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Evidence of recent seismicity on the West African Craton: the seismites of Bamako, Mali

N'dji dit Jacques DEMBÉLÉ [a b†]

a. Institut Supérieur des Mines et de la Géologie de Boké, Republic of Guinea

b. Faculté d'Histoire et Géographie, Université des Sciences Sociales et de Gestion de Bamako (USSGB), Mali

Abstract

The West African Craton (WAC) has been considered tectonically inactive and stable since the Proterozoic. The later findings of seismites embedded in the Quaternary lacustrine and fluvial deposits of the Niger River valley at Bamako, Republic of Mali, seem to certify the contrary. The seismites discovered in the deposits include three clastic dikes, soft-sediment faults, microfaults and folds, convolutes, and ball structures. The clastic dikes were studied during various fieldwork campaigns: samples were collected for grain-size and heavy-mineral analyses and OSL dating. The results show that 2 of the clastic dikes (clastic dike 01 and clastic dike 03) are oriented 285 degrees and are about 4 kilometers apart, but parallel. They measure 80 to 100cm wide. The third is oriented 170 degrees but is smaller, with a width of 40 cm. The grain-size analysis shows that the clastic dikes are polygenic, with three modes, and are entirely different from the lacustrine deposits they crosscut. The heavy-mineral analysis also confirms the markedly different mineralogical composition between the clastic dikes and the adjacent horizontal layers. The vertical clastic dikes have higher zircon, tourmaline, and rutile contents, attesting that they were extruded and remobilized from the adjacent lacustrine layers. OSL dating gives approximately the same ages for the lacustrine and clastic dikes, at 280 and 250 Ka, respectively. However, the event that triggered the formation of the clastic dikes is much younger than the lacustrine limit, and the fluvial deposits that it cross-cuts date to 17 Ka. Three main conclusions can be drawn from the clastic dikes. Their direction suggests two different seismic events. The two widest parallel dikes are from a seismic event different from the small one. The direction of the seismic waves can also be assessed. They are perpendicular to the dikes and are inferred to be 15 degrees NNE, with some easily identifiable faults present in the area. The epicenter that triggered the earthquake can also be set to a 20 km radius around the dikes. Lastly, the magnitude of the earthquake that caused them can also be inferred to be around M6.5 or M7, depending on their width, which is usually proportional to the earthquake's magnitude. The presence of these seismites at Bamako, on the West African Craton, is very significant in certifying that the Craton is not as stable as previously thought and to put into context the contemporary earthquakes that have been reported on the area: Ghana (1939), Odienné, Ivory Coast (2007 and 2020), Kolokani, Mali (1999), Diangounté Kamara, Mali (2018).

Keywords: Craton, recent seismicity, seismites, Mali, West Africa.

Résumé

Le craton ouest-africain (COA) a longtemps été considéré comme tectoniquement inactif et stable depuis le Protérozoïque. La découverte récente de séismites incluses dans les dépôts lacustres et fluviatiles quaternaires de la vallée du fleuve Niger à Bamako, au Mali, semble indiquer le contraire. Ces séismites comprennent trois dykes clastiques, des failles dans les sédiments meubles, des microfailles et des plis, des convolutes et des structures sphériques. Les dykes clastiques ont été étudiés lors de différentes campagnes de terrain : des échantillons ont été prélevés pour des analyses granulométriques et minéralogiques, ainsi que pour une datation OSL. Les résultats montrent que deux des dykes (dykes clastiques 01 et 03) sont orientés à 285° et distants d'environ 4 km, tout en étant parallèles. Leur largeur varie de 80 à 100 cm. Le troisième, orienté à 170°, est plus petit, avec une largeur de 40 cm. L'analyse granulométrique révèle que les dykes clastiques sont polygéniques, présentant trois modes de formation, et qu'ils diffèrent totalement des dépôts lacustres qu'ils recoupent. L'analyse des minéraux lourds confirme également la composition minéralogique nettement différente entre les dykes clastiques et les couches horizontales adjacentes. Les dykes clastiques verticaux présentent des teneurs plus élevées en zircon, tourmaline et rutile, attestant de leur extrusion et de leur remobilisation à partir des couches lacustres adjacentes. La datation OSL donne des âges approximativement identiques pour les dykes lacustres et clastiques, respectivement de 280 et 250 ka. Cependant, l'événement à l'origine de la formation des dykes clastiques est bien plus récent que la limite lacustre, et les dépôts fluviatiles qu'ils recoupent datent de 17 ka. Trois conclusions principales peuvent être tirées de l'étude des dykes clastiques. Leur direction suggère deux événements sismiques distincts. Les deux dykes parallèles les plus larges proviennent d'un événement sismique différent de celui de moindre importance. La direction des ondes sismiques peut également être déterminée. Ces structures sont perpendiculaires aux digues et leur orientation est estimée à 15 degrés NNE. Des failles facilement identifiables sont présentes dans la zone. L'épicentre du séisme à l'origine de ces structures se situe dans un rayon de 20 km autour des digues. Enfin, la magnitude du séisme qui les a provoquées est estimée entre M6,5 et M7, selon leur largeur, généralement proportionnelle à la magnitude du séisme. La présence de ces séismites à Bamako, sur le craton ouest-africain, est très significative. Elle confirme que le craton est moins stable qu'on ne le pensait et permet de contextualiser les séismes récents survenus dans la région : Ghana (1939), Odienné, Côte d'Ivoire (2007 et 2020), Kolokani, Mali (1999) et Diangounté Kamara, Mali (2018).

Mots-clés : Craton, sismicité récente, séismites, Mali, Afrique de l'Ouest.

Corresponding author : N'dji dit Jacques DEMBÉLÉ, ndjijac@gmail.com

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1. Introduction

Quaternary deposits, usually unconsolidated, are crucial recorders of recent geological events. They have recorded neotectonic events as seismites or soft-sediment deformation structures (SSDS) (Bezerra et al., 2001; Mazumber, 2006; Montenat, Barrier, et al., 2007; Deev et al., 2009; Ezquerro, 2015; Üner, Özsayın, and Selçuk, 2019; Lu, 2024). The term "seismites" was first coined by Seilacher (1969; Loon, 2009; Van Loon, 2014) and has been widely used, although some researchers caution against its use (Shanmugam, 2016). Since the beginning of the last century, significant progress has been made in understanding the conditions under which seismites occur, including the processes involved, environmental conditions, intervening factors, and the lithological facies concerned. Their importance in deciphering neotectonic events has also been studied: seismic intensity, seismic wave direction, and distance to the epicenter of the triggering earthquake (Bertrand, 2008; Doughty, 2014; Ezquerro, 2015, 2015; Üner, Özsayın and Selçuk, 2019; Lu, 2024).

Research has shown that seismites are composed essentially of clastic dikes (Newsom, 1903; Jenkins, 1925; Dionne, 1974; Demoulin, 1996), faults, micro-faults (Seilacher, 1969, Vittori, Sylos Labini and Serva 1991; Onorato, Perucca et al., 2016), folds, ball and pillow structures (Owen 1978, 1982; Üner, Özsayın and Selçuk 2019), and ball structures. The formation of each seismite has been studied. The role of sand liquefaction during earthquakes in the formation of clastic dikes has been emphasized (Kuribayashi & Tatsuoka, 1975; Audemard & de Santis, 1991; Hibsch, Alvarado et al., 1997; Obermeier, 1998; Moretti & Sabato, 2007; Owen & Moretti, 2011; Shao, 2020).

This research presents different seismites found in Quaternary sediments along the Niger River at Bamako, Republic of Mali, within the West African Craton, and infers their significance for assessing the craton's neotectonics during the Quaternary period. The West African Craton is thought to be tectonically stable despite some light earthquakes felt on its margins, in Ghana (1862, 1906, 1939), on the Cameroonian coast, and the 6.2 magnitude earthquake in Guinea in December 1983 (Wright, 1985; Ennih & Liégeois, 2008; Jessell & Liégeois, 2015). Apart from these isolated and marginal earthquakes, the main parts and the interior of the West African Craton are thought to be aseismic.

The discoveries presented in this research address this thought and provide evidence that the stability of the Craton should be approached with caution and a certain degree of relativity.

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2. Regional setting

The outcrops are located in Bamako, Mali, at 12º37'03'' N and 7°55'50" W. The city, located on the West African Craton, extends along both banks of the Niger River, which flows through the city from west to east. These outcrops consist of Quaternary alluvium in two main facies.

The city of Bamako is composed of four different rock formations:

- The Archean and Proterozoic crystalline basement found on the southern edge of the city
- Two Paleozoic sandstone formations cover the crystalline basement: the Sotuba and Koulouba Sandstone.
- Dolerite intrusions form the sills of Sotuba. The Niger River crosses these dolerite intrusions, forming rapids known as the Sotuba rapids.
- Quaternary alluviums formed of 2 strata: a fluviatile sand layer covering a laminated lacustrine silt layer. The fluviatile sediments lie in disconformity on the lacustrine deposits as shown in Figure 5. Therefore, no transition exists between the two, supposing a brutal and catastrophic change of facies. These lithological formations are presented in Figures 1 and 2.

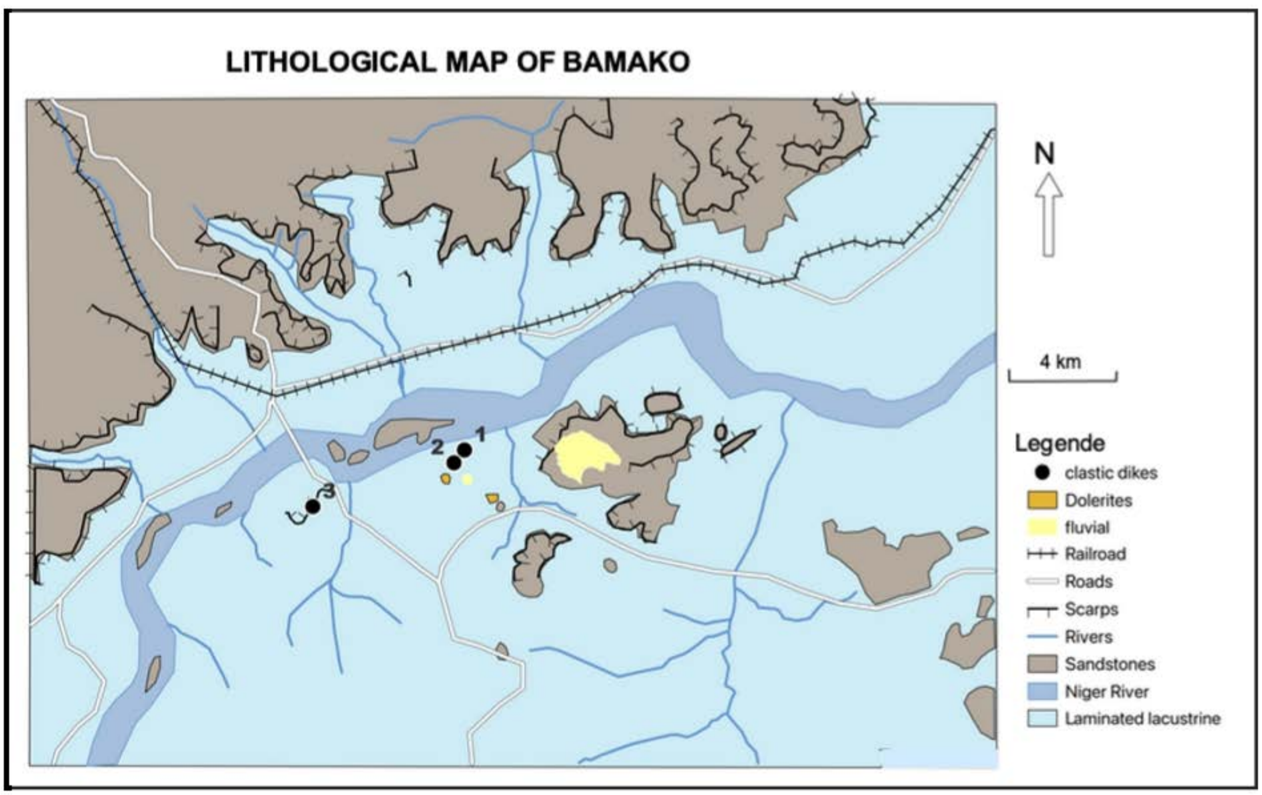

Figure 1. Lithological map of Bamako

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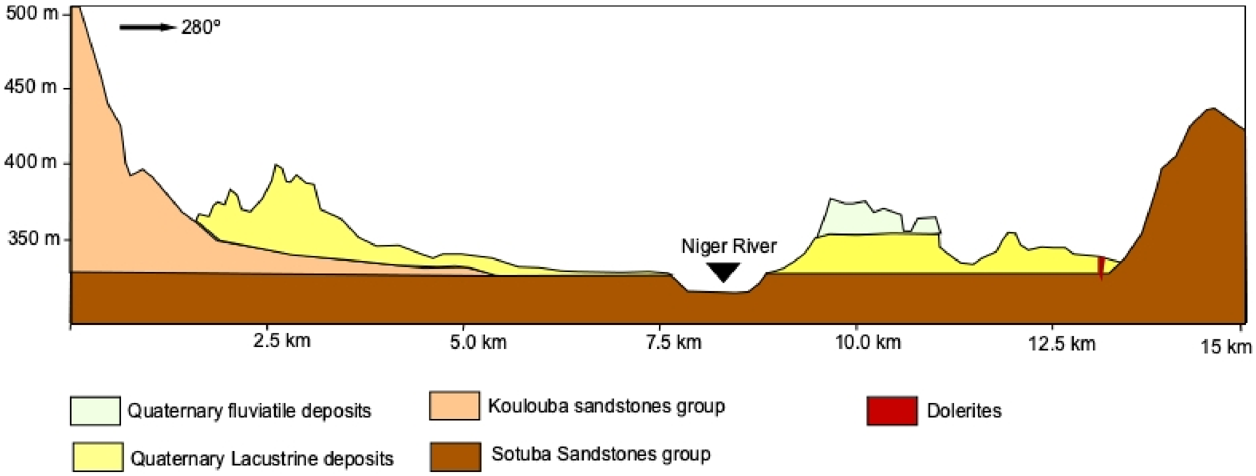

Figure 2. Geological cross-section of Bamako

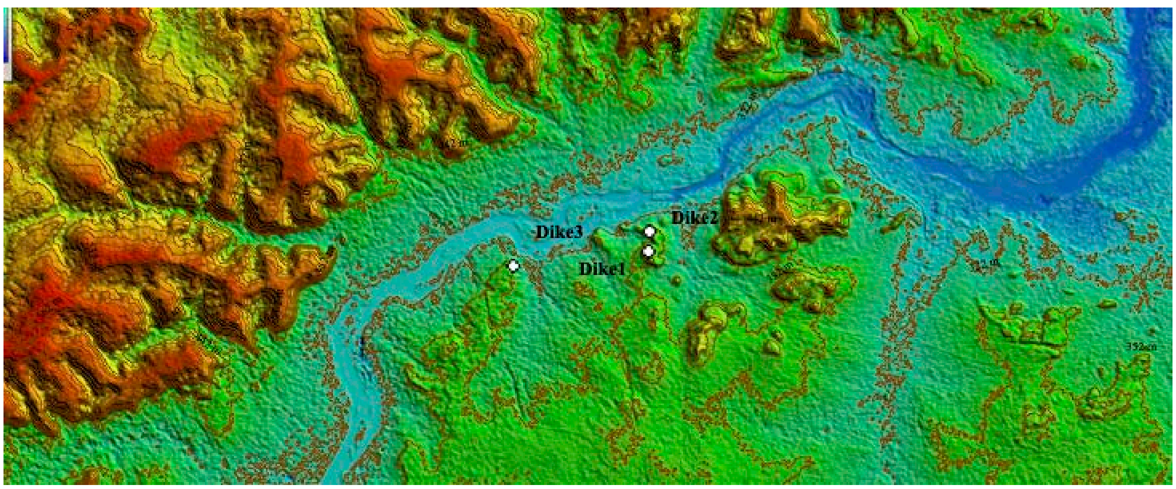

Figure 3. DEM capture of the site of Bamako showing the clastic dikes near the Sotuba Sills

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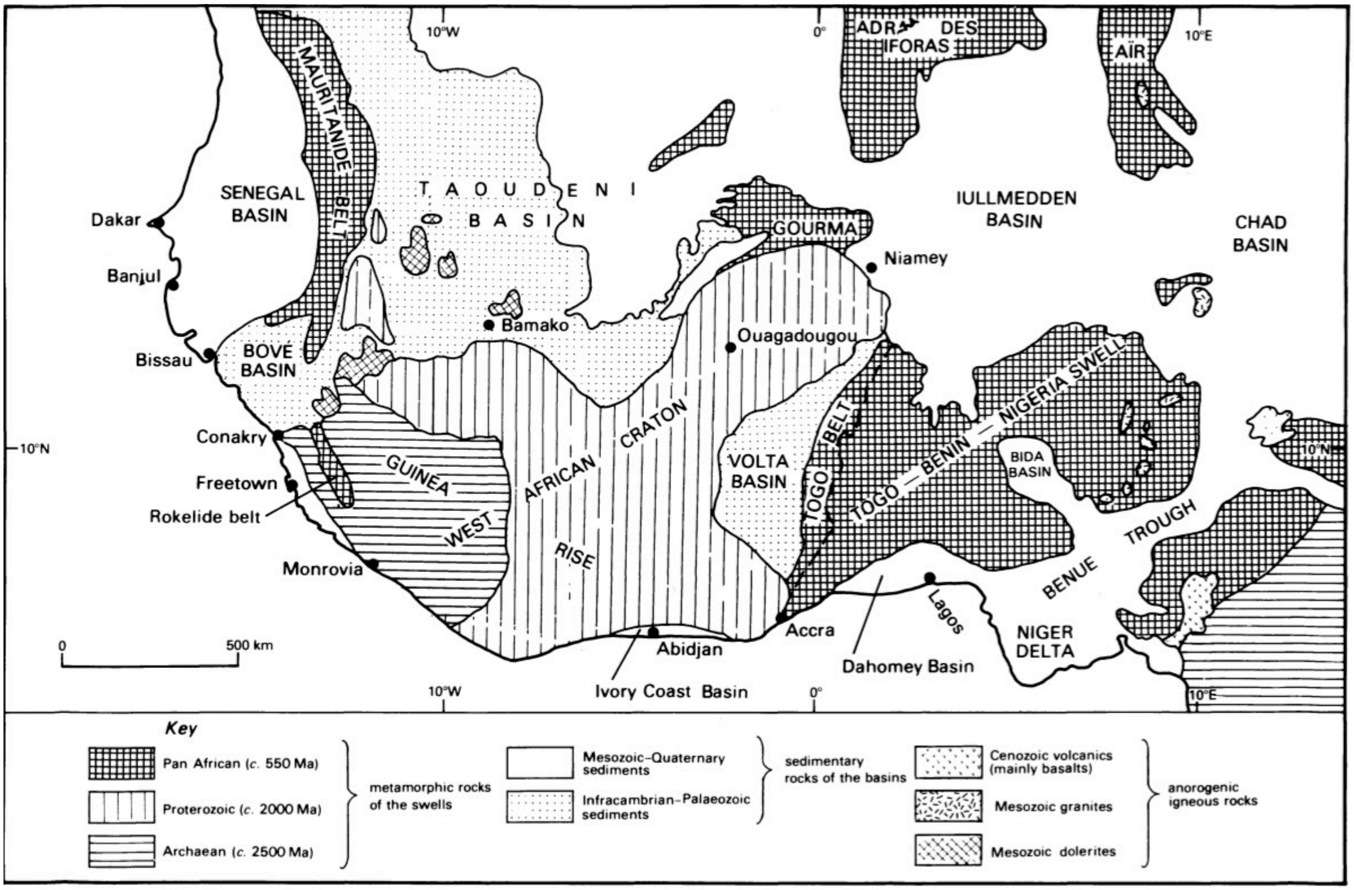

Figure 4. Geological map of the West African Craton with the location of Bamako after Wright (Wright, 1985)

The geomorphology of the city is mainly fluvial, with landscapes formed by the Niger River and small tributaries flowing over Quaternary alluvium and cutting through the alluvial hills. The altitudes of the city range between 500 meters, which compose the sandstone hills, and 300 meters, the altitude of the Niger River bed. The city's landforms are tailored to the Manding Plateau, the eastern border of the Futa Jalon highlands. Three levels of landforms can be seen in the city from North to South:

- The sandstone hills covered by duricrusts connect to the valley of the Niger River through high cliffs of about 50 to 70 meters. The well-known are the Koulouba and Point G cliffs.
- A glacis connects the cliffs to the Niger River floodplain.
- The right bank of the Niger River is constituted of alluvium hills that have a duricrust cap. The altitude of the hills is below 350 meters. They constitute the terraces of the Niger River.

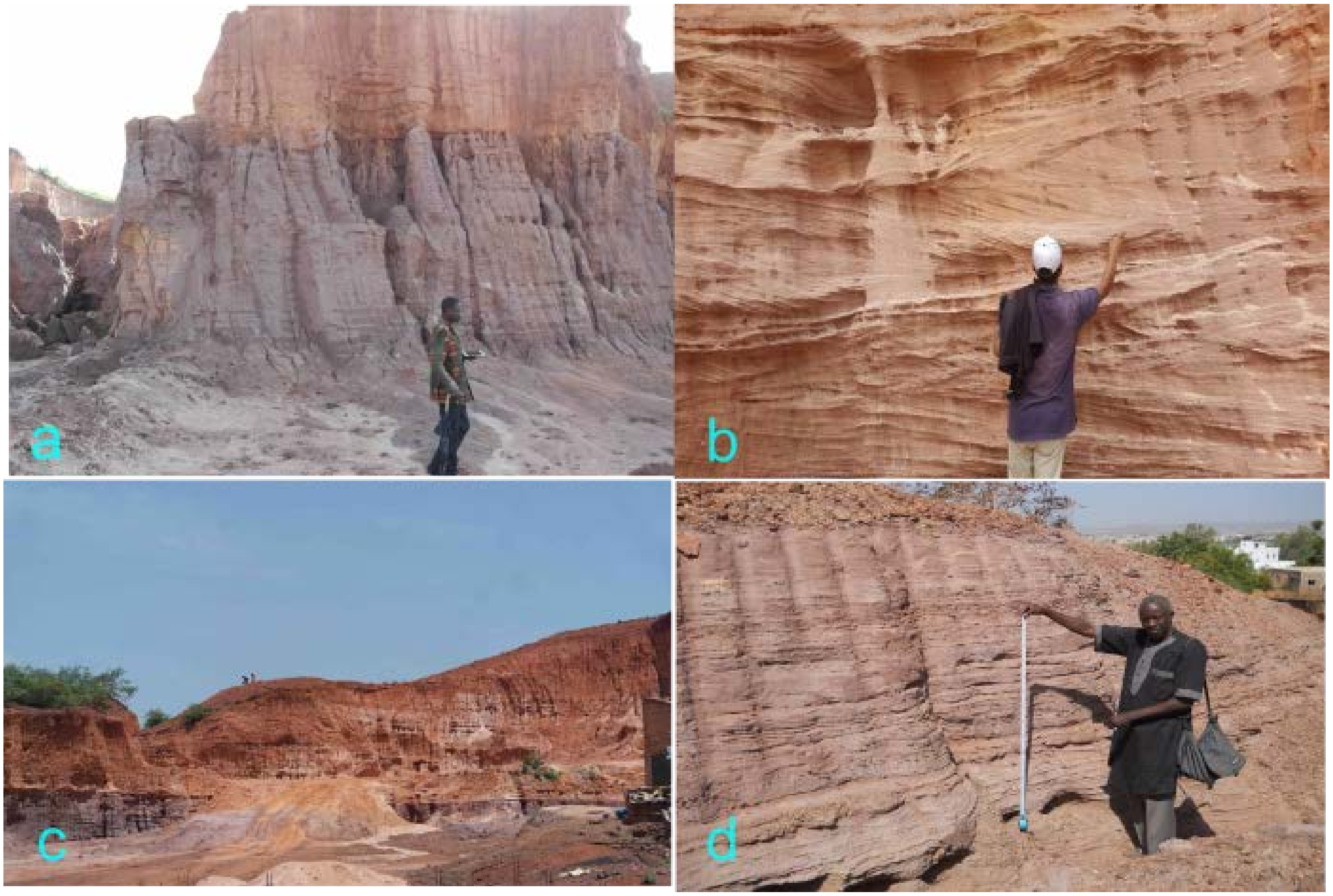

Figure 5. Quaternary profiles of the city of Bamako a. The profile shows the laminated lacustrine sediments covered by the fluviatile layer. b. Cross-bedded fluviatile sediments, c. large view of the profile with the lacustrine layer at the bottom and the fluviatile sand layer above, d. close view of the laminated lacustrine deposits.

Structurally, the area of Bamako is characterized by many linear features, some of which are faults. Unfortunately, to date, published literature regarding the structural characterization and kinematic history of these faults remains scarce. Figure 6 below presents the lineaments visible in the Google Earth image.

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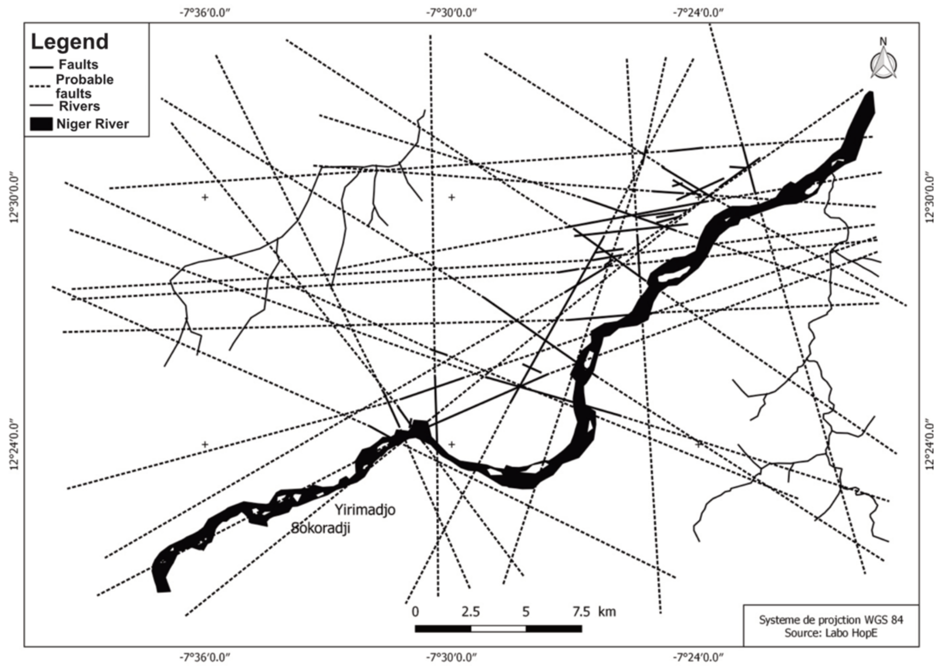

Figure 6. Map of the lineaments of Bamako made from satellite images

3. Methodology

The alluvial hills of Bamako have been cut over the last 20 years to provide construction mud for city building projects. These provided magnificent Quaternary lacustrine and fluviatile outcrops bearing the seismites that are the focus of this research. The seismites were discovered by chance. Different steps of work have been undertaken on them.

- They have been recorded and identified on the outcrops. The widths and orientations of the clastic dikes, faults, and folds were recorded using a GPS. In total, three clastic dikes were identified, but not simultaneously. The first was discovered in 2013, the second in 2016, and the third in 2020. They are presented in order as clastic dike 01, clastic dike 02, and clastic dike 03. The faults and the folds were discovered during different field sessions. Hence, the first clastic dike was thoroughly studied.
- Three samples were taken horizontally: one in the clastic dikes and two in the laminated lacustrine deposits on both sides of the clastic dikes. The objective was to obtain a broad comparison of the clastic dike and the adjacent lacustrine layers. The three samples were submitted for grain-size analysis using a Mastersizer 2000 at the Laboratory of Xuchang University in Henan Province, China. They were also subjected to heavy-mineral composition analysis at the Chengxin Geological Service Company in Langfang, China.

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- Four samples were also taken: one on the clastic dike, the second in the lacustrine sediments horizontally to the clastic dikes, the third at the base of the lacustrine deposits, and the last at the contact between the lacustrine and the fluviatile deposits. These samples were submitted to OSL dating at the Three Gorges Research Center for Geohazards of China University of Geosciences in Wuhan, China.

The statistical data from these analyses contributed to understanding the type of sediment, its granulometry, mineralogical composition, and age.

4. Results

4.1 Clastic dikes

4.1.1 Description of the clastic dikes

Three clastic dykes were identified in the unconsolidated deposits along the right bank of the Niger River in Bamako. These are labeled clastic dike 01, clastic dike 02, and clastic dike 03, in the order of their discovery. Details about their location, thickness, and azimuthal orientations are provided in Table 1.

Table 1. Location Direction Width

	Location	**Direction**	**Width**
Clastic dike 01	12º37’46.09 N ; 7º56.07.86 W	285°	0.80 to 1.10 m
Clastic dike 02	12º37’44.80 N ; 7º56’11.84 W	170°	0.4 m
Clastic dike 03	12º36’55.86 N ; 7º58’57.46 W	288º	1 m

Table 1 above shows that the clastic dykes are all located on the right bank of the Niger River in Bamako, within the alluvium of Magnambougou, Sokorodji, and Badalabougou, as they appear in figures 1 and 3.

The analysis of the directional data shows that clastic dikes 01 and 03 are parallel and oriented NW-SE, while clastic dike 02 intersects them and is slightly offset from the first, trending NNW-SSE. The first two clastic dikes are only 500 to 800 meters apart; therefore, they are almost located in the same place. The last one is located about 06 kilometers west. The parallel orientation of clastic dikes 01 and Clastic dike 03 is evident despite the distance separating them and is characteristic of clastic dikes of tectonic origin.

An essential difference between the three clastic dikes is that clastic dike 01 is straight, vertical, and linear, while clastic dikes 02 and 03 drift to the left as they move toward the top of the sedimentary profile. The origin of this drift should be found in the genesis of the clastic dikes and their upward movement through two different media, layers with various textures and structures: they originate in the laminated lacustrine layer and enter the fluviatile sand layer. They drift just at the contact of the two layers.

Figure 7. First clastic dike (Clastic dike 01)

Figure 8. Second clastic dike (clastic dike 02)

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Figure 09. Third clastic dike (clastic dike 03)

4.1.2 Grain size and mineralogical characteristics of the clastic dikes

The grain-size analysis of the clastic dykes was carried out on clastic dike 01. It focused on three samples; one sample was taken from the clastic dyke layer, and the other two from the silt layers on each side of the dike. The grain-size analysis results showed that the silt layers on both sides have the same grain-size texture, whereas three modes distinguish the clastic dike.

The two samples taken from the lacustrine layers on both sides of the clastic dike reveal an interesting pattern: the distribution curves indicate they are similar in texture but differ in some respects. Although the three samples have high silt content, the silt content in the clastic dike is higher. The two lacustrine samples have a higher content of coarse and very coarse sand (particle sizes between 2mm and 0.5mm), whereas the clastic sample is depleted of these grain sizes. Accordingly, the content of very fine sand and fine sand and medium sand (particle size between 0.500mm and 0.063mm) of the clastic dike is high, while those grain size classes are absent or very low in the lacustrine layers. This can be explained by the mobilization of the fine sand and medium sand to form the clastic dike because the clastic dike is the result of sand liquefaction during an earthquake(Moretti, 2014; Moretti and Ronchi, 2011).

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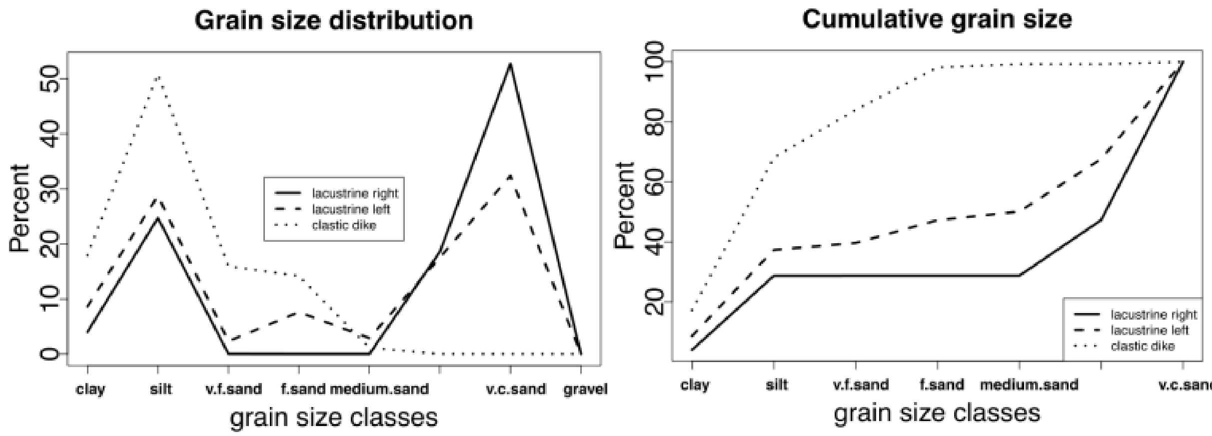

Figure 10. histogram, cumulative diagram, and grain size of the clastic dike and adjacent lacustrine sediments

The particle-size curves for the three samples are shown in the two figures above.

4.1.3 Mineralogical analysis of the clastic dike

The mineralogical analysis was carried out by comparing the heavy mineral composition of the laminated silt deposits on either side of the clastic dyke with that of the dyke itself.

The heavy mineral composition is presented in 2 groups, as shown in Figure 11: electromagnetic and non-electromagnetic heavy minerals. The analysis of the first group shows that the lacustrine samples and the clastic dike contain significant amounts of hematite, with the lacustrine samples exhibiting higher hematite content. At the same time, the lacustrine samples are depleted of tourmaline, electromagnetic rutile, leucoxene and ilmenite. The lacustrine layers contain specularites that are absent in the clastic dike. The analysis of the non-electromagnetic heavy minerals shows that the three samples have roughly equal contents of zircon and anatase because zircon is very abundant in silt deposits, and, as presented above, the silt content is higher across the three samples. The lacustrine right and the clastic dike contain equal content of non-electromagnetic rutile and leucoxene. None of the samples contains apatite, an important indicator of chemical weathering. Apatite usually does not resist heavy chemical weathering in tropical regions.

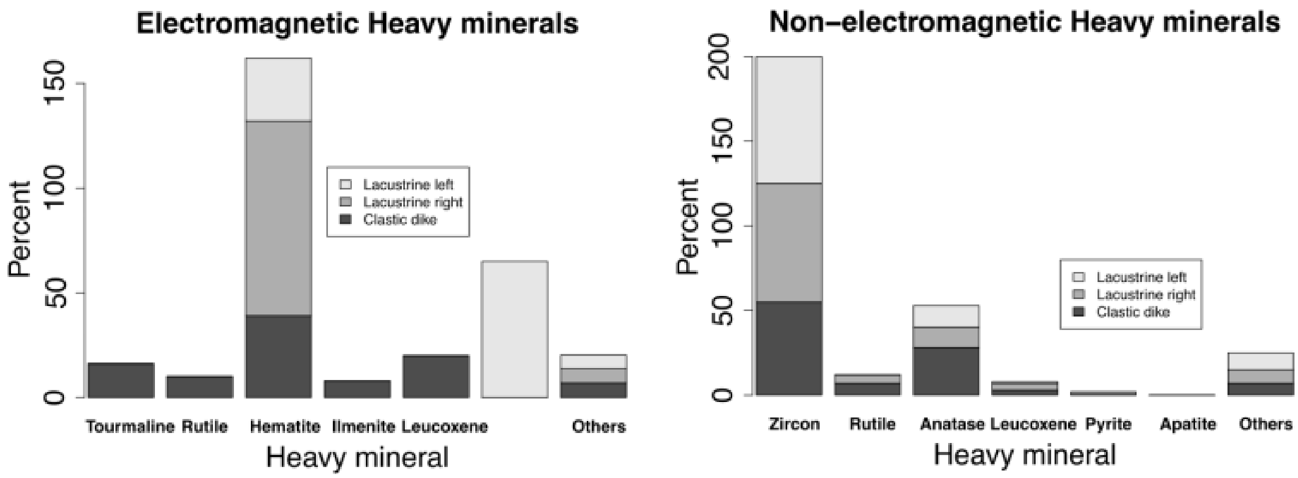

Figure 11. Heavy minerals composition of the clastic dike and adjacent lacustrine deposits

4.1.4 Dating of the clastic dikes

The absolute ages of the sediment samples taken from the silt layers and from the clastic dike were obtained using the optically stimulated luminescence (OSL) dating method. In total, four samples were taken: three from the lacustrine laminated profile and one from the clastic dike. The samples in the lacustrine layer were collected at 10 meters, 27 meters, and 33 meters from the surface of the base rock. The third sample, collected at 33 meters, was taken at the contact between the layers of fluvial sands and laminated silts. The sample at 27 meters from the silt layer was collected at the same height as the sample from the clastic dike. The dating carried out at the China University of Geosciences laboratory gave the ages, which are recorded in Table 2 below.

The results show that the contact of the fluviatile and the lacustrine layers is at 176 ka. The bottom of the profile is at 310ka, and the middle is at 283 ka. The clastic dike is 252ka meaning that it is more contemporaneous than the lacustrine layer. In fact, the date obtained from the clastic dike is the age of the deposits, but not the age of the earthquake event, which should be much younger, as the clastic dike crosses the contact between the two layers and intrudes far into the fluvial-lacustrine deposits.

Table 2: OSL dates of the clastic dike and the profile

Position on the outcrops (m)	**Date (ka)**	**Uncertainty (ka)**
10	310.2	± 21.9
27	283.6	± 14.4
33	176.0	± 14.4

Clastic dike	252.4	±11.9

4.2 Faults and micro-faults

A characteristic of seismites in the Quaternary alluvium of Bamako is the presence of faults and micro-faults. Figure (12a) shows a fault line in the fluviatile sediments. Figures (12b) and (12c) show a fault in the lacustrine and an inverse micro fault in the lacustrine deposits.

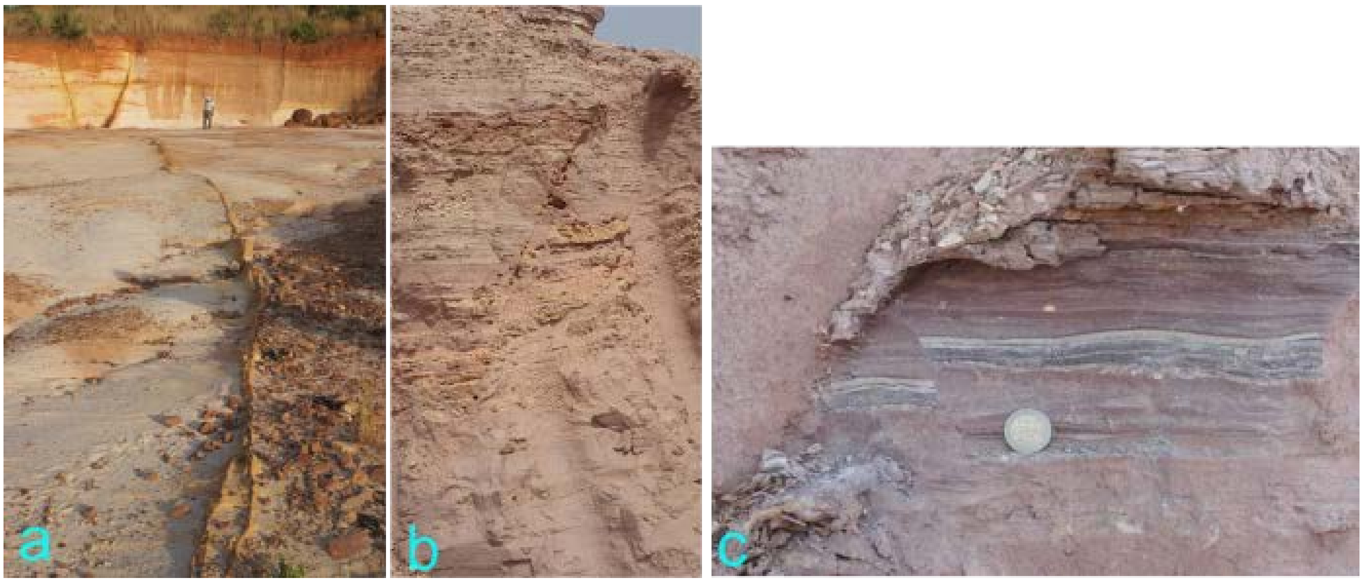

Figure 12. a. faults in fluviatile sand b. fault in laminated lacustrine deposits c. micro-fault in lacustrine deposits

4.3 Folds, ball and pillow structures

The folds result from the compression of plastic sediments during earthquakes. They are the result of the directional force that provoked the compression. In the Quaternary alluvium of Bamako, they are seen in the lacustrine sediments as undulations of laminas. The ones visible were about 100 meters long (Figure 13).

Figure 13. Folding in lacustrine deposits (a), balls and pillow structures (b)

They are highly deformed beds that become circular. An example is shown in figure 13b

5. Discussion

The seismites discovered on the Quaternary alluvium at Bamako, Mali, are soft-sediment deformations that can be used to infer Quaternary seismicity. They are clastic dikes, faults and micro-faults, folds, and ball and pillow structures. The presence of all these types of deformations in the same area attests to active tectonics in the recent past.

In Bamako, the quaternary deposits provide an adequate environment for the development of clastic dikes during earthquake movement, as they usually form in lacustrine sediments (Hibsch, Alvarado et al. 1997, Marjanac, Marjanac et al. 2001, Guo, He and Li 2023).

5.1 Significance of the clastic dikes

The clastic dykes discovered in the stratigraphic profiles of the city of Bamako provide evidence of deformation of the Quaternary soft sediments, thereby enabling reconstruction of the geological forces that formed them (Galli, 2000; Moretti, 2014). The size and orientation of the clastic dykes allow reconstruction of the environmental conditions under which they formed. The clastic dykes studied have widths reaching a meter or more and are very deep. At first glance, the external factors that enable the formation of clastic dykes are not significant in Bamako. The tectonic context of the study area indicates that the clastic dykes are not isolated but are accompanied by several other pieces of evidence of neotectonics, as presented by Dembélé (Dembélé, N.J. 2016). It is, therefore, logical to link clastic dykes, as well as other earthquakes, to its movements.

Moreover, the pioneering work of Seilacher (1969) demonstrated correlations between clastic dykes and seismic movements. Since then, a relationship has been shown between the size of clastic dykes and the seismic events that formed them; their presence also indicates the direction of seismic waves (Seilacher, 1984; Guiraud, 1993; Ezquerro, 2015; Novak & Egenhoff, 2019; Lu, 2024). The clastic dikes would be perpendicular to the seismic waves that created them. The application of this principle to the clastic dykes of Bamako makes it possible to deduce that, since the dykes are oriented NW-SE, the seismic waves were oriented NE-SW. The deep faults associated with such movements are located in the northern part of the city. They are generally perpendicular to the clastic dikes and, therefore, perpendicular to the direction of the waves. Seilacher and others (Seilacher, 1984; Moretti & Ronchi, 2011; Ezquerro, 2015; Üner et al., 2019) also demonstrated that the size of clastic dikes depends on their distance from the epicenter. The maximum size is obtained within a radius of 20 km. The exceptional size (1 m or more) of the Bamako clastic dikes shows that the epicenter of the earthquakes that created them was within this norm or range (20 km). The dating of the clastic dykes and adjacent layers shows that the clastic dike is recent, more recent than the layers in place, both the layer of laminated silts and that of fluvial sands. OSL dating made it possible to date the sediments that form the clastic dike (Porat et al. 2007, Moura-Lima, Bezerra et al. 2011), but did not allow determination of its formation time based on the chronology of the earthquake in question.

Applying the principle of cross-cutting makes it possible to confirm this hypothesis insofar as the clastic dike cuts across the boundary between the two layers dated at 176 ka. It extends deep into the river sand layer. The direction of intrusion can also be deduced. In most cases, clastic dykes form from the bottom up when sand liquefies during earthquakes (Berardi, Margottini, et al., 1991; Obermeier, 1998; Jolly and Lonergan, 2002; Green, Obermeier, and Olson, 2005; Owen & Moretti, 2011; Shao, 2020). The strike of all clastic dikes is vertical in the silty layer. This direction is deviated when it crosses the sandy layer. This is easily understood if we consider the grain-size difference that causes refraction in the clastic dike. Finally, the size of the clastic dikes allows assessment of the magnitude and intensity of past seismic activity. Galli found that clastic dikes generally form when seismic waves reach or exceed M=6.5. There is also a relationship between the size of the clastic dike created and the magnitude and intensity of the earthquake to which it is linked. An earthquake of M=6.5 produces a clastic dike of approximately 10 cm (Galli, 2000; Lunina, 2019). Based on these data, we can safely state that the earthquake or earthquakes that produced the Bamako clastic dykes reached this intensity or even M=7.

The differences in the orientations of the clastic dikes indicate that they were formed by distinct seismic events. The clastic dike 01 and 03, which are perpendicular, were formed during the same event, different from the one that formed the clastic dike 02. In total, the discovery of the clastic dike indicates that Bamako has experienced at least two major earthquakes in the Quaternary.

5.2 Significance of the faults, folds, and ball structures

The presence of soft-sediment deformations such as faults in fluviatile and lacustrine sediments at Bamako, folds in laminated sediments, and ball structures in lacustrine sediments is evidence of compressional forces in the area. The presence of reverse faults and micro-faults in the Quaternary sediments is the result of recent earth movements in the area. McCalpin and Carver (McCalpin and Carver, 2009) present the compressional characteristics of the reverse faults and their link to surface folds that express them. In Bamako, the same behavior is interpreted as faults, and reverse faults are usually found deep, at 30 to 40 meters, whereas folds are located near the surface.

6. Conclusion

The presence of deformation structures in Quaternary soft sediments generally indicates neotectonic movements in a given region. This study presented the Bamako clastic dikes as part of such deformation structures. It is possible to inform the direction of the seismic waves, the location of the epicenter of the earthquakes, and the magnitude of the seismic shock from the morphological characteristics of the dykes. In Bamako, the application of deduction methods made it possible to demonstrate that the seismic waves had a NW-SE orientation, that the epicenter lay within a radius of 20 km, and that the magnitude of the earthquake that generated them must have exceeded M6.5 or M7. These neotectonic movements are also evidenced by the numerous faults, folds and ball structures found in the area. Very few studies have examined the seismicity of the Bamako area and the West African craton. It is essential to emphasize the existence of this evidence nowadays as the basis for further enquiries into neotectonics in the region, as cities are getting bigger and deadliest earthquakes have lately been linked to previously unknown and not thought to be active faults.

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