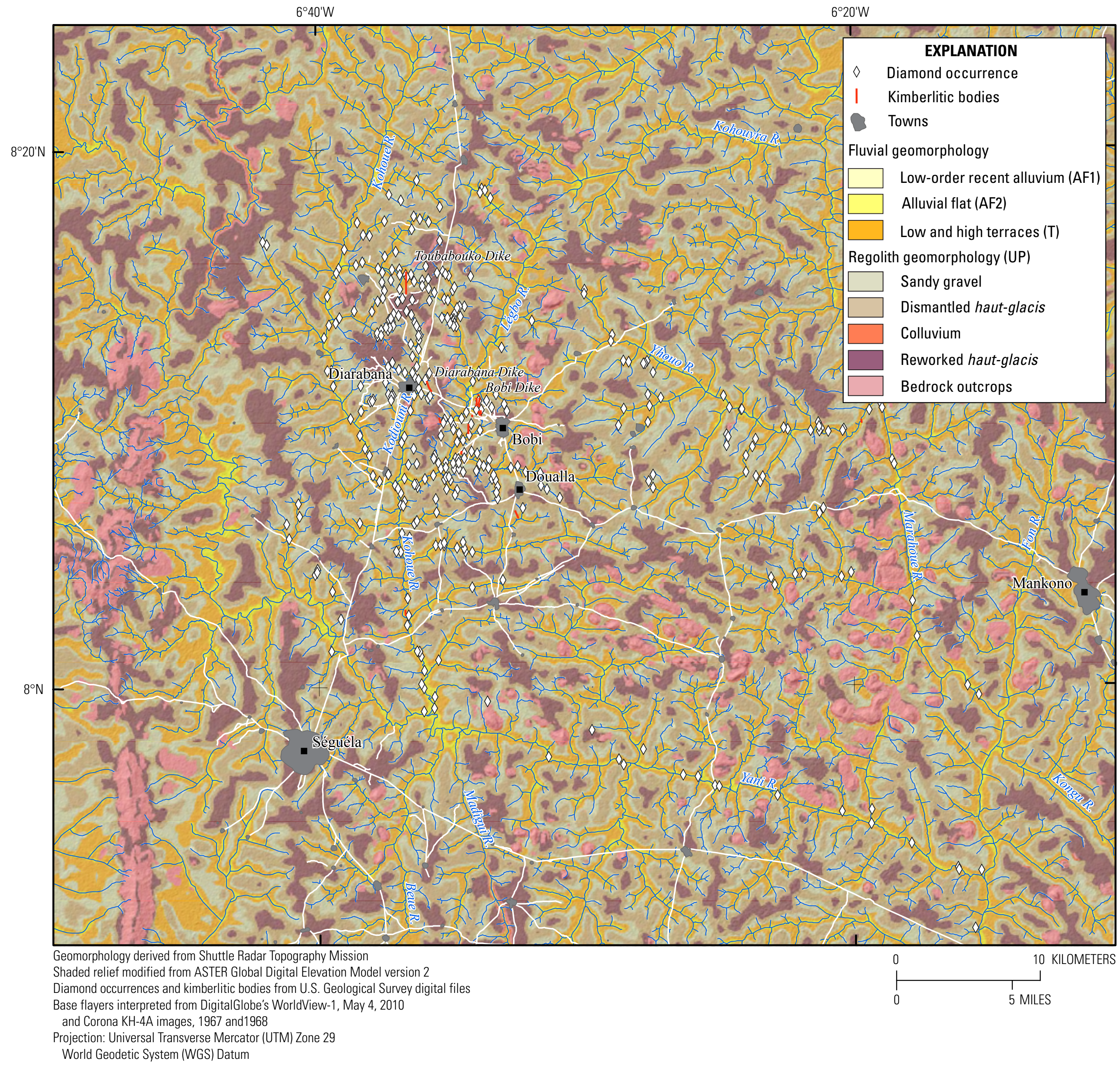


Figure 9. Geomorphic map of Séguéla, Côte d'Ivoire.

The Tortiya Deposits

The Tortiya Diamonds

The diamonds in the Tortiya deposits are well crystallized and of high quality, resembling those found in the Birim of Ghana, though they are in general larger and of better quality because they originate from a much larger detrital series and contain conglomerates absent in the Birim. Sixty percent are gem quality, and the diamonds are small, with 10 to 12 stones to the carat, though stones of 1 to 4 kt are not uncommon. The size of the stones decreases in general from north to south, from 4 to 5 stones per carat to 15 to 18 stones per carat (Bardet, 1974). The average grade of the alluvial deposits exploited by Waston and SAREMCI during 1963–1977 is around 0.25 kt/m^3.

Sources of the Tortiya Diamonds

The primary source of the Tortiya diamonds may have intruded as early as the Precambrian, during the Eburnean Orogeny (2.1–2 billion years ago) (Milési and others, 1992). However, the concentration of the currently mined placer deposits at Tortiya is the result of erosion and accumulation during the Quaternary (Teeuw, 2002). Since the Precambrian, the region has been affected by several periods of erosion in addition to the Eburnean Orogeny, namely the Pan African Orogeny (650–600 million years ago), the Ordovician glaciation (500 million years ago), and the opening of the Atlantic Ocean (200–100 million years ago). The Tortiya diamond fields are situated in Proterozoic metavolcanics and metasediments and occur among graywacke, schists, pelites, quartzites, arkoses, and conglomerates of the Birimian Supergroup. The diamond deposits in the Tortiya region can be found in eluvial, colluvial, alluvial, or alluvial/colluvial deposits, but the majority of the diamond concentrations are found within alluvial/colluvial deposits, most likely of Quaternary age, formed by the weathering, erosion, and reconcentration of older deposits. Most of the artisanal mining activity in the region has occurred within the Pekoua Creek drainage basin, along the valleys of the Pekoua Creek, which meets the River Bou at Tortiya (fig. 10). Arkosic conglomerate bedrock is thought to be the main host rock for the diamonds. Teeuw (2002) concludes that Tortiya's diamond deposits are not the result of extensive fluvial transport, because some of the associated mineral types would not have survived extensive weathering, and points to the fact that the diamonds have sharp crystal facets, indicating that there must be a more local source. Although it is possible that a portion of the diamonds were carried downstream during several different fluviatile cycles, some of the diamonds remained in the weathering zone. These eluvial deposits were further enriched and concentrated during a period of lateritization. This superficial lateritic gravel layer was originally exploited at a depth of about 2 m. However, concentrations of diamonds can also be found in desiccation cracks, which were filled with enriched deposits. A typical cross section of such a deposit would contain 1 m of sterile silt, up to 12 m of poorly enriched lateritic eluvium (0.20 kt/m^3), and 1 m of enriched gravel (up to 10 kt/m^3) at the base (Bardet, 1974). Similar desiccation cracks in the Birim diamond fields of Ghana also have been associated with enriched diamond concentrations (Teeuw, 2002).

Geomorphology of Tortiya

The geomorphology of the Tortiya study area is similar to that of Séguéla, because the region was affected by the same climatic events in the Quaternary which resulted in the erosion of the *cuirasses* and the subsequent redistribution of ferricrete debris. The relief of the Tortiya study area is dominated by extensive gently sloping interfluves, some of which are capped with ferricrete corresponding to the *haut-glacis*. Ferricrete caps are generally found at elevations of 360 m around Tortiya. These caps are remnants of what appears to be a once near-continuous ferricrete cover in Tortiya. The interfluves in the region can consist of partially eroded ferricrete plateaus and mesas, or areas of exposed bedrock corestones in which the ferricrete was completely eroded following saprolite erosion (Teeuw, 2002). The plateaus are more heavily ferruginized to the north of Tortiya, and they become less ferruginized further south, until little evidence of ferricrete caps remains. Outcrops and blocks of ferricrete materials can be found on the more dismantled plateaus (Poss, 1982). Additionally, there is evidence of recemented ferricrete at the base of most valley slopes (Teeuw, 2002).

As in the Séguéla region, Tortiya also has several distinct zones within the alluvial system, defined in this study as the alluvial flat zone and the terrace zone. These alluvial flats and terraces have the potential to be diamondiferous because diamonds are transported downstream from their secondary source rocks, so these flats and terraces were modeled as part of this study. The surrounding geomorphic zones also were modeled, using the same regolith zones applied to the Séguéla study area (with the exception of the granite outcrops), because the geomorphic landscapes are very similar. The regolith was separated into classes of gravelly sand, dismantled *haut-glacis*, colluvium, and reworked *haut-glacis* (fig. 11).

The large hill pictured above consists of mine tailings from 1960s- and 1970s-era industrial mining operations conducted by SAREMCI in Tortiya, Côte d'Ivoire. Photo by Pete Chirico, U.S. Geological Survey.

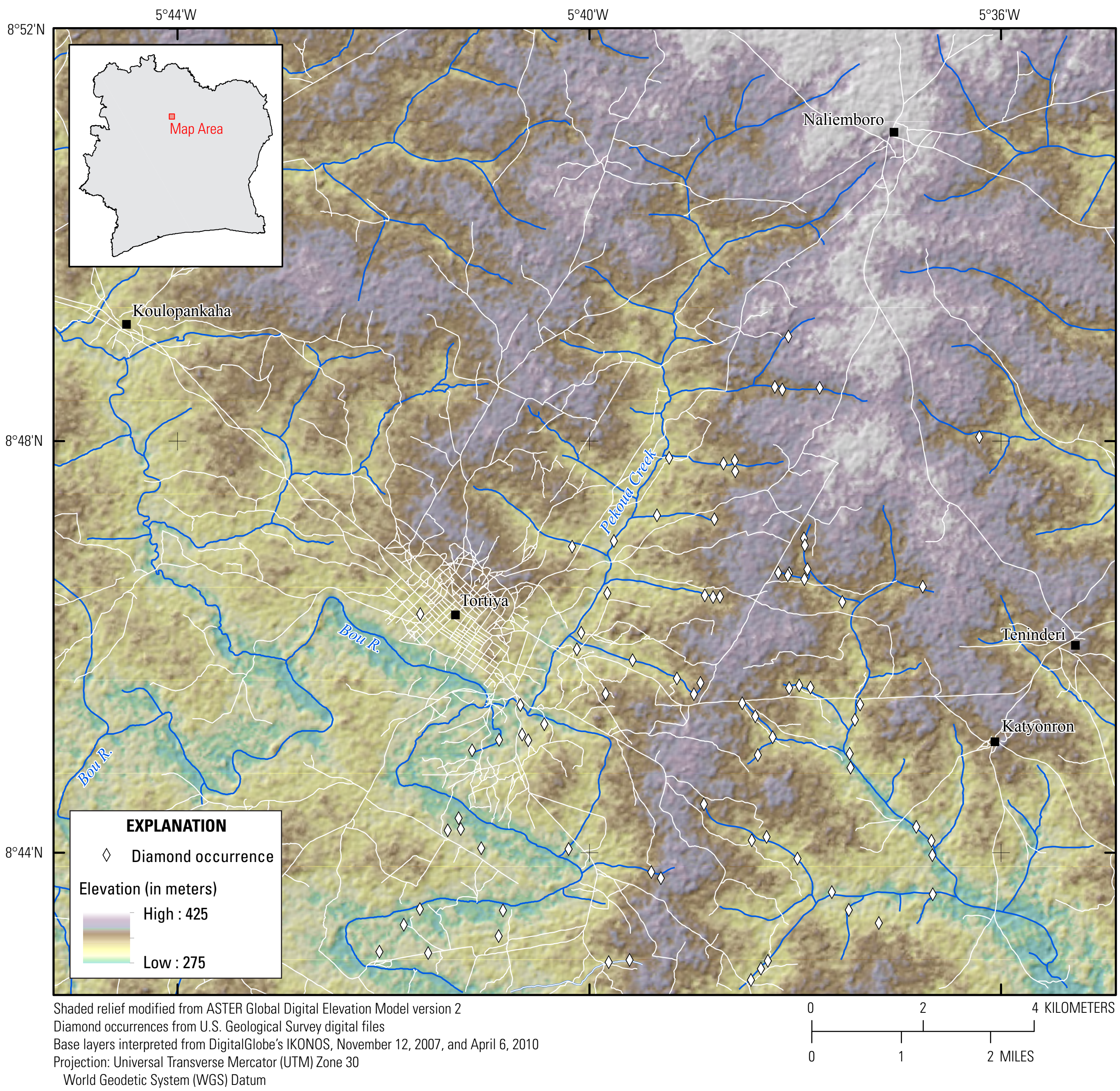


Figure 10. Topographic map of the Tortiya, Côte d'Ivoire, study area showing diamond occurrences.

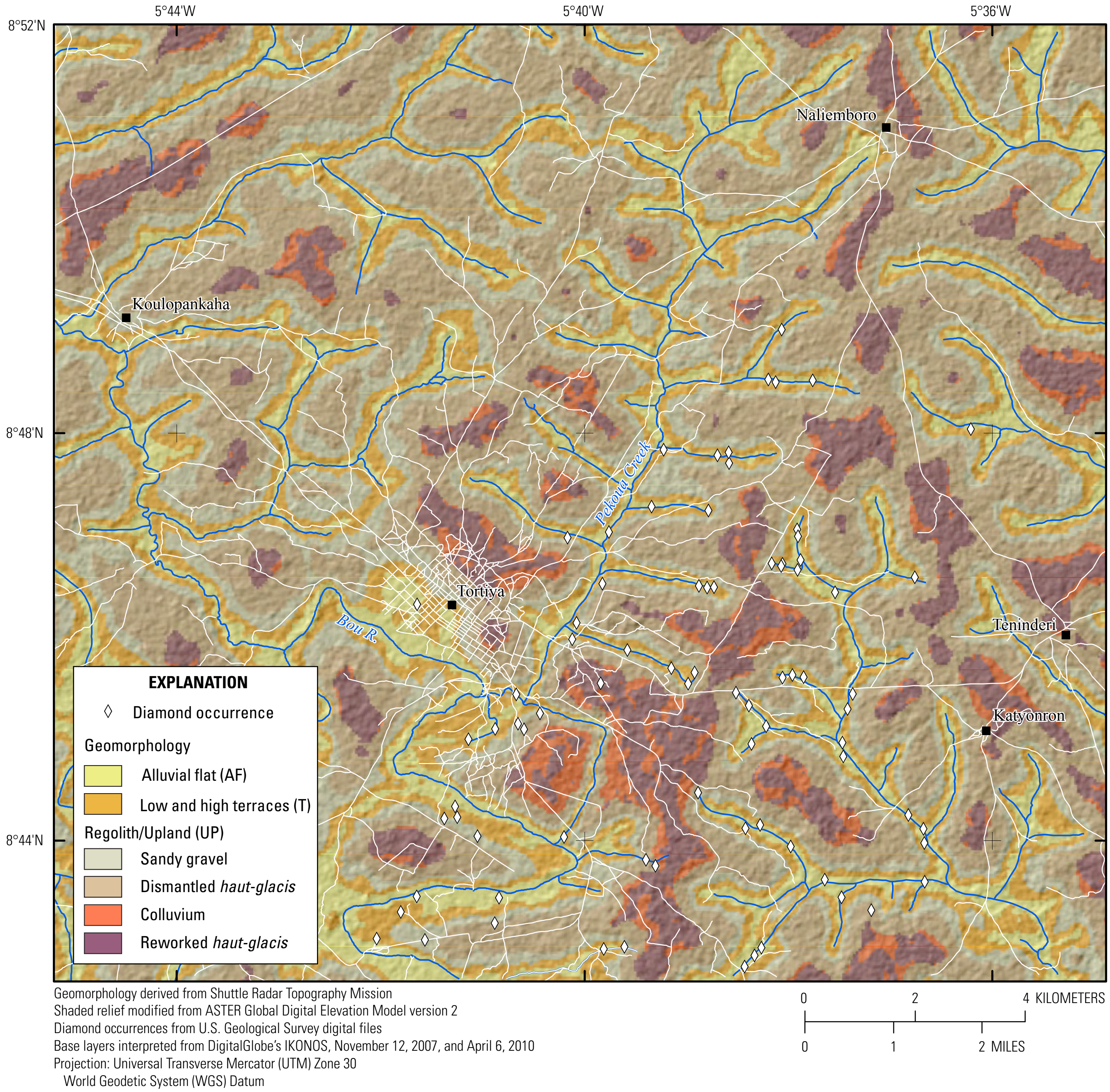


Figure 11. Geomorphic map of Tortiya, Côte d'Ivoire.

Potential Diamond Deposits in the Haut Nzi Area

In 1958, SAREMCI found several diamond occurrences along the upper, or "Haut," Nzi River (Knopf, 1970). SODEMI began prospecting along the northern reaches of the Haut Nzi River in the early 1960s. In 1963, several diamond occurrences were noted, grouped between the Katiola-Dabakala and Ngolodougou-Kong roads (fig. 12). The stones recovered there closely resembled those found in Séguéla, suggesting that they too originated from kimberlites. Over the next several years, the Direction de la Géologie et de la Prospection Minière de la Côte d'Ivoire (DGPM) and the BRGM searched for the source of the known diamond occurrences. During this process, SODEMI sampled the alluvium of 102 test pits. In 1964, kimberlitic magnesian illmenite was discovered along the right bank of the Haut Nzi River, roughly 20 km from the town of Katiola (SODEMI, 1964). In 1967, a team from the Compagnie Générale de Géophysique found a kimberlitic pipe, oriented 130–140° with a weak inclination (5–10°). It is largely made up of gray clay composed of kaolinite and montmorillonite and is very rich in magnesian illmenite. The BRGM also studied the Nzi fault, which is a large zone of 1–2 km imposed on a convex fold of schistose and arkosic rocks to the west and granitized parametamorphites to the east (SODEMI, 1967). The BRGM defined the Nzi diamondiferous zone as being within a 32- by 15-km rectangle in which the river recuts the Nzi conglomerate several times (SODEMI, 1965). Although diamond occurrences have been found along the Haut Nzi River, no alluvial concentrations have yet been discovered. However, it is likely that artisanal miners have done some small-scale exploitation of the diamondiferous zone. The discovery that the Haut Nzi River drains a kimberlitic field suggests that these deposits may be worth further scientific investigation.

Database Development

Isolated occurrences of alluvial diamonds have been recorded throughout the country. Diamonds have been found in central Côte d'Ivoire along the Bandama, Bandama Blanc, and Nzi Rivers, along the northern border with Burkina Faso, on the Komoé River, as well as in the southeast along the Agnbey River and southern reaches of the Komoé River. However, the diamond fields of Séguéla and Tortiya are the only currently mined deposits and as such are the focus of this assessment.

Basic Research and Bibliographic Study

This study involved the research, collection, and organization of all available data related to diamond resources and production in Séguéla and Tortiya. Reports completed by SODEMI in the 1960s, 1970s, and 1980s, annual production reports by the Direction des Mines et de la Géologie from 1969 through 1975, geologic and minerals maps, as well as SODEMI maps documenting the locations of prospected zones and deposits, were collected during the research phase. Any data on the location of occurrences, the geomorphology of the deposits (in particular, the thickness of the gravel and overburden layers), the grade of the deposits, and production figures were collected and cataloged in a GIS database. This database was used to create maps of the diamond-mining areas and to focus the analysis on the most intensively mined zones within Séguéla and Tortiya. Additionally, a detailed database cataloging previous mining activities in the Séguéla region by SODEMI and Waston was compiled from a 1:50,000-scale map produced by Waston in 1974 (Loukou, 1974) and a 1:10,000-scale map of the Bobi-Diarabana area produced by SODEMI in 1978.

Development of Base Map and Topographic Datasets

High-resolution satellite imagery was used to create base-map data within the Séguéla and Tortiya study areas. A hierarchy of images at varying scales and coverages was used to create a base-map dataset comprising primary and secondary roads, rivers and streams, lakes, and villages. Base-map data were digitized at a scale of 1:10,000 for the most intensively mined area of the Séguéla region (225 km² in area), located south and east of the town of Diarabana, by using a 1-m-resolution panchromatic image collected by DigitalGlobe's WorldView-1 satellite. A 1:25,000-scale database was completed for the remainder of the 5,000-km² study area by using a series of 2.75-m-resolution images collected by the Corona KH-4A satellite in 1967 and 1968. A 2011 Landsat image was used to geographically register the WorldView and Corona images. In the Tortiya study area, a 3-m-resolution multispectral IKONOS image collected on April 6, 2010, and a 1-m-resolution IKONOS image collected on November 12, 2007, were used to create base-map data at a scale of 1:25,000 for a 400-km² area.

In addition to the use of visible imagery, digital elevation models (DEMs) were employed to characterize the regional terrain and hydrologic network and to perform digital terrain mapping of the sites' geomorphology. For this phase of the analysis, a 50-m-resolution hydrologically enforced DEM was created by using the elevation values of a 90-m Shuttle Radar Topography Mission (SRTM) dataset and a streams-network database developed from high-resolution satellite imagery of the site. The elevation points and stream network were loaded into a topo grid algorithm in a GIS to derive a higher resolution topographic dataset which more accurately represents the rivers, streams, and ephemeral drainage channels of the region (Hutchinson, 1989).

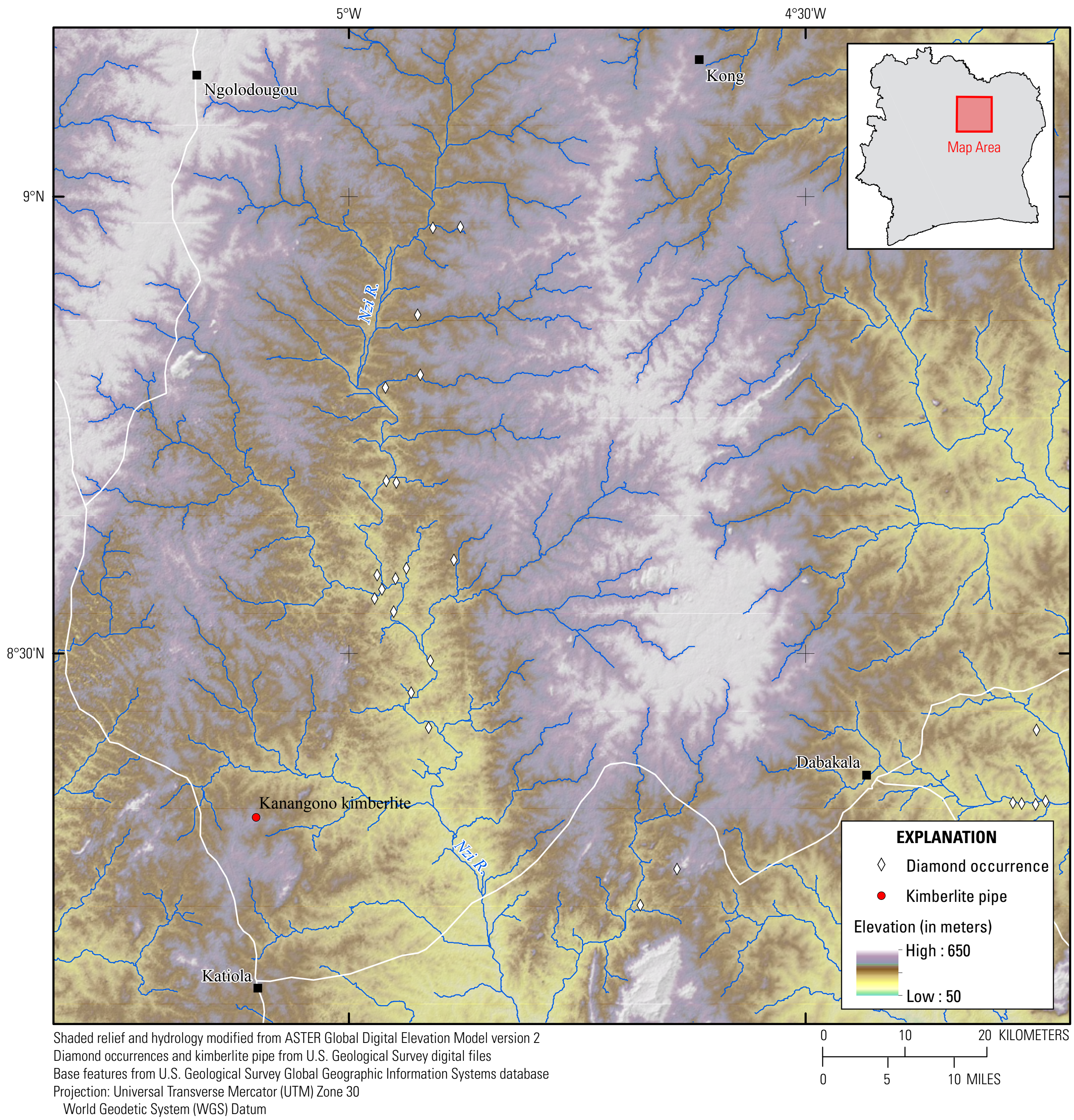


Figure 12. Topographic map of Haut Nzi, Côte d'Ivoire, showing locations of known diamond occurrences and a kimberlite pipe.

Fieldwork

Two separate fieldwork missions were conducted in Côte d'Ivoire. The first took place September 23–28, 2012, and was a joint mission of the USGS, WGDE, UNGoE, and the European Commission Joint Research Centre (JRC). The fieldwork consisted of a helicopter overflight of the Séguéla region and 3 days on the ground in Séguéla to assess the activity levels of artisanal miners in Diarabana, Bobi, Fourouna, and Doualla. The second mission took place February 19–24, 2013, and included members of the USGS and UNGoE. During this trip, diamond mining sites in the Séguéla and Tortiya regions were visited (figs. 13 and 14).

The goal of the fieldwork missions was to map in detail active and inactive alluvial and primary diamond mining sites. As part of the data-collection process, the team interviewed artisanal miners and local GVCs. A number of geologic sediment samples were also collected at several artisanal mining pits, and the analysis of these samples is currently underway. The data collected during the field exercises assisted researchers in assessing the accuracy of the satellite-image interpretation methods used in this study and the production-capacity estimates of artisanal mining in the region.

Modeling

Watershed Analysis and Alluvial Modeling

It is important to note that the watersheds within the Séguéla and Tortiya study areas are not equally endowed with diamond deposits. With regard to the Séguéla deposits, which originate from primary kimberlitic rocks, examining only those watersheds with a known diamond occurrence would not account for the fact that the diamonds were originally transported downstream from their source rocks, passing through watersheds upstream of their current locations. These upstream watersheds have the potential to be diamondiferous and must be represented in the analysis. In order to most accurately model Séguéla's diamondiferous watersheds, two categories of watersheds were developed: "diamondiferous" watersheds and "potentially diamondiferous" watersheds (fig. 15). The diamondiferous watersheds were defined on the basis of a known diamond occurrence, whereas the potentially diamondiferous watersheds are those contributing watersheds located upstream of the diamondiferous watersheds. The Strahler stream-order system was used to define the watershed boundaries and establish the relationship of the diamondiferous watersheds and the upper-reach watersheds. Specifically, these watersheds were created using streams of Strahler order 2 and higher. For the Tortiya region, watersheds with a known diamond occurrence were labeled as diamondiferous, and several watersheds upstream of the Pekoua Creek, which is cited in the literature as being diamondiferous throughout its extent, were labeled as potentially diamondiferous. Other watersheds upstream of the diamondiferous watersheds were not included in the analysis because these diamonds originated from secondary-source local bedrock and not kimberlitic bodies (fig. 16). Furthermore, Teeuw (2002) believes the Tortiya deposits have not traveled far from their sources. Examination of the deposits in relation to their stream order supports Teeuw's theory, because most of the deposits are located in order 1 streams.

Alluvial zones were then derived for the extent of the diamondiferous and potentially diamondiferous watersheds of Séguéla and Tortiya. For the Séguéla region, low-order recent alluvium, alluvial flats, terraces (low and high), and regolith were defined by using a relative relief model of the terrain above the base flow of the closest river segment. For the Tortiya region, the alluvial flats, terraces, and regolith were defined, following the same method.

Geomorphic Modeling

The five regolith geomorphic zones distinguished for the Séguéla study area were derived by using previously published geomorphic maps, 30-m-resolution Landsat imagery, a relative DEM (elevation above base streamflow), and a slope dataset. To begin, the relative DEM was reclassified into four classes: 0–5 m, 5–10 m, 10–20 m, and 20–232 m elevation; and the slope model was reclassified into three classes: 0–2°, 2–5°, and 5–30° slope. These elevation and slope ranges were identified as corresponding to the alluvial flat, low terrace, high terrace, and upland zones based on historical topographical maps and high-resolution satellite imagery. By using raster mathematical processing, the reclassified relative elevation and slope datasets were added together, forming 12 new classes. By using a geomorphic map of the region by Avenard (1977), each of the 12 classes was attributed according to 5 regolith geomorphic zones present in the region: gravelly sand, dismantled *haut-glacis*, colluvium, reworked *haut-glacis*, and granite outcrops. Once each class was assigned a regolith zone, the dataset was reclassified so that each of the original 12 classes was assigned a new numerical value based on its corresponding regolith zone.

The Séguéla region is underlain with granite, and throughout the landscape granite outcrops or inselbergs are evident. Not all of the granitic outcrops were identified by the relative DEM and slope model, so additional outcrops were digitized by using 30-m-resolution Landsat data and converting it to a raster layer, to be combined with the outcrops defined by the model. The final component of the model was the alluvial-zone analysis consisting of the low-order recent alluvium, alluvial flats, and terraces. The alluvial zones, granite outcrops, and regolith zones were then mosaicked together in the GIS to produce the final comprehensive model containing eight classes: low-order recent alluvium, alluvial flats, terraces, gravelly sand, dismantled *haut-glacis*, colluvium, reworked *haut-glacis*, and granite outcrops (fig. 9).

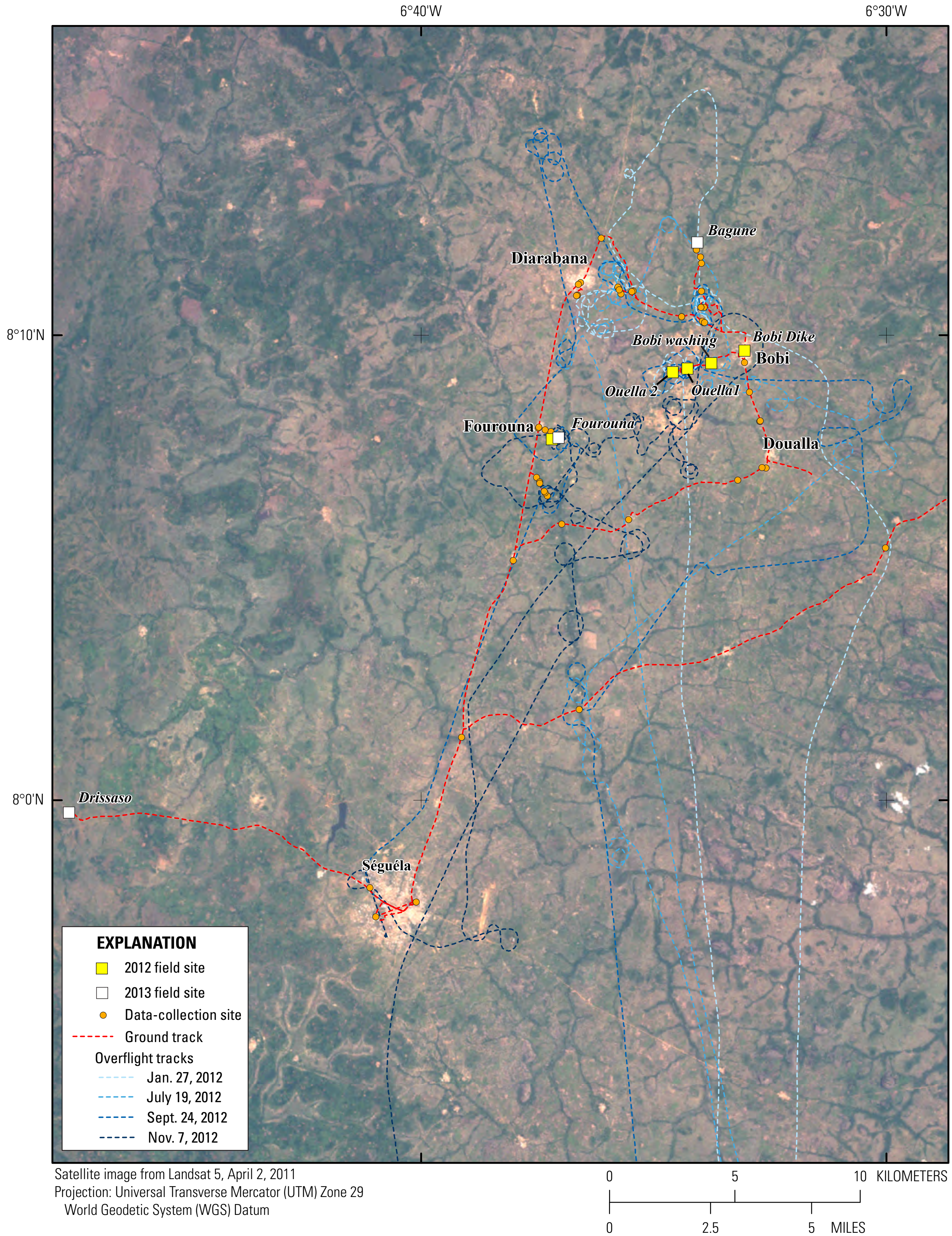


Figure 13. Field sites visited in the Séguéla region, Côte d'Ivoire.

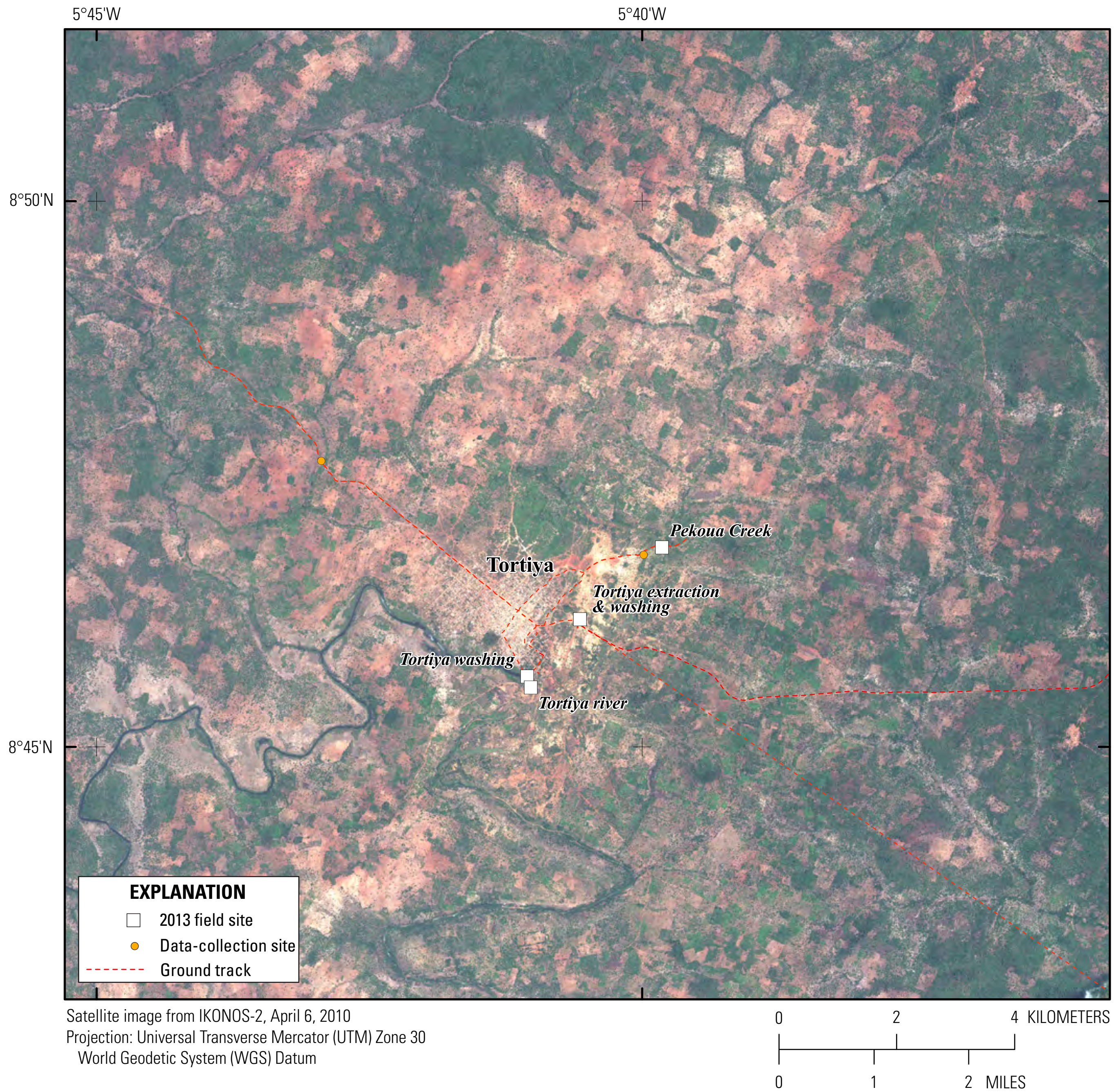


Figure 14. Field sites visited in the Tortiya region, Côte d'Ivoire.

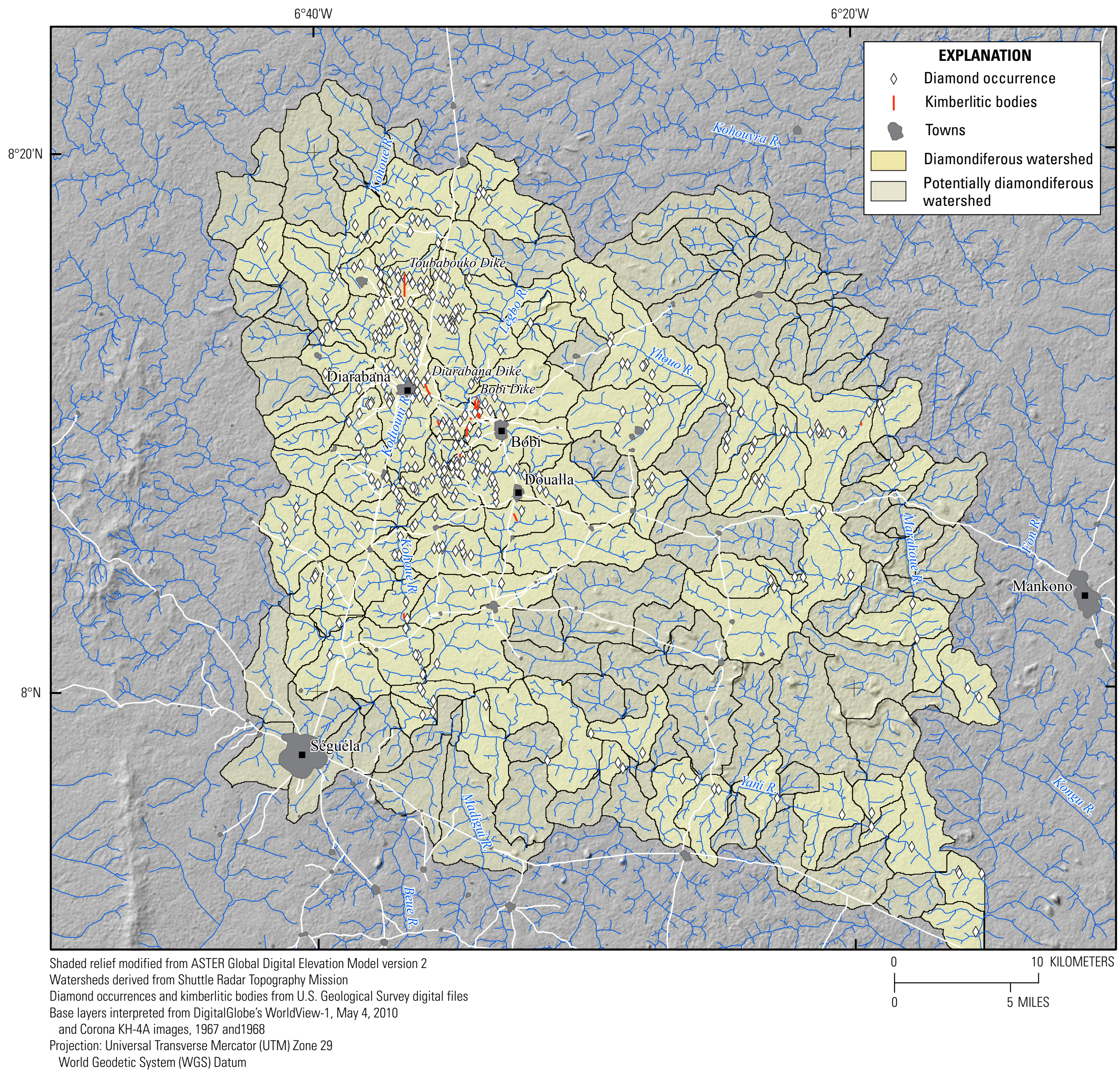
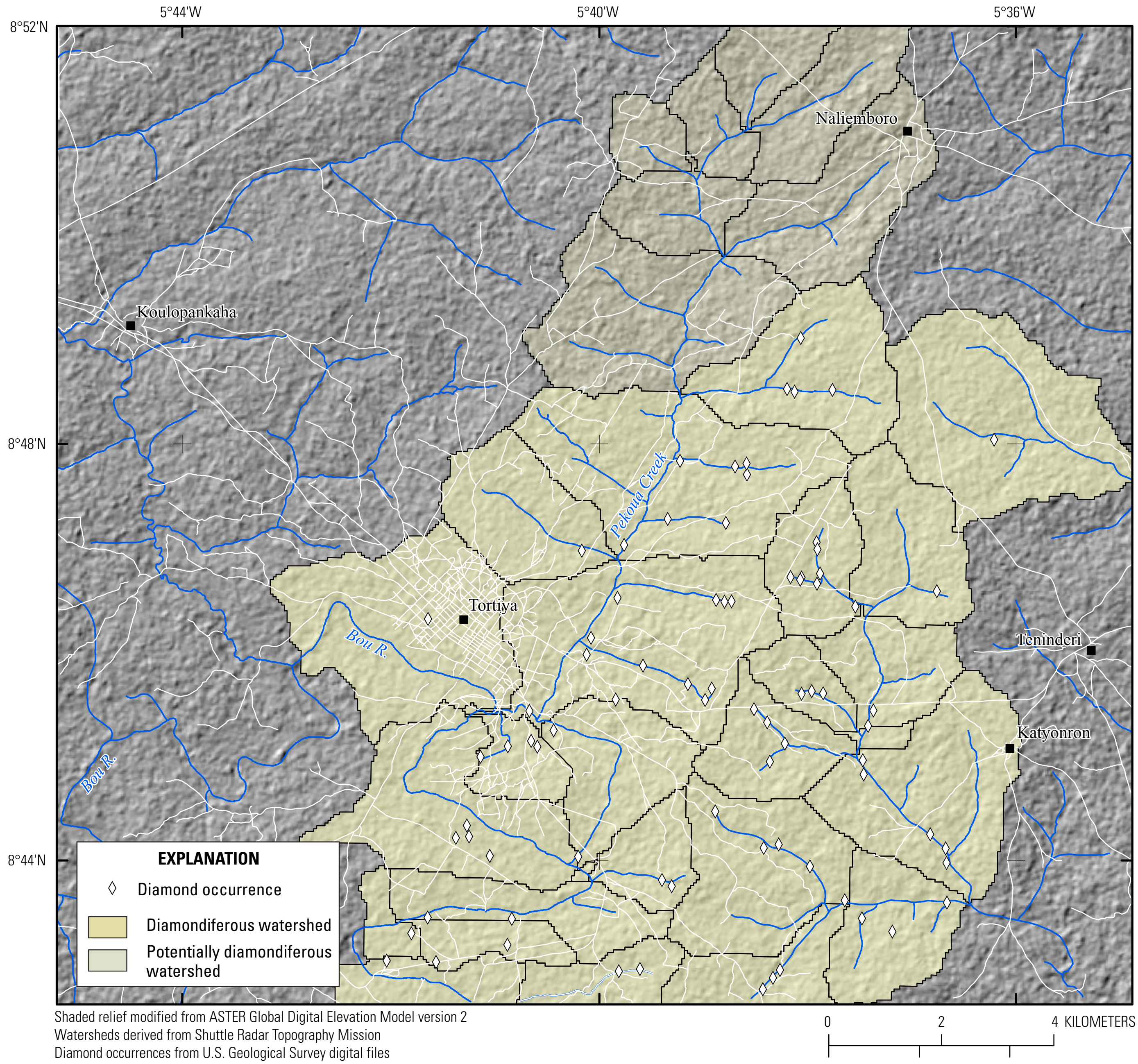


Figure 15. Diamondiferous and potentially diamondiferous watersheds in the Séguéla, Côte d'Ivoire, study area.



Shaded relief modified from ASTER Global Digital Elevation Model version 2
Watersheds derived from Shuttle Radar Topography Mission
Diamond occurrences from U.S. Geological Survey digital files
Base layers interpreted from DigitalGlobe's IKONOS, November 12, 2007, and April 6, 2010
Projection: Universal Transverse Mercator (UTM) Zone 30
World Geodetic System (WGS) Datum

Figure 16. Diamondiferous and potentially diamondiferous watersheds in the Tortiya, Côte d'Ivoire, study area.

A similar method was used to create the geomorphic model of the Tortiya study area. The relative elevation and slope classes were reclassified into four and three classes, respectively. The relative elevation classes were 0–5 m, 5–10 m, 10–20 m, and 20–47 m, whereas the slope classes were 0–2°, 2–5°, and 5–10°. These two reclassified datasets were added together by using raster mathematical operators, and, as with Séguéla, 12 new classes were produced. By using previously published geomorphic reports by Teeuw (2002) and Poss (1982), 4 regolith zones were identified and assigned to the 12 classes: gravelly sand, dismantled *haut-glacis*, colluvium, and reworked *haut-glacis*. Once this dataset was reclassified according to the regolith zones, it was mosaicked together with the alluvial model of Tortiya. The final model for the Tortiya study area contains the following six classes: alluvial flats, terraces, gravelly sand, dismantled *haut-glacis*, colluvium, and reworked *haut-glacis* (fig. 11).

Estimating the Alluvial Diamond Resource Potential of Séguéla and Tortiya

Volume and Grade Approach

A methodology developed by Barthélémy and others (2006) for the independent verification of alluvial diamond resources was modified for this study to calculate the diamond resource potential of Séguéla and Tortiya. The original methodology, first applied by the BRGM in an assessment of the diamond deposits of the Republic of the Congo, is known as the volume and grade approach and is expressed mathematically as $P = (V \times T1) + (1/3V \times T2)$, where P is the estimated diamond resource potential, V is the total volume of the alluvium, $T1$ is the basic grade of the deposit which is applied to the whole volume, and $T2$ is the concentration grade of the deposit, applied to a fraction of the volume. The volume of the deposit is calculated by multiplying the surface area of each of the geomorphic zones by their respective gravel thicknesses. Two gravel grades are used in the formula to account for variations in depositional history, which lead to an unequal distribution of diamonds. The basic grade is applied to the entire volume of alluvial gravels and is determined on the basis of previous field observations, whereas the concentration grade is applied to a fraction of the gravels. The fraction to which the concentration grade is applied varies across study areas and is based on the unique characteristics of the deposits (Barthélémy and others, 2006).

Modified Volume and Grade Approach

The volume and grade approach was modified to more accurately model the characteristics of the Séguéla and Tortiya deposits. For the Séguéla region, the modified approach is expressed mathematically as $P = (0.90V \times T1) + (0.1V \times T2)$. $T1$ is the basic grade, which was applied to 90 percent of the total alluvial volume, whereas $T2$ is the concentration grade, applied to 10 percent of the total alluvial volume. The concentration grade for each of the geomorphic zones was calculated on the basis of 25 grade values reported during SODEMI pit sampling at Séguéla and 20 average grade values reported by SODEMI between the years 1963 and 1988. SODEMI pit sampling also revealed that 8 percent of their sampled pits were diamondiferous. However, many of these pits were further downstream from the kimberlites, in areas that would be expected to be less diamondiferous. Therefore, a slightly higher value of 10 percent of the alluvium was deemed to have a concentration grade, because mineralization is likely to increase closer to the kimberlitic bodies. The basic grade values were applied to the remaining 90 percent of the alluvium.

The grade and gravel thickness values attributed to each geomorphic zone differed for Séguéla and Tortiya. In Séguéla, low-order alluvium (AF1) was calculated to have an average basic grade of 0.08 kt/m^3 and an average concentration grade of 0.2 kt/m^3, alluvial flats (AF2) were calculated to have an average basic grade of 0.1 kt/m^3 and an average concentration grade of 0.3 kt/m^3, and terraces (T) were calculated to have an average basic grade of 0.05 kt/m^3 and an average concentration grade of 0.15 kt/m^3. Gravel thicknesses in Séguéla were estimated to be 0.2 m, 0.8 m, and 0.2 m for AF1, AF2, and T, respectively. In Tortiya, alluvial flats were estimated to have an average basic grade of 0.1 kt/m^3 and a concentration grade of 0.3 kt/m^3, whereas terraces were estimated to have an average basic grade of 0.05 kt/m^3 and a concentration grade of 0.2 kt/m^3. Gravel thicknesses in Tortiya were estimated to be 0.7 m and 0.4 m for alluvial flats and terraces, respectively. The modified volume and grade formula was used to calculate the total remaining reserves both within Séguéla and Tortiya's diamondiferous zones, as well as within the potentially diamondiferous zones.

Results of the Modified Volume and Grade Approach

Resource potential as calculated via the modified volume and grade approach amounts to approximately 23,600,000 kt in the Séguéla study area and approximately 2,600,000 kt in the Tortiya study area (table 2). However, it is necessary to subtract from these figures the number of previously mined carats. A total of 15,000,000 kt are estimated to have been mined from the region since production began in the 1940s. It was then estimated that 90 percent of this production came from Séguéla and 10 percent came from Tortiya. Therefore, the total remaining resources in Séguéla and Tortiya are estimated to be approximately 10,100,000 kt and 1,100,000 kt, respectively. In both regions, the majority of the resources are within the alluvial flat deposits, because the volume of gravel is greatest and the grade is highest in these deposits.

Table 2. Results of the modified volume and grade approach as applied to Séguéla and Tortiya.

[m^2, square meter; m, meter; m^3, cubic meter; kt, carat; kt/m^3, carat per cubic meter]

Geomorphic zone	Total surface area (m^2)	Average gravel thickness (m)	Total alluvial volume (m^3)	Volume of concentration grade deposit (m^3) (10% of total alluvial volume)	Concentration grade (kt/m^3)	Concentration grade reserves (kt) (10%)	Volume of basic grade deposit (m^3) (90%)	Basic grade (kt/m^3)	Basic grade reserves (kt)	Total reserves (kt)
				Séguéla diamondiferous watersheds						
Alluvial flat 1	36,470,000	0.2	7,294,000	729,400	0.2	145,880	6,564,600	0.08	525,168	671,048
Alluvial flat 2	104,587,500	0.8	83,670,000	8,367,000	0.3	2,510,100	75,303,000	0.1	7,530,300	10,040,400
Terrace	213,252,500	0.2	42,650,500	4,265,050	0.15	639,758	38,385,450	0.05	1,919,273	2,559,030
Subtotal						3,295,738			9,974,741	13,270,478
				Séguéla potentially diamondiferous watersheds						
Alluvial flat 1	25,847,500	0.2	5,169,500	516,950	0.2	103,390	4,652,550	0.08	372,204	475,594
Alluvial flat 2	80,185,000	0.8	64,148,000	6,414,800	0.3	1,924,440	57,733,200	0.1	5,773,320	7,697,760
Terrace	180,980,000	0.2	36,196,000	3,619,600	0.15	542,940	32,576,400	0.05	1,628,820	2,171,760
Subtotal						2,570,770			7,774,344	10,345,114
Total reserves										**23,615,592**
Estimated previously mined reserves										**13,500,000**
Total calculated reserve remaining										**10,115,592**

Geomorphic zone	Total surface area (m^2)	Average gravel thickness (m)	Total alluvial volume (m^3)	Volume of concentration grade deposit (m^3) (10% of total alluvial volume)	Concentration grade (kt/m^3)	Concentration grade reserves (kt) (10%)	Volume of basic grade deposit (m^3) (90%)	Basic grade (kt/m^3)	Basic grade reserves (kt)	Total reserves (kt)
				Tortiya diamondiferous watersheds						
Alluvial flat	18,062,500	0.7	12,643,750	1,264,375	0.3	379,313	11,379,375	0.1	1,137,938	1,517,250
Terrace	21,382,500	0.4	8,553,000	855,300	0.2	171,060	7,697,700	0.05	384,885	555,945
Subtotal						550,373			1,522,823	2,073,195
				Tortiya potentially diamondiferous watersheds						
Alluvial flat	4,750,000	0.7	3,325,000	332,500	0.3	99,750	2,992,500	0.1	299,250	399,000
Terrace	5,650,000	0.4	2,260,000	226,000	0.2	45,200	2,034,000	0.05	101,700	146,900
Subtotal						144,950			400,950	545,900
Total reserves										**2,619,095**
Estimated previously mined reserves										**1,500,000**
Total calculated reserve remaining										**1,119,095**
Total calculated reserve remaining: Séguéla and Tortiya										**11,234,687**

Estimating the Production Capacity of Séguéla and Tortiya

Production Capacity Analysis of Alluvial Deposits

Diamond production capacity refers to the current total number of carats that can be produced by means of current human and physical resources. The estimate of diamond production capacity does not reflect the possibility of the future introduction of new financial investment or improved exploration or mining techniques, nor does it model increases of human resources in the mining sector. Rather, it is a measure of the current state of the diamond-mining sector. Barthélémy and others (2006) developed the following formula to calculate alluvial diamond production capacity: $P_i = (Vm/d \times g)\, d \times A_i$, where P_i is the total current production capacity, Vm/d is the volume of material worked per digger per day, g is the average gravel grade, d is the total number of days a digger works per year, and A_i is the total number of diggers estimated to be actively mining diamonds.

Modified Alluvial Production Capacity Approach

In the study conducted by Barthélémy and others (2006) and subsequent studies by Chirico and others (2010a, b, c, and 2012), the majority of the data required to calculate production capacity were collected during multiple fieldwork missions to the study areas. Owing to the unstable political situation in Côte d'Ivoire over the past decade, researchers were unable to conduct fieldwork on a yearly basis; therefore, an alternative approach for measuring production capacity was developed and employed in this study. This approach can be expressed mathematically as $P_i = p(V \times g_c)$, where P_i is the total current production capacity; p is the total number of pits; V is the volume of material, calculated by multiplying the area by the gravel thickness; and g_c is the concentration grade of the deposit. The grades and gravel thicknesses applied to AF1, AF2, and T were the same as those used in the volume and grade approach calculations, averaged from the SODEMI reports. The grade and gravel thickness values applied to the regolith deposits (UP) were based on the SODEMI reports' estimates of Séguéla's primary deposits. These regolith deposits are mostly eluvial/primary dikes and blows and, therefore, their grade and gravel thicknesses are more similar to those of primary deposits than secondary alluvial deposits. This modified production capacity approach was based on manual satellite image interpretation of the two most intensively mined regions of Séguéla. The first region, Bobi/Diarabana, is approximately 140 km² in area and is south and east of the town of Diarabana. The second region, Toubabouko, is approximately 120 km² in area and is north and west of Diarabana (fig. 4). The results of the Bobi/Diarabana and Toubabouko analyses were then extrapolated to create a final production capacity analysis encompassing the entire Séguéla region.

Methodology for Identifying Alluvial Artisanal Pits in Satellite Imagery

In order to develop a consistent methodology for identifying and characterizing alluvial artisanal mine pits in satellite imagery, the USGS began collaborating with the JRC in May 2012. Prior to collaboration, the USGS and JRC had been working independently to assess mining activity in Côte d'Ivoire in support of the KP, using different satellite imagery interpretation methods and techniques. The two organizations began working together to develop a set of common image interpretation guidelines through data and methods sharing, and the combined strengths and expertise offered by both organizations led to the final methodology. The following description of the methodology for identifying alluvial pits is the end result of the USGS–JRC collaboration.

Imagery for Pit Interpretation

The acquisition of appropriate resolution satellite imagery is essential for conducting a successful pit identification analysis. Of particular importance are the spatial resolution, which refers to the size of the pixels that make up an image, and the spectral resolution, which refers to the ability of the sensor to distinguish between wavelength intervals in the electromagnetic spectrum. Artisanal mine pits are often only several meters in dimension, and therefore imagery with a spatial resolution of 1 m or less may be needed to distinguish pits of this size. In terms of its spectral resolution, satellite imagery can be either panchromatic (grayscale) or multispectral (color). Whereas panchromatic data are typically of higher spatial resolution, the high spectral resolution of multispectral data provides an added level of detail, assisting with the identification of vegetation, spoil material piles, water saturation, and shadows. Table 3 lists detailed information on the high-resolution imagery used in this study.

Types of Alluvial Pits

Several different categories of artisanal mining pits were visible in the high-resolution imagery: active extraction pits, active exploration pits, gravel washing pits, inactive previously-mined exploration pits, and inactive previously-mined extraction pits. Several techniques were used to distinguish the different types of pits. In general, active extraction pits are identified in the imagery by a combination of several characteristics. First, active pits have the appearance of a bright rim of reflective sandy material and (or) nearby spoil material piles. Second, these pits have little or no water at the bottom. Third, active pits are generally greater than 4 m in diameter. Finally, large active pits in alluvial flats often exhibit

Table 3. Detailed information on the high-resolution imagery used in this study.

[GMT, Greenwich Mean Time; GSD, ground sample distance; m, meters. Acquisition date is in order of month/day/year]

Ground coverage	Satellite	Organization	Acquisition date (GMT)	Acquisition time (GMT)	GSD (m)	Spectral resolution	Coverage
Bobi/Diarabana	IKONOS-2	DigitalGlobe	3/6/2006	11:02	0.84/4	Panchromatic/ Multispectral	Stereo
Bobi/Diarabana	IKONOS-2	DigitalGlobe	3/6/3007	10:58	1/4	Panchromatic/ Multispectral	Stereo
Bobi/Diarabana	IKONOS-2	DigitalGlobe	12/14/2007	11:06	1/4	Panchromatic/ Multispectral	Mono
Bobi/Diarabana	IKONOS-2	DigitalGlobe	5/2/2008	11:05	1/4	Panchromatic/ Multispectral	Stereo
Toubabouko	IKONOS-2	DigitalGlobe	6/20/2008	10:51	1/4	Panchromatic/ Multispectral	Mono
Bobi/Diarabana	IKONOS-2	DigitalGlobe	5/21/2009	10:54	1	Panchromatic	Stereo
Bobi/Diarabana	WorldView-1	DigitalGlobe	5/4/2010	11:16	1	Panchromatic	Mono
Bobi/Diarabana	WorldView-1	DigitalGlobe	1/10/2011	11:19	0.5	Panchromatic	Mono
Bobi/Diarabana & Toubabouko	WorldView-1	DigitalGlobe	2/3/2012	11:22	0.5/2	Panchromatic/ Multispectral	Mono
Bobi/Diarabana	WorldView-2	DigitalGlobe	2/14/2013	11:15	0.51/2	Panchromatic/ Multispectral	Mono

some degree of organized sequential excavation, known as "benching." These benches are cut in a stepwise fashion, enabling deeper gravels to be exposed incrementally with less risk of sidewall collapse (fig. 17). However, not all active extraction pits exhibit benching characteristics, because many times the deposits are shallow enough that benches are not required. For example, small shallow pits do not require this technique, nor do some very deep pits which employ shaft and tunnel techniques as an alternative. Meanwhile, inactive extraction pits may be filled with water or show some degree of vegetation regrowth, depending on how recently the pit was abandoned. Additionally, abandoned square pits typically collapse after a period of time in response to precipitation and groundwater fluctuations, and they begin to resemble roughly circular shapes.

Exploration pits were defined as those that are 3 m or less in diameter. These pits often appear in clusters of several dozen to several hundred and are indicative of miners working individually or in small groups, searching for signs of mineral deposition. If diamonds are not found, the miner likely begins a new exploration pit nearby. This pattern of activity results in large, dense clusters of small pits, most often visible in terraces.

Washing and reservoir pits, while not directly contributing to production, are a part of the mining process and represent activity. Washing pits are abandoned extraction pits which have filled with water and are used by miners to wash newly extracted gravels or to rewash previously extracted gravels in search of small stones which may have been missed during the original washing phase (fig. 18). These pits are typically near active extraction pits and are often surrounded by gravel piles which have been transported to the pit for washing. It is also important to note that the act of washing gravel disturbs and mixes sediments in the water, giving the water a bright reflectance in the imagery. However, water color is not necessarily indicative of mining activities; other possible explanations for brightly reflected water include the collapse of sediments from the sides of pits or fluctuations in the water table or precipitation. Reservoir pits can also be used as part of the mining process, though they may not always be present at a mine site. These are abandoned pits adjacent to active extraction pits into which miners pump water accumulating in the active pit (fig. 19). Active pits can fill with water in response to precipitation or groundwater infiltration, and this water must be removed in order for extraction activities to continue.

Inactive extraction and exploration pits are formerly active pits which have since been abandoned by miners. Such abandonment typically occurs when the pit is no longer believed to be productive or has been completely mined out. Inactive pits show vegetative regrowth, are often filled with water, and resemble roughly circular shapes as sidewalls collapse over time. The degree to which these characteristics are visible depends on the length of inactivity. A recently inactive pit exhibits signs of minimal vegetative regrowth, sidewall collapse, or ponding of water. The classification of recently inactive pits is dependent both on the number of satellite images being analyzed within one season and the dates of the images. For example, if only one image is used to characterize the activity of a mining season, recently inactive pits would include

Figure 17. Example of an active extraction pit in Côte d'Ivoire.

Figure 18. Example of a washing pit in Guinea.

Figure 19. Example of a reservoir pit, adjacent to an active extraction pit, in Côte d'Ivoire.

those which were active any time from the start of the mining season to the date of image collection. If multiple images are available for the mining season being evaluated, recently inactive pits represent those which were active during the period between image collection. It is particularly important to include recently inactive pits in the analysis if the only available image was collected towards the end of the mining season. In such cases, many of the pits which were active during the early and mid-dry-season months may have been mined out by the time the image was collected. Therefore, it would be expected that a larger number of the pits would fall under the category of recently inactive than if the image had been collected at the beginning of the dry season.

Interpretation Criteria for Identifying Mining Activity

On the basis of the types of alluvial artisanal mine pits described above, the USGS and JRC developed a set of interpretation criteria for determining the activity level of any given identified pit. Specifically, eight principal criteria were agreed upon: presence of benching, percentage of pit rim lacking vegetation, size of the pit, presence of water, color of water if present, flooding of the pit, number of sharp-angled corners, and distance to the closest active extraction pit. A score system was developed to integrate these criteria. For each criterion, several values are possible. For example, water color (as seen in satellite imagery) can be black, blue/green, yellowish, or light yellow/white. Each of these values corresponds to a separate score. Everything else being constant, a higher score for a given variable corresponds to a higher chance that the pit in question is active, or (for inactive pits) corresponds to a shorter period of inactivity. Although other methodologies are possible, it is suggested here that the arithmetic sum of all scores can be used to derive an index of activity for each pit. For a given mining pit, once the correct score has been attributed for each criterion, all the scores are summed up and a decision can be made as to the activity level of the pit. For example, a large pit with benching, with no water (hence not flooded), with 2 or more sharp angles, and in close proximity to another active pit will get a score of 13 and therefore be considered an active pit per a decision rule given in Kauffmann and others (2013).

Accuracy Assessment of Pit Identification Methodology

In order to assess the accuracy of the image interpretation of active and inactive mining pits, based on the pit characteristics explained above, a methodology was developed by the USGS and JRC in which active pits were identified in several sets of aerial overflight and ground-based photographs which were geographically referenced against high-resolution satellite images. A set of aerial photographs collected on January 27, 2012, was used in conjunction with a satellite image collected on February 3, 2012. Given the temporal proximity of the aerial photography and satellite image pairs, the methodology is based on the assumption that pits identified as active in the aerial photographs were also active during the time of satellite image collection. The aerial photographs therefore can be used as a ground-truth dataset (fig. 20). The extents of 28 aerial photographs were located in the satellite image. Pits which had been identified as active in the satellite image were then located within their corresponding aerial photographs, and the activity level was reassessed on the basis of the aerial photographs.

In order to quantify the accuracy of the pit identification methodology, a classification error matrix was created (table 4). The matrix compares the results of the classification of pits in the aerial photographs to the results of the classification of pits in the satellite imagery, on a pit by pit basis. A producer's accuracy, user's accuracy, and overall accuracy were calculated for pits classified as being active extraction pits, washing pits, or inactive pits. The overall accuracy of the pit identification methodology is 94 percent. Of the 82 pits assessed, all of the washing pits were correctly identified, whereas there were three errors of omission (identifying a pit as inactive when it was active) and two errors of commission (identifying a pit as active when it was inactive).

Methodology for Estimating the Production Capacity of Séguéla's Alluvial Deposits

High-resolution imagery with coverage of the Bobi/Diarabana area was available for the years 2006–2010 and 2012–2013, whereas imagery with coverage of the Toubabouko area was available for the years 2008, 2012, and 2013 (table 3). The detailed methodology employed to reach the total alluvial production capacity for the Séguéla region had multiple steps. The first step involved manually cataloging all active extraction and washing pits with a diameter of 4 m or greater for each year with available imagery in the Bobi/Diarabana and Toubabouko areas. However, because it is difficult to reliably identify whether washing pits are active, they were not incorporated in the production capacity analysis. The next step was to estimate the number of 1- to 3-m pits for the two areas. The third step of the methodology involved estimating the number of pits in the remainder of the diamondiferous watersheds, because the Bobi/Diarabana and Toubabouko study areas only compose 36 percent of the total diamondiferous watersheds in Séguéla. The final step was to calculate the overall production capacity for the entire Séguéla study area.

Table 4. Classification error matrix showing the results of the accuracy assessment of the pit identification methodology.

	Reference data (aerial photographs, January 27, 2012)			
Classification data (satellite image, February 3, 2012)	**Active extraction (pits)**	**Washing (pits)**	**Inactive (pits)**	**Row total (pits)**
Active extraction (pits)	20	0	2	22
Washing (pits)	0	6	0	6
Inactive (pits)	3	0	51	54
Column total (pits)	23	6	53	82
Accuracy type	**Active extraction (%)**	**Washing (%)**	**Inactive (%)**	**Combined (%)**
Producer's accuracy[1]	87	100	96	94
User's accuracy[2]	91	100	94	95
Overall accuracy	94			

[1]A measure of errors of omission.

[2]A measure of errors of commission.

Satellite image from DigitalGlobe's WorldView-2, February 3, 2012
Aerial photographs courtesy of Simon Gilbert, UNGoE
Projection: Universal Transverse Mercator (UTM) Zone 29
World Geodetic System (WGS) Datum

Figure 20. A comparison of oblique aerial photography and a Worldview-2 satellite image. The Worldview-2 image, collected on February 3, 2012, shows the intense mining activities of artisanal miners in a flood plain in Séguéla. Oblique photography collected at the same site one week prior, on January 27, 2012, shows a detailed view of the active and inactive mining pits. *A*, Large inactive mining pit, which has now filled with water. *B*, Two previously mined pits that have filled with sedimented water, indicating that they were recently used for washing and sorting gravel. *C*, A recently abandoned pit with eroded headwalls that has not yet filled with water, indicating recent but completed activity. *D* and *E*, Large active mining pits with the headwalls visible where miners are in the process of excavating. The particularly bright reflectance of the recently removed spoil materials surrounding the pits in the satellite image is further evidence of the pits' activity. *F*, A cluster of small exploration pits in the low terrace geomorphic zone.

Manual Interpretation of Alluvial Mining Pits

All pits greater than 4 m in diameter (16 m² in area) were digitized for the years 2006–2010 and 2012–2013 for the Bobi/Diarabana area and for the years 2008, 2012, and 2013 for the Toubabouko area (fig. 21, 22, and 23). Each pit was attributed with a size, in increments of 5 m, based on the diameter of the pit. Each pit fell into one of six categories: 5 m, 10 m, 15 m, 20 m, 25 m, or >25 m. For example, pits with diameters ranging from 4 to 5 m were attributed with a "5," pits with diameters ranging from 6 to 10 m were attributed with a "10," etc. Each pit was also attributed with a geomorphic zone (AF1, AF2, T, or UP) based on the geomorphic model. Once the pits were cataloged and attributed for each year, a production capacity of 5- to >25-m pits was calculated for the years 2006–2010 and 2012–2013 for Bobi/Diarabana and for 2008–2010 and 2012–2013 for Toubabouko by using the equation $P_i = p(V \times g_c)$. Calculating production capacity was dependent on distinguishing the geomorphology and size of each pit. The pits were categorized first on the basis of their geomorphic zone (AF1, AF2, T, or UP). Within each geomorphic zone category, pits were then organized on the basis of the six size categories (5 m, 10 m, 15 m, 20 m, 25 m, or >25 m). The production capacity was based on the volume of the pits and the grade of the pits. Volume was calculated by multiplying the area of the pits (25 m^2, 100 m^2, 225 m^2, 400 m^2, 625 m^2, or >625 m^2) by the gravel thickness of their respective geomorphic zone (0.2 m for AF1, 0.8 m for AF2, 0.2 m for T, and 1 m for UP). Grade was calculated on the basis of geomorphic zone (0.2 kt/m^3 for AF1, 0.3 kt/m^3 for AF2, 0.15 kt/m^3 for T, and 1 kt/m^3 for UP) and was multiplied by the volume to arrive at the number of carats per pit ($(V \times g_c)$). The number of pits per size category within each geomorphic zone was calculated to arrive at p. The final step was to multiply the number of pits by the number of carats per pit, to arrive at P_i. This calculation was performed for each year of available imagery, for both areas.

The production capacity was estimated for the years 2009–2010 for the Toubabouko area by comparing the 2008 Toubabouko production to the 2008 Bobi/Diarabana production and the 2012 Toubabouko production to the 2012 Bobi/Diarabana production. By doing so, it was calculated that the Toubabouko production levels were 31 percent of the Bobi/Diarabana production levels for those two years. Therefore, the 2009 Toubabouko production capacity was estimated by multiplying the 2009 Bobi/Diarabana production capacity figure by 31 percent. The same method was applied to calculate the 2010 Toubabouko production capacity. It is also important to note that the 2013 imagery coverage for Toubabouko did not include the northern quarter of the study area; therefore, the estimated numbers of pits within this area were based on the percentage of 2008 and 2012 pits in that quarter.

Estimation of Exploration Pits

Although all 4 m or greater extraction pits were catalogued for each year, it was also important to account for the smaller, 1- to 3-m-diameter exploration pits. Though these pits are high in number, they are low in yield because they usually are dug in terrace deposits. All active 1- to 3-m exploration pits were cataloged in the Bobi/Diarabana area for the year 2006. Owing to their small size, these pits could not be accurately discerned in the subsequent images; therefore, the number of exploration pits was estimated in Bobi/Diarabana for the years 2007–2010 and 2012–2013 and in Toubabouko for the years 2008–2013. This was done by comparing the number of 2006 exploration pits to the number of 2006 extraction pits. By doing so, it was found that exploration pits make up 75 percent of the total number of pits in 2006. Therefore, the number of exploration pits was calculated for each subsequent year by adding 75 percent of the total number of pits to the total. This method was applied to the Bobi/Diarabana area for the years 2007–2010 and 2012–2013 and to the Toubabouko area for the years 2008, 2012, and 2013. To estimate the number of exploration pits in Toubabouko in 2009 and 2010, the number of exploration pits in Bobi/Diarabana for the corresponding years were multiplied by 31 percent, because Toubabouko production levels are 31 percent of the Bobi/Diarabana production levels. To calculate the production capacity of these pits, an average area of 5 m^2 was calculated. This area was multiplied by the terrace gravel thickness (0.2 m) to arrive at a volume of 1 m^3. Not all of the exploration pits are diamondiferous, and even the diamondiferous ones are of a low grade. Therefore, a grade of 0.075 kt/m^3 was applied to these pits. Production capacity was then calculated by multiplying the number of carats (volume times grade) by the number of exploration pits.

Estimating Production in Remaining Watersheds

The production capacity calculated for the Bobi/Diarabana and Toubabouko areas accounts for only 36 percent of the area of diamondiferous watersheds in the Séguéla, Côte d'Ivoire study area. By using the production capacity values calculated for the Bobi/Diarabana and Toubabouko watersheds, the production capacity was calculated for the remainder of the diamondiferous watersheds. As previously stated, the diamondiferous watersheds were defined as those with a known diamond occurrence. This diamond-occurrence database is based on records of occurrences in the literature, primarily found in SODEMI maps of Séguéla. Each diamondiferous watershed therefore has a record of at least one occurrence within its boundaries. To estimate the production capacity of the remaining diamondiferous watersheds, it was first necessary to estimate the number of active pits within them. A number of 5- to >25-m pits per occurrence was calculated for each year by examining the Bobi/Diarabana and Toubabouko watersheds that contained both active pits and occurrences

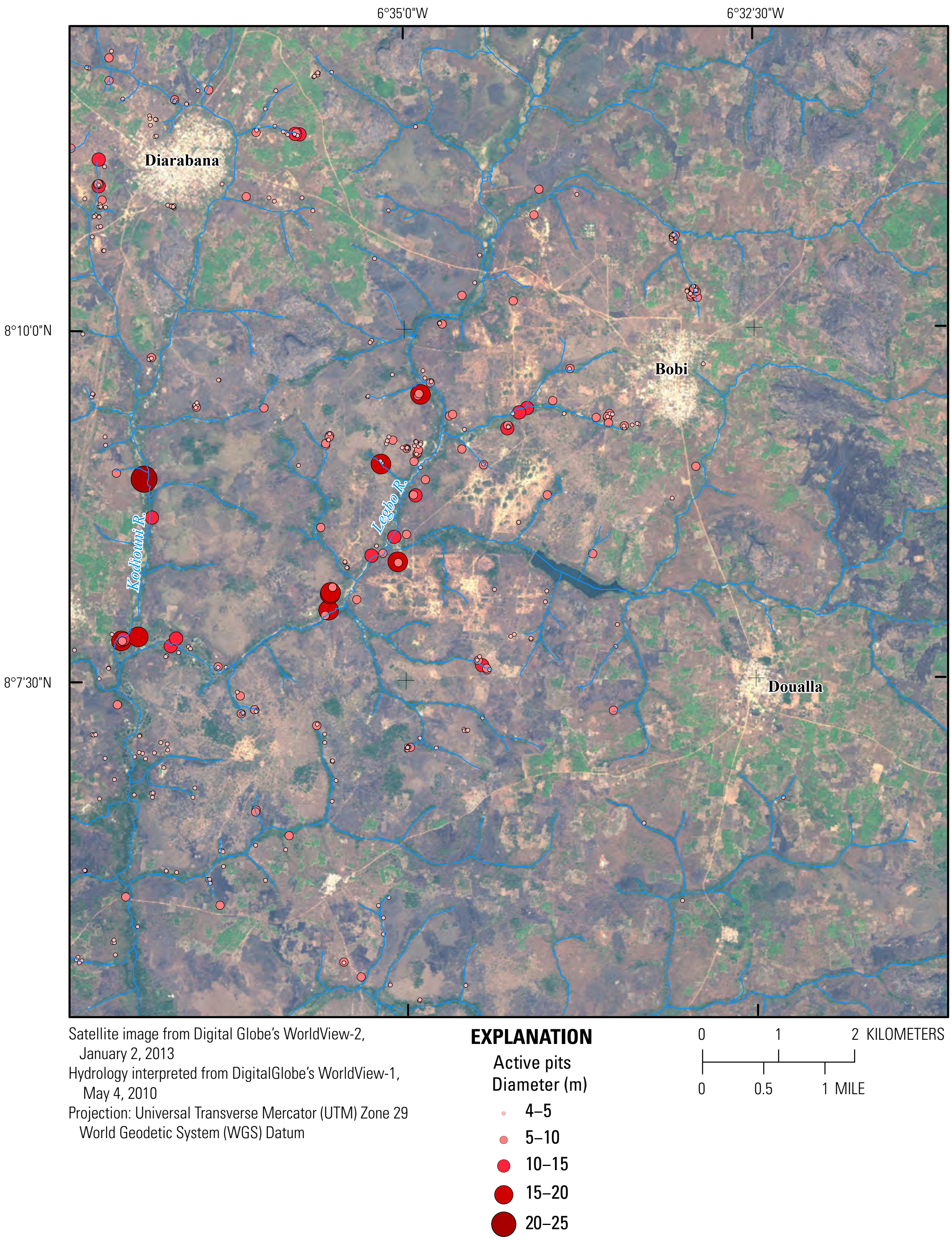


Figure 21. Number of 5- to 25-meter pits in the Bobi/Diarabana area of Côte d'Ivoire in 2013.

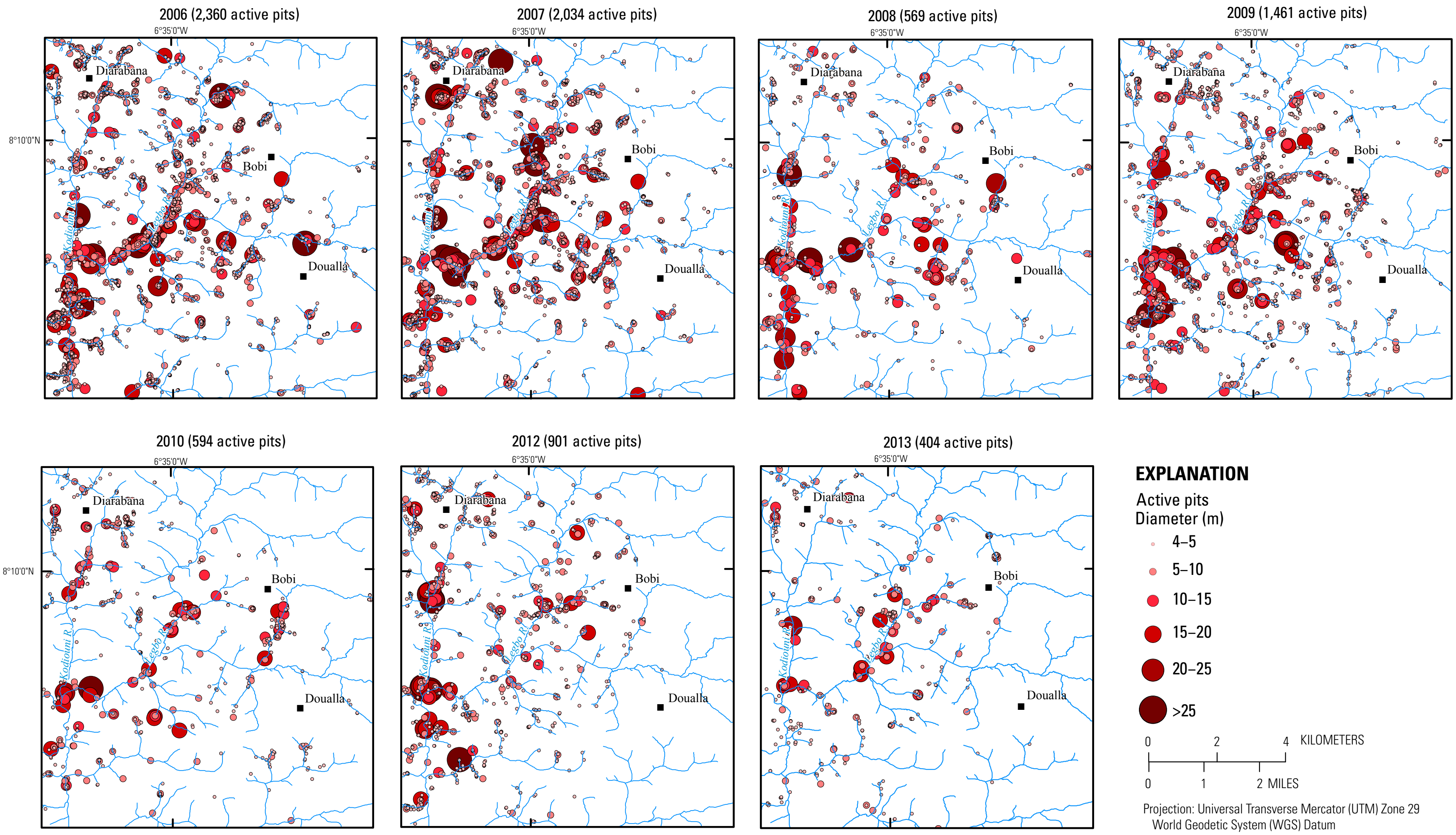


Figure 22. Number of 5- to >25-meter pits per year in the Bobi/Diarabana area of Côte d'Ivoire.

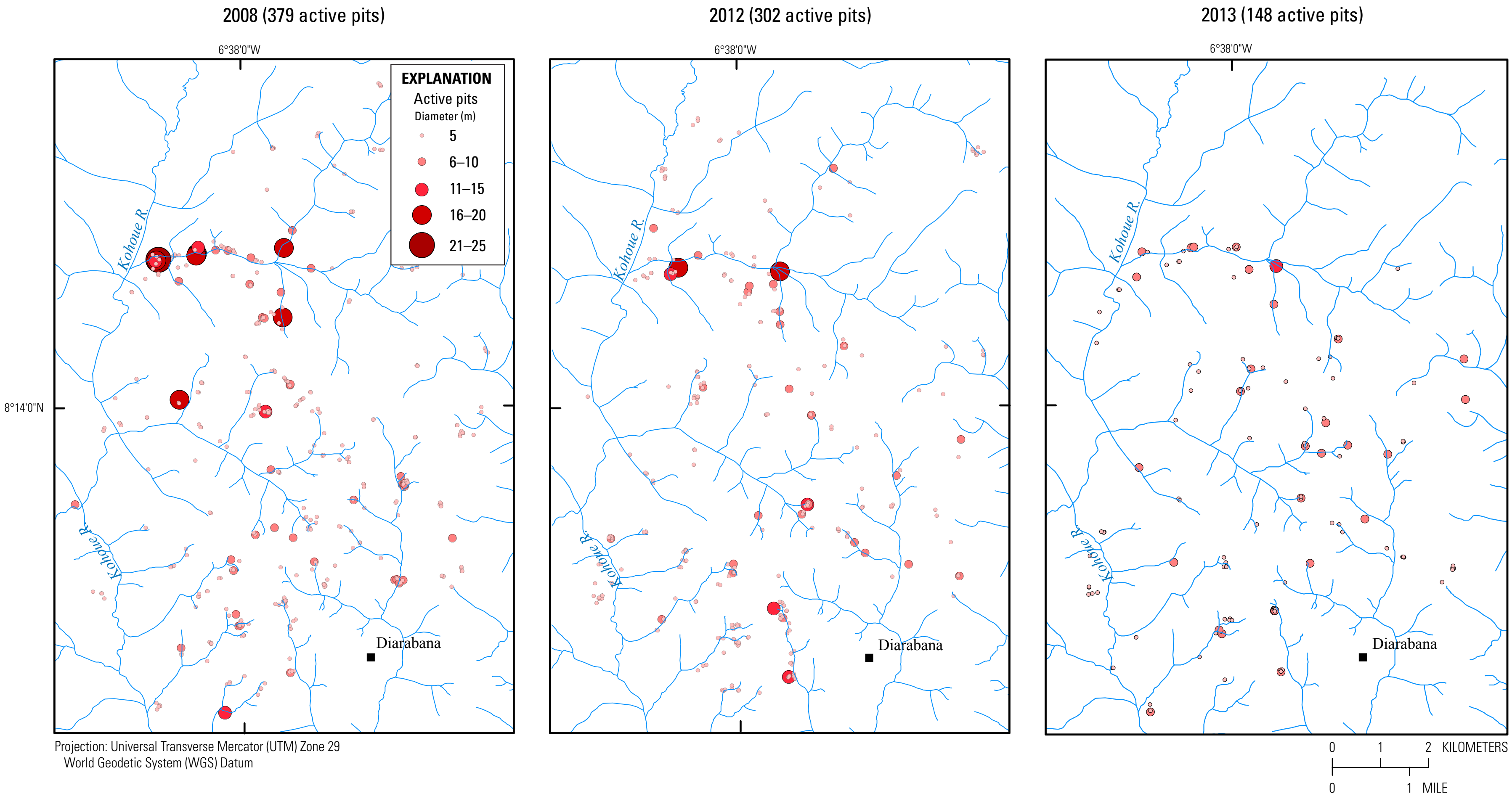


Figure 23. Number of 5- to 25-meter pits in 2008, 2012, and 2013 in the Toubabouko area of Côte d'Ivoire.

and calculating the number of pits per occurrence ratio. This average value was then multiplied by the number of occurrences for each watershed outside the Bobi/Diarabana and Toubabouko areas, providing an estimated number of 5- to >25-m pits for the remaining watersheds. The number of pits was then summed for each year.

To calculate production capacity for these watersheds, however, it was necessary to break the yearly sum total by geomorphic zone and pit size, as was done in the Bobi/Diarabana and Toubabouko areas. The first step was to calculate the percentage of pits in each geomorphic zone for each year in the Bobi/Diarabana area. This percentage was then multiplied by the estimated number of pits in the remaining watersheds to get a total number of pits within each geomorphic zone. The next step involved calculating the number of 5-, 10-, 15- , 20- , 25- , and >25-m pits within the AF1, AF2, T, and UP zones. By looking at the number of pits from each size category within each geomorphic zone in the Bobi/Diarabana area, a percentage of each pit size within each zone was calculated for the remaining watersheds for each year. This percentage was multiplied by the number of AF1, AF2, T, and UP pits to arrive at the number of pits for each size category within each geomorphic zone. Once these totals were calculated, the production capacity equation was employed. The same AF1, AF2, and T grade and gravel thickness estimates used for Bobi/Diarabana and Toubabouko were used in the calculation. However, for the UP zone, a grade of 0.1 kt/m^3 and a gravel thickness of 0.1 m was used because these upland deposits are secondary in nature, not eluvial/primary as is the case in Bobi/Diarabana and Toubabouko, and therefore they have a lower grade and thinner gravel layer. The 1- to 3-m exploration pits were calculated for the remaining watersheds as well, by using the same method as before. The production capacity of the 1- to 3-m pits was added to the production capacity of the 5- to >25-m pits to arrive at a total production capacity for the remaining watersheds.

Estimating Production Capacity of Séguéla's Alluvial Deposits

For each of the three areas (Bobi/Diarabana, Toubabouko, and the remaining watersheds), the production capacity was calculated separately for 5- to >25-m pits and 1- to 3-m pits for each year. These two production capacity values were then summed. A final production range was obtained for each area by adding and subtracting 6 percent from the calculated production capacity. This was done to account for the fact that the pit identification methodology is estimated to be 94 percent accurate, so providing a range of values is a more accurate approach for estimating production than reporting a single value. The final production capacity was calculated for each area, for each year. Production capacity results were calculated for the Bobi/Diarabana area and the remaining watersheds for the years 2006–2010 and 2012–2013 and for the Toubabouko area for the years 2008–2010 and 2012–2013.

Methodology for Estimating the Production Capacity of Tortiya's Alluvial Deposits

The manual interpretation of pits from satellite imagery was not feasible for the Tortiya, Côte d'Ivoire study area because it was not possible to distinguish alluvial artisanal diamond mining sites from alluvial artisanal gold mining sites in the available satellite imagery. Therefore, to calculate the production capacity of the Tortiya study area, a modified version of the equation developed by Barthélémy and others (2006) was employed. This equation can be expressed mathematically as $P_i =(((Vm/d \times g_c) d \times A_i) \times 0.1) +(((Vm/d \times g_b) d \times A_i) \times 0.9)$, where P_i is the total current production capacity, Vm/d is the volume of material worked per digger per day, g_c is the concentration gravel grade applied to 10 percent of production, g_b is the basic gravel grade applied to 90 percent of production, d is the total number of days a digger works per year, and A_i is the total number of diggers estimated to be actively mining diamonds. Vm/d was estimated to be 0.75 m^3, g_c was estimated to be 0.2 kt/m^3, g_b was estimated to be 0.075 kt/m^3, and d was estimated to be 200. In 2011, the UNGoE estimated that there were between 1,000 and 2,000 miners operating in Tortiya. Therefore, when calculating the production capacity for the years 2006–2009, a value of 1,500 miners was used, based on the UNGoE estimate. During this period, much of the activity in Tortiya involved the recycling of old diamond mining spoil material piles. However, fieldwork conducted in the region in 2013 showed that the activity had switched to gold panning, with fewer people involved in recycling. It is important to note that miners migrate between gold and diamonds based largely on the number of local diamond buyers and the market price of gold. Gold prices experienced peaks in August to September of 2011 and again in September to October 2012, which may be one explanation for the change in mining activities. Miners interviewed during fieldwork also revealed that many of them were leaving Tortiya to mine gold deposits further north. On the basis of these observations, it was assumed that a decrease in diamond miners likely occurred beginning in 2010. Therefore, production capacity for the years 2010–2013 was calculated by keeping all variables the same with the exception of the number of diggers (A_i), which was reduced to 1,000.

Production Capacity Analysis of Primary Deposits

The production capacity of primary deposits, which include kimberlitic pipes, dikes, lamproites, lamprophyres, and blows, must be analyzed separately from alluvial deposits because the characteristics of these deposits are very different. There are 14 known kimberlitic dikes, lamproites, and lamprophyres in the Séguéla region. Two of these dikes were known to be active during the years covered in this study, the Bobi Dike and the Diarabana Dike.

Methodology for Estimating the Production Capacity of the Bobi and Diarabana Dikes

The equation to measure the production capacity of the Bobi and Diarabana Dikes can be expressed mathematically as $P_i = (V \times g)$, where P_i is equal to production capacity, V is the volume of the deposit, and g is the average grade of the deposit. Different methodologies were used to calculate the volume (V) of the dikes. The calculation of the volume of the Bobi Dike deposits was based on the derivation of 2-m-resolution DEMs from stereoscopic satellite imagery collected during 2006–2008. Each elevation model was sequentially subtracted from the elevation model of the following year (for example, 2007 DEM – 2006 DEM) to arrive at the difference in elevation between the two years. Positive values represented the accretion of material, mainly in the form of spoil piles, whereas negative values represented excavation depth. The accreted material was filtered out of the analysis to focus only on newly excavated ground for each year. On the basis of years for which there was available stereoscopic imagery, the volume of excavated material was calculated for 2006–2008. An average grade of 1 kt/m^3 was assumed on the basis of previous SODEMI estimates and was multiplied by the calculated volumes to arrive at an estimated production capacity for 2006–2008.

The Bobi Dike has continued to be active through 2013 and has been visible in satellite imagery and field observations, though activity decreased noticeably in 2012. However, the volume of material could not be calculated by means of this methodology for the remaining years because stereoscopic imagery was not available for the creation of DEMs. Therefore, production at the Bobi Dike for the years 2009–2013 was estimated on the basis of UNGoE observations and fieldwork. Production in 2009 was estimated to have increased by 20 percent from the previous year. This percentage was selected because production at the dike was noted to increase from 2006 to 2009, though it is likely that production was increasing at a declining rate. For each year within this range, production increased by approximately half the rate of the previous year. For example, from 2006 to 2007, production increased by 90 percent and from 2007 to 2008 production increased by 40 percent. Therefore, it was assumed that this decline in the rate of production increase continued through 2009, and was approximately 20 percent (half of 40 percent). In 2010, production was estimated to have decreased by 50 percent. This large decrease is due to the fact that although the number of miners may have increased from 2009 to 2010, as speculated by the UNGoE, miners were forced to dig deeper into the dike as mining activities at the dike progressed, requiring more time and resources to exploit a smaller deposit, as the dike narrows with depth. Furthermore, miners were beginning to mine the weathered bedrock and weathered kimberlitic dike material at the margins of the dike, which is less well mineralized. Production was decreased by 50 percent based on the horizontal surface expression of the dike visible in imagery, aerial overflight photography, and on-the-ground field observations. By 2012, production at the Bobi Dike had significantly decreased, with far fewer miners working the site. Production was decreased again therefore by 50 percent for 2011–2013.

Exploitation of the Diarabana Dike began in 2009. Although stereoscopic imagery is available for 2009, it is not available for the subsequent years, and therefore the DEM change detection methodology could not be used to calculate the volume of material at this dike. Volume was calculated instead by measuring the length and width of the active dike for each year and multiplying these values by an estimated depth of excavation of 1 m. The depth of the annual excavation of the dike by artisans is unknown, and therefore a conservative estimate of 1 m was used. Data on the grade of the Diarabana Dike deposits is also unavailable, and therefore the average grade of the Bobi Dike deposits, 1 kt/m^3, was applied to the Diarabana Dike deposits. The volume was multiplied by the grade to arrive at an estimated production capacity of the Diarabana Dike for 2009–2012. Production in 2013 was estimated to be 25 percent of 2012 production. Although the length and width of the exploited dike remained approximately the same from 2012 to 2013, the number of working miners observed at the dike during aerial overflight and field observations decreased significantly, resulting in a significant decrease in production capacity.

Results of the Production Capacity Analysis of Séguéla and Tortiya

Table 5 and figure 24 present the results of the production capacity analysis for the alluvial and primary deposits at Séguéla for 2006–2013. Examination of Séguéla's annual alluvial production versus total primary production and total annual production (alluvial and primary) reveals several trends. The lowest alluvial production is seen in 2013, followed by 2012, with production peaking in 2006. Primary production increases steadily from 2006 to 2009, then falls from 2010 on. The total Séguéla production is lowest in 2013 and 2006, because primary production is very low in these years, and peaks in 2009 when primary production is at its highest, before beginning a gradual descent thereafter. The large increase in total production from 2008 to 2009 is due to the introduction of exploitation at the Diarabana Dike. However, alluvial production drops significantly from 2009 to 2010 (by 50 percent) and then from 2010 to 2012 (by 20 percent), bringing the overall Séguéla production down from 2010 to 2012, irrespective of exploitation occurring at both the Bobi and Diarabana Dikes during these years.

Primary production is greater than alluvial production in all years except 2006, because production at the Bobi Dike had only recently begun and had not yet started at the Diarabana Dike at that time. Though both the alluvial and primary deposits are exploited artisanally, primary dike deposits are very rich, with a relatively high average gravel grade and large volume of diamondiferous ore, resulting in production values that are significantly higher than those of the alluvial deposits.

Table 5. Results of the production capacity analysis for the Séguéla and Tortiya study areas, 2006–2013.

[Est. prod., estimated production; kt, carats; --, no data available]

Study area	Est. prod. 2006 (kt)	Est. prod. 2007 (kt)	Est. prod. 2008 (kt)	Est. prod. 2009 (kt)	Est. prod. 2010 (kt)	Est. prod. 2012 (kt)	Est. prod. 2013 (kt)
Séguéla alluvial deposits							
Bobi/Diarabana	21,625–24,386	24,534–27,667	9,607–10,834	18,579–20,838	6,332–7,140	7,894–8,901	3,810–4,297
Toubabouko	--	--	3,574–4,030	5,826–6,570	2,003–2,258	2,007–2,263	1,780–2,000[a]
Remaining watersheds	38,699	29,472	11,935	21,657	15,059	8,568	8,883
Total alluvial	**60,324–63,085**	**54,006–57,139**	**25,116–26,799**	**46,062–49,065**	**23,394–24,457**	**18,469–19,732**	**14,473–15,180**
Séguéla primary deposits							
Bobi Dike	9,656	97,752	166,604	200,000[b]	100,000[b]	25,000[b]	12,500[b]
Diarabana Dike	NA[c]	NA[c]	NA[c]	129,600	129,600	43,264	10,816
Total primary	**9,656**	**97,752**	**166,604**	**329,600**	**229,600**	**68,264**	**23,316**
Total (alluvial and primary)	**69,980–72,741**	**151,758–154,891**	**191,720–193,403**	**375,662–378,665**	**252,994–254,057**	**86,733–87,996**	**37,789–38,496**
Tortiya alluvial deposits							
Tortiya (mean est. prod.)	**19,688**	**19,688**	**19,688**	**19,688**	**13,125**	**13,125**	**13,125**
Total (Séguéla and Tortiya)	**89,668–92,429**	**171,445–174,579**	**211,408–213,091**	**395,350–398,353**	**266,119–267,182**	**99,858–101,121**	**50,914–51,621**

[a]Owing to inadequate imagery extent for 2013, the number of pits was estimated for 25 percent of the Toubabouko area based on analysis conducted for 2012.

[b]Estimate based on average mean production of Bobi Dike, 2006–2008.

[c]NA, not applicable. Diarabana Dike not discovered until 2009.

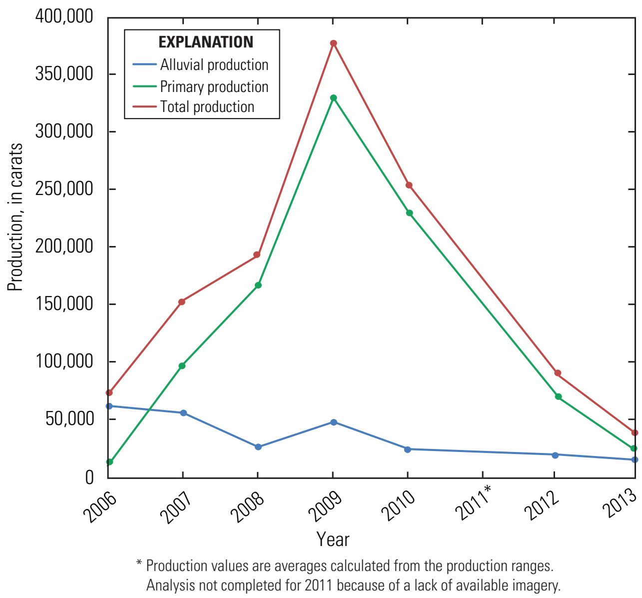


Figure 24. Graph showing average alluvial production, primary production, and total production for Séguéla, Côte d'Ivoire, 2006–2013.

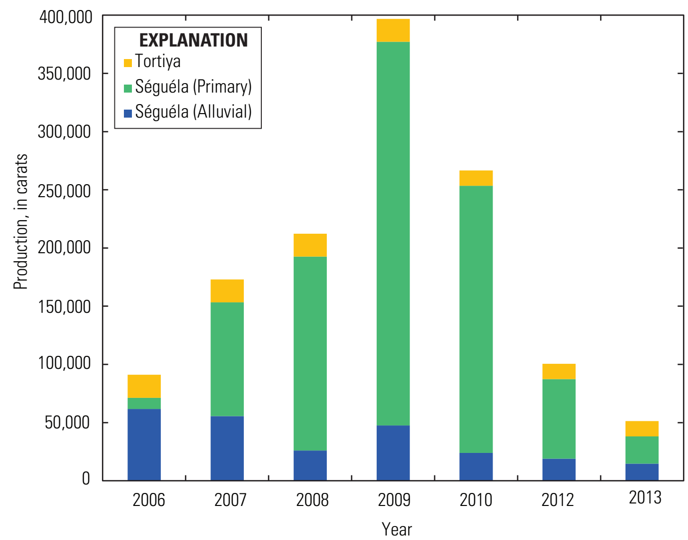


Figure 25. Chart showing the relationship between Séguéla average alluvial production, Séguéla primary production, and Tortiya production in Côte d'Ivoire.

The detailed analysis of production in Séguéla, Côte d'Ivoire, resulted in the identification of several notable trends. Total production in Séguéla increased by 82 percent from 2006 to 2009, dropped by 33 percent from 2009 to 2010, then dropped by 38 percent from 2010 to 2013. The runup to Côte d'Ivoire's long postponed elections coincides with an increase in production, and following the 2010 elections production drops. This trend could be the result of several external factors, and it is possible that the election cycle influenced production. The discovery of the Diarabana Dike in 2009 is a second influential factor, leading to the peak in total production that year. After the discovery of the dike, alluvial production decreased as more miners chose to exploit the richer primary deposits.

Tortiya's diamond deposits are all alluvial in nature, and the mining of this region is less intense than in Séguéla. Additionally, the size of the diamondiferous zone is roughly 10 percent the size of Séguéla's diamondiferous zone; therefore, this region attracts fewer miners. These factors result in a relatively low production capacity when compared to that of Séguéla (table 5 and fig. 25). Owing to constraints on the availability of data, two production capacity values were calculated for Tortiya and applied to the years 2006–2009 and 2010–2013, respectively. Production estimated in Tortiya range from approximately 20,000 kt for the years 2006–2009 (when the number of miners is estimated to have been 1,500) to 13,000 kt for the years 2010–2013 (when the number of miners is estimated to have been 1,000). More specific annual production values could not be calculated for Tortiya following the methodology employed in Séguéla, owing to a lack of available imagery and difficulties associated with distinguishing alluvial gold mining from alluvial diamond mining.

The 2011 UNGoE report contains production estimates for Seguela and Tortiya for 2007 and 2008, based on preconflict alluvial mining data. For Séguéla, 2007 production was estimated to be between 104,000 kt and 173,000 kt, whereas 2008 production was estimated to be between 135,800 kt and 277,000 kt (UNGoE, 2011b). The total primary and alluvial estimates for Séguéla produced in this study for those same years are between approximately 152,000 to 155,000 kt and 192,000 to 193,000 kt, respectively. These estimates fall within the range reported by the WGDE. For Tortiya, the WGDE estimated that between 10,000 kt and 15,000 kt were produced in 2007 and 2008 (UNGoE, 2011b). This study estimated a production of 20,000 kt for Tortiya during those years, exceeding the estimate by several thousand carats. In 2012, the UNGoE estimated total production in Séguéla and Tortiya to be between 100,000 and 150,000 kt. This study estimates that approximately 100,000 kt were produced in 2012, coinciding with the lower end of the UNGoE estimate. Finally, in 2013, the UNGoE estimated total production to be between 50,000 and 100,000 kt, whereas this study estimated production to be approximately 50,000 kt, again falling at the lower end of the UNGoE estimate.

Conclusion

The goal of this study was to estimate the alluvial diamond resource endowment and the alluvial and primary production capacity of Côte d'Ivoire's two most intensively mined regions, Séguéla and Tortiya. A modified volume and grade approach was used to estimate the remaining diamond reserves. Approximately 10,100,000 kt are estimated to remain in Séguéla, and approximately 1,100,000 kt are estimated to remain in Tortiya. Two different approaches were used to calculate alluvial production capacity. One relied on high-resolution satellite imagery to identify and catalog pits, and the other relied on data concerning the number of diggers and their productivity. A third method was developed to estimate the production of primary dike deposits, using high-resolution DEMs and satellite imagery. For the Séguéla region, production was estimated to range from 38,000 to 375,000 kt during 2006–2013. Meanwhile, estimated production in the smaller and less active region of Tortiya ranged from 13,000 to 20,000 kt during 2006–2013.

The availability of high-resolution imagery coverage of the Bobi/Diarabana and Toubabouko areas within the Séguéla study area allowed for a detailed and thorough analysis of the level of activity in this region. However, it remains challenging to acquire accurate grade and gravel-thickness data, which is a key component of calculating both the diamond reserve estimates and production capacity estimates. An additional challenge lies in the inability to conduct annual fieldwork during 2006–2013. Although fieldwork was conducted in 2012 and 2013, only a limited number of sites were visited; therefore, in order to conduct a regional scale annual analysis, a new approach was required. A new technique centered on the interpretation of remotely sensed data and elevation models was developed for this study and resulted in a detailed analysis of the diamond deposits of Séguéla and Tortiya.

References Cited

Avenard, J.M., 1971, Aspects de la géomorphologie: Paris, Office de la Recherche Scientifique et Technique Outre-Mer, 72 p.

Avenard, J.M., 1977, Cartographie géomorphologique dans l'ouest de la Côte d'Ivoire: Paris, Office de la Recherche Scientifique et Technique Outre-Mer, 99 p., 3 pls.

Bagarre, E., and Tagini, B., 1965, Carte géologique de la Côte d'Ivoire: Abidjan, Direction des mines et de la géologie, scale 1:1,000,000.

Bardet, M.G., 1974, Géologie du diamant, gisements de diamants d'Afrique: Bureau de Recherches Géologiques et Minières Memoir, v. 2, no. 83, 223 p.

Bardet, M.G., and Vachette, M., 1966, Détermination d'âges de kimberlites de l'Ouest africain et essai d'interprétation des datations des diverses venues diamantifères dans le monde: Bureau de Recherches Géologiques et Minières report, DS 66 A 59, 15 p.

Barthélémy, Francis; Eberlé, J.M.; Duguey, E.; Jézéquel, P.; Husson, Y.; Moumpossa, R.; and Boutin, P., 2006, Republic of the Congo, diamond potential, production capacity, and the Kimberley Process—Final report: Bureau de Recherches Géologiques et Minières, RC-54589-EN, 99 p.

Bermúdez, Omayra, 1999, The mineral industry of Côte d'Ivoire: U.S. Geological Survey Minerals Yearbook, v. 3, 3 p.

Bermúdez-Lugo, Omayra, 2004, The mineral industries of Central African Republic, Côte d'Ivoire, and Togo: U.S. Geological Survey Minerals Yearbook, v. 3, 5 p.

Bermúdez-Lugo, Omayra, 2007, 2007 minerals yearbook—Central African Republic, Côte d'Ivoire, and Togo: U.S. Geological Survey Minerals Yearbook, v. 3, 7 p.

Chirico, P.G.; Barthélémy, Francis; and Ngbokoto, F.A., 2010a, Alluvial diamond resource potential and production capacity assessment of the Central African Republic: U.S. Geological Survey Scientific Investigations Report 2010–5043, 22 p.

Chirico, P.G.; Barthélémy, Francis; and Koné, Fatiaga, 2010b, Alluvial diamond resource potential and production capacity assessment of Mali: U.S. Geological Survey Scientific Investigations Report 2010–5044, 23 p.

Chirico, P.G.; Malpeli, K.C.; Anum, Solomon; and Phillips, E.C., 2010c, Alluvial diamond resource potential and production capacity assessment of Ghana: U.S. Geological Survey Scientific Investigations Report 2010–5045, 25 p.

Chirico, P.G.; Malpeli, K.C.; van Bockstael, Mark; Diaby, Mamadou; Cissé, Kabinet; Diallo, T.A.; and Sano, Mahmoud, 2012, Alluvial diamond resource potential and production capacity assessment of Guinea: U.S. Geological Survey Scientific Investigations Report 2012–5256, 59 p.

Direction des Mines et de la Géologie, 1971, Rapport sommaire sur l'activité du secteur minier en 1971: République de Côte d'Ivoire, 5 p.

Direction des Mines et de la Géologie, 1973, Rapport sommaire sur l'activité du secteur minier en 1973: République de Côte d'Ivoire, 3 p.

Direction des Mines et de la Géologie, 1975, Activités minières en Côte d'Ivoire en 1975: République de Côte d'Ivoire, 4 p.

Faure, Stephane, 2010, World kimberlites CONSOREM database version 3: Montréal, Consortium de Recherche en Exploration Minérale, Université de Québec.

Greenhalgh, P.A.L., 1985, West African diamonds, 1919–1983—An economic history: Manchester, UK, Manchester University Press, 306 p.

Guesnet, Lena; Müller, Marie; and Schure, Jolien, 2009, Natural resources in Côte d'Ivoire—Fostering crisis or peace?—The cocoa, diamond, gold and oil sectors: Bonn International Center for Conversion, Brief 40, 79 p.

Hutchinson, M.F., 1989, A new procedure for gridding elevation and stream line data with automatic removal of spurious pits: Journal of Hydrology, v. 106, p. 211–232.

Knopf, D., 1970, Les kimberlites et les roches apparentées de Côte d'Ivoire: Abidjan, Direction des Mines et de la Géologie de Côte d'Ivoire, 202 p.

Kimberley Process Certification Scheme (KPCS), 2005, Resolution adopted by the Kimberley Process Plenary Meeting, Moscow, 15–17 November 2005, on the subject of illicit diamond production in Côte d'Ivoire: Moscow, Kimberley Process Certification Scheme, November 8, 2 p.

Kimberley Process Certification scheme (KPCS), 2007, Brussels Initiative on diamond from Côte d'Ivoire: Brussels, Kimberley Process Certification Scheme, 1 p.

Kauffmann, Mayeul; Al-Khudhairy, D.H.A; Louvrier, Christophe; Chirico, P.G.; and Malpeli, K.C., 2013, Joint EU-US methodology for monitoring alluvial diamond mining activities in Cote d'Ivoire—A European Commission (JRC) and United States Geological Survey (USGS) report: EC-JRC/84711.

Loukou, Y., 1974, WASTON—Champ diamantifère de Séguéla carte d'ensemble: Bouaké, WASTON, scale 1:50,000.

Milési, Jean-Pierre; Ledru, Patrick; Feybesse, Jean-Louis; Dommanget, Alain; and Marcoux, Eric, 1992, Early Proterozoic ore deposits and tectonics of the Birimian orogenic belt, West Africa: Precambrian Research, v. 58, p. 305–344.

Mobbs, P.M., 1996, The mineral industry of Côte d'Ivoire: U.S. Geological Survey Minerals Yearbook, v. 3, 3 p.

Mobbs, P.M., 1997, The mineral industry of Côte d'Ivoire: U.S. Geological Survey Minerals Yearbook, v. 3, 2 p.

Moyar, Antoine, 1957, The diamond industry in 1956–1957: Antwerp, Drukkerijen C. Govaerts, 169 p.

Moyar, Antoine, and Buxtant, E., 1963, The diamond industry in 1960–1961: Antwerp, Drukkerijen C. Govaerts, 112 p.

Peltre, P., 1978, Le 'V Baoulé'—Héritage géomorphologique et paléoclimatique dans le tracé du contact forêt-savane: Paris, Office de la Recherche Scientifique et Technique Outre-Mer, 193 p.

Pouclet, André; Allialy, M.; Daouda-Yao, B.; and Esso, B., 2004, Découverte d'un diatrème de kimberlite diamantifère à Séguéla en Côte d'Ivoire: Comptes Rendus Geoscience, v. 336, no. 1, p. 9–17.

Poss, R., 1982, Étude morpho-pédologique de la région de Katiola (Côte d'Ivoire)—Cartes des paysages et des unités morpho-pédologiques: Paris, Office de la Recherche Scientifique et Technique Outre-Mer, 142 p.

Schlüter, Thomas, 2006, Geological atlas of Africa, with notes on stratigraphy, tectonics, economic geology, geohazards and geosites of each country: Berlin, Springer, 272 p.

Société Pour le Développement Minier de la Côte d'Ivoire, 1964, Compte rendu de l'exercice 1964: Abidjan, 28 p.

Société Pour le Développement Minier de la Côte d'Ivoire, 1965, Compte rendu de l'exercice 1965: Abidjan, 28 p.

Société Pour le Développement Minier de la Côte d'Ivoire, 1967, Compte rendu de l'exercice 1967: Abidjan, 36 p.

Société Pour le Développement Minier de la Côte d'Ivoire, 1970, Compte rendu de l'exercice 1970: Abidjan, 2 p.

Société Pour le Développement Minier de la Côte d'Ivoire, 1976, Rapport annuel 1976: Abidjan, 1 p.

Société Pour le Développement Minier de la Côte d'Ivoire, 1978, Carte d'ensemble—Champ diamantifère de Bobi: SODEMI, scale 1 :10,000.

Société Pour le Développement Minier de la Côte d'Ivoire, 1988, Rapport annuel 1988 du 1er octobre 1987 au 30 septembre 1988: Abidjan, 28 p.

Soto-Viruet, Yadira, 2010, The mineral industries of Central African Republic, Côte d'Ivoire, and Togo: U.S. Geological Survey Minerals Yearbook, v. 3, 5 p.

Szczesniak, P.A., 2000, The mineral industries of Côte d'Ivoire, Guinea, Liberia, and Sierra Leone: U.S. Geological Survey Minerals Yearbook, v. 3, 5 p.

Szczesniak, P.A., 2001, The mineral industries of Côte d'Ivoire, Guinea, Liberia, and Sierra Leone: U.S. Geological Survey Minerals Yearbook, v. 3, 7 p.

Teeuw, R.M., 2002, Regolith and diamond deposits around Tortiya, Ivory Coast, West Africa: Catena, v. 49, p. 111–127.

United Nations Group of Experts (UNGoE), 2005, Report of the Group of Experts submitted pursuant to paragraph 7 of Security Council resolution 1584 (2005) concerning Côte d'Ivoire: New York, United Nations Security Council, 69 p.

United Nations Group of Experts (UNGoE), 2006, Update report of the Group of Experts submitted pursuant to paragraph 2 of Security Council resolution 1632 (2005) concerning Côte d'Ivoire: New York, United Nations Security Council, 26 p.

United Nations Group of Experts (UNGoE), 2007, Report of the Group of Experts on Côte d'Ivoire appointed by the Security Council pursuant to resolution 1727 (2006): New York, United Nations Security Council, 32 p.

United Nations Group of Experts (UNGoE), 2008, Report of the Group of Experts submitted in accordance with paragraph 10 of Security Council resolution 1782 (2007): New York, United Nations Security Council, 59 p.

United Nations Group of Experts (UNGoE), 2009a, Report of the Group of Experts on Côte d'Ivoire pursuant to paragraph 11 of Security Council resolution 1842 (2008): New York, United Nations Security Council, 39 p.

United Nations Group of Experts (UNGoE), 2009b, Final report of the Group of Experts on Côte d'Ivoire pursuant to paragraph 11 of Security Council resolution 1842 (2008): New York, United Nations Security Council, 123 p.

United Nations Group of Experts (UNGoE), 2010, Report of the Group of Experts on Côte d'Ivoire pursuant to paragraph 12 of Security Council resolution 1893 (2009): New York, United Nations Security Council, 31 p.

United Nations Group of Experts (UNGoE), 2011a, Report of the Group of Experts on Côte d'Ivoire pursuant to paragraph 14 of Security Council resolution 1980 (2011): New York, United Nations Security Council, 34 p.

United Nations Group of Experts (UNGoE), 2011b, Report of the Group of Experts on Côte d'Ivoire pursuant to paragraph 11 of Security Council resolution 1946 (2010): New York, United Nations Security Council, 80 p.

United Nations Group of Experts (UNGoE), 2012, Letter dated 14 September 2012 from the Group of Experts on Côte d'Ivoire addressed to the Chair of the Security Council Committee established pursuant to resolution 1572 (2004): New York, United Nations Security Council, 124 p.

United Nations Group of Experts (UNGoE), 2013, Final report of the Group of Experts on Côte d'Ivoire pursuant to paragraph 16 of Security Council resolution 2045 (2012): New York, United Nations Security Council, 297 p.

United Nations Security Council (UNSC), 2004, Resolution 1572 (2004)—Adopted by the Security Council at its 5078th meeting, on 15 November 2004: New York, United Nations Security Council, November 15, 5 p.

United Nations Security Council (UNSC), 2005, Resolution 1643 (2005)—Adopted by the Security Council at its 5327th meeting, on 15 December 2005: New York, United Nations Security Council Press Release, December 15, 4 p.

United Nations Security Council (UNSC), 2012, Resolution 2045—Adopted by the Security Council at its 6761st meeting, on 26 April 2012: New York, United Nations Security Council Press Release, April 26, 6 p.

Wright, J.B., Hastings, D.A., Jones, W.B., and Williams, H.R., 1985, Geology and mineral resources of West Africa: London, Allen and Unwin, 187 p.

A woman washing gravel in search of diamonds and gold along the Pekoua Creek, Tortiya, Côte d'Ivoire. Photo by Pete Chirico, U.S. Geologicial Survey.

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