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ARTICLE

Geotechnical Risk Assessment and Geological Origin of Building Fracturation in Agadez City (North Niger)

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ABSTRACT

The Agadez city is built on the faulted and fractured sandstone formation of the "Agadez Sandstones", which was deposited in unconformity on the Precambrian basement of the Aïr Mountain. The present study focuses on the geotechnical risk assessment and geological origin of building fracturation in Agadez city. A methodological approach integrating measurement of fractures planes affecting the buildings and their statistical analysis has been implemented. Statistical analysis of obtained data showed that in 100 fractured buildings, about 3% of buildings are at risk of collapse (very high risk), 64% of buildings are fractured (medium risk of collapse), and 34% of buildings are cracked (lower risk of collapse). These results showed as well that the nature of the material (rheology) influences the buildings fracturation. Indeed, buildings made from cement are more easily fractured than buildings made from clay materials. Statistical analysis of fracture planes reveals that the geotechnical risk associated with building's fracturation propagates in NW-SE, corresponding to the major directions of risk propagation, mainly dipping in northwest sectors (zones) of the Agadez city. The interpretation of geological and geophysical data combined with those obtained in the case of this study, reveals that the risk associated with buildings fracturation in Agadez city is caused by geological seismic events and or anthropogenic activities (explosive firing on the uranium mining sites like Somaïr and Cominak).

1. Introduction

The Agadez city is built on a fractured sandstone formation, called "Grès d'Agadez" according to the Agadez sandstones nappes map [1], depositing in unconformity on the Aïr Mountains Precambrian basement (Figure 1). Along the western edge of the Aïr Mountains, the sedimentary cover exhibits a succession from Devonian to Lower Cretaceous as revealed by the geological data carried out in the Tim Mersoi basin [2]. According to the previous geological data [1,3-5], all these geological units (basement and basin) are affected by brittle deformations in the

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state faults and or fractures with several orientations. Thus the main directions of faults are as follows (Figures 1 and 2):

- At a regional scale, the In-Azaoua-Arlit fault system, N0° trending and the Madaouéla N30° fault system (Figure 1),
- The N130° to N140° trending faults system, affecting the Aïr Mountains, is less frequent in the Tim Mersoï basin,
- The N70°-N80° fault system (farther to the west in the DASA area) has been reactivated in dextral sense during the Upper Cretaceous as indicated by the results of structural study obtained in the Tim Mersoi basin [5,6].
- Another active SSE-NNW system fault was highlighted by the seismic map of African continent [7] on the Eastern edge of Air Mountains and in oriental sedimentary basin of Niger (Figure 2).

On the one hand, these faults and fractures networks would control the setting up of the uranium mineralization in the Tim Mersoï basin as indicated by structural study and mining exploration [5,6,8] and, on the other hand, they present a geotechnical risk in the mining of uranium deposits as suggested by structural study in the Akola uranium ore deposit (Arlit) [9] and on the buildings in the surrounding urban centers.

In the Agadez city, the phenomenon of building fracturation is observed, as well as, on the buildings made from clay materials and those made from cement. The associated risks present in the state of cracks, fractures and faults, often leading to the collapse of buildings resulting in loss of life and property damage. Despite the materials and human damages due to this phenomenon, no significant scientific study has been carried out about the causes and consequences of this geotechnical risk in this town. In addition, the scientific questions in this study involve: what kind of building is more affected by the fracturation? What is the mean direction of the georisk propagation related to this fracturation?

This preliminary study on buildings fracturation aims to assess the geotechnical risks related to the buildings fracturation that occurs in Agadez city. To reach this objective, a methodological approach combining in situ measurements and statistical analyses of obtained data and current state of geological research was implemented.

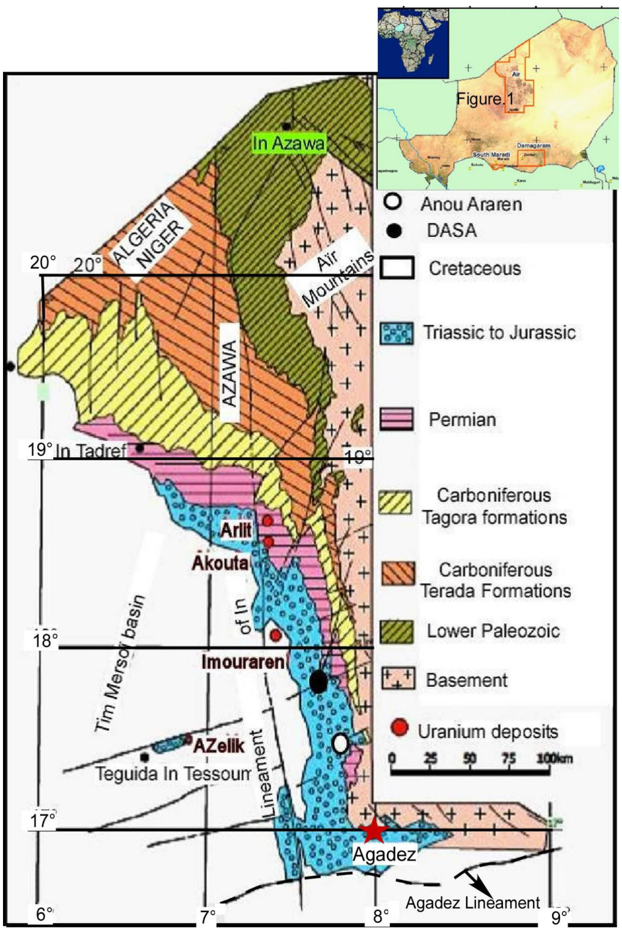

Figure 1. Location of Agadez city on the geological map of the Eastern part of Tim Mersoï Basin, from the previous geological data [1,3-5].

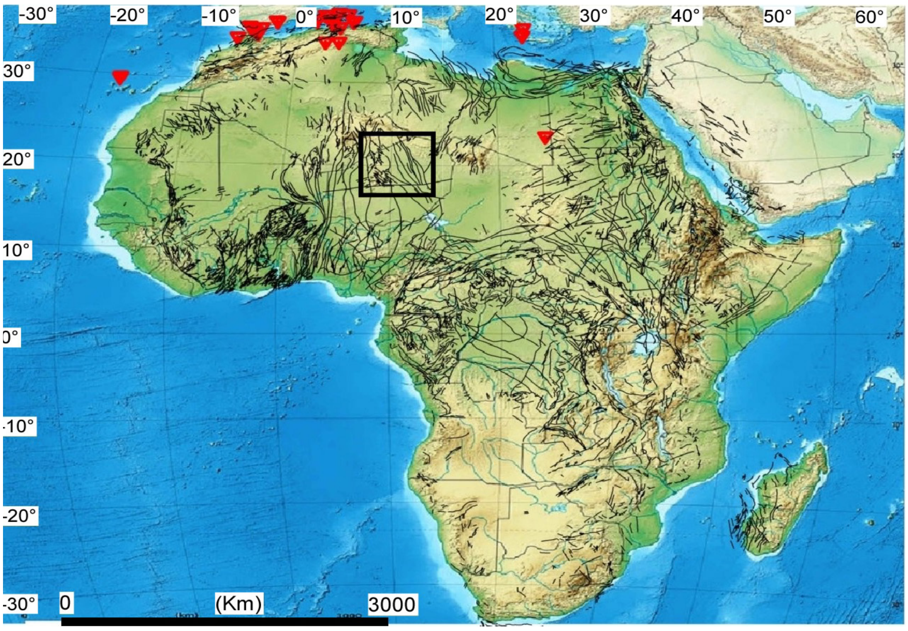

Figure 2. Location of seismic centers (red point) within the tectonic map of Africa seismic, showing the NNW-SSE system fault (black rectangle) on the Eastern edge of Air Mountains and in the oriental sedimentary basin of Niger from OTICE [7].

Note: The original language is French.

2. Materials and Methods

The methodological approach adopted in the case of this study is based on both review literature on the study area, field investigation and processing and statistical analysis of collected data:

1) The review literature focused on bibliographic research of thesis, articles, scientific reports and all other documents relative to the geology of the studied zone,

2) The field investigation consisted of prior identification of the most affected sectors by fracturation and in situ structural measurement of fracture planes. This stage was carried out with material as follows: GPS (for site location), Compass (for direction and dip acquisition of a structure), and acquisition form of structural data, presented in Appendix A1. Data acquisition method was based on the determination of the state structure (crack, fracture fault), its direction and dipping sector and also the type of building affected (from clay material, from cement).

3) Processing and statistical analysis of measured structures was carried out by using the software SPSS.20.0 and MS. Excel 2013, well known for the statistical analysis. Based on risk assessment associated to the building fracturation, this stage consists of:

(1) The classification of collapsing risk according to the opening width of fractures, (2) Risk assessment according to the type of buildings and (3) Risk assessment according to the directions and dip sectors of risk propagation.

3. Results and Discussions

3.1 Identification and Classification of Geotechnical Risks

The obtained data come from the buildings made from cement and those made from clay materials of 10 sites, most affected by the fracturation (Figure 3). The GPS coordinates of different sites are indicated in Appendix A2. The deformation structures identified were classified according to their opening width (Figure 4). The different structures identified are:

- cracks (fine close fractures having a millimetric width Figure 4A) which are considered to be a low-risk structure;
- fractures in the strict sense (the opening of the lips has a millimetric to centimetric width, Figure 4B): these types of structures present a lower risk of building collapse;
- faults planes (these are fractures along which collapse can be observed in buildings, Figure 4C). They present a high geotechnical risk, usually leading to the abandonment or reconstruction of the building.

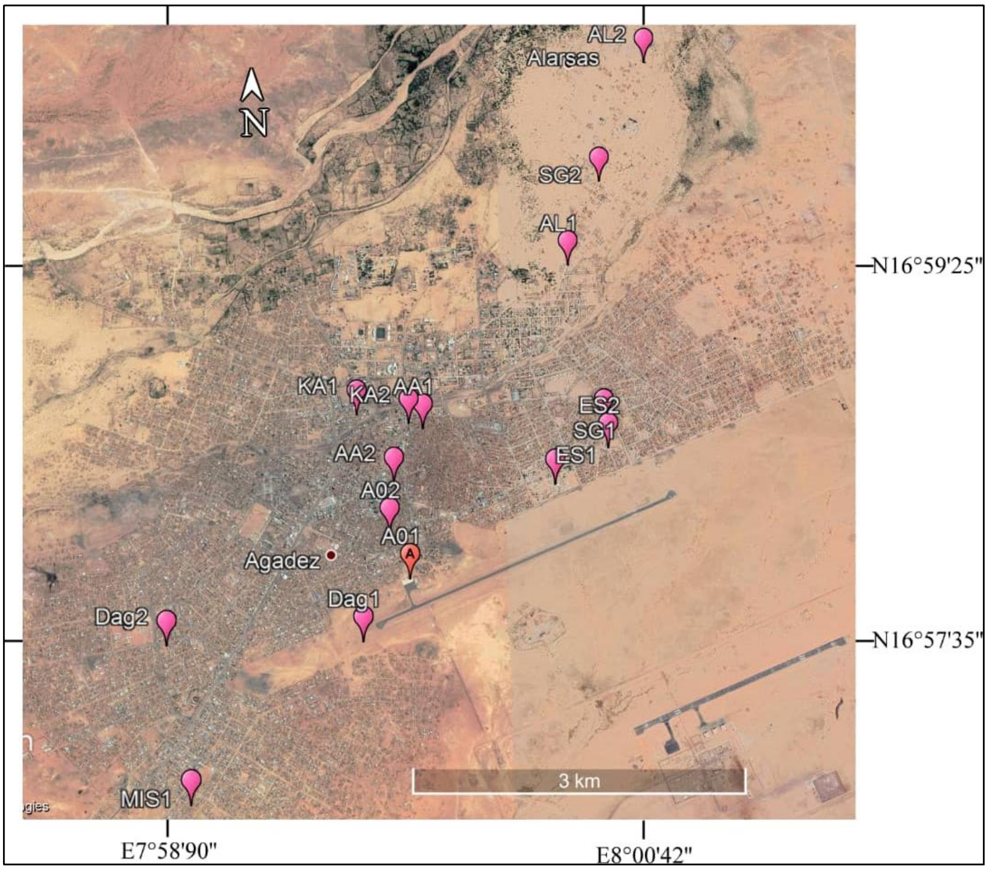

Figure 3. Google Earth location map of the measurement sites for the different fracture planes.

Note: **Sites abbreviations**: **AO**: Airport/Obitara, **ES**: Emair/Sabon Gari, **Mis**: Misrata; **AL**: Tadalanfai/Alaghsass; **KA**: Katanga/Amarewat; **AA**: Amarewat/amdite; **Dag**: Dagmanet; **SG**: Sabon Gari.

3.2 Risks Assessment According to the Type of Buildings

A total of 220 fractures planes affecting the buildings were identified and measured. All of the collected data (structural data and type of buildings studied) are indicated in the Appendix C at the separated excel file. The statistical analysis of measured structures by type of dwelling (Table 1) concerns over 200 structures:

- 74 of measured structures correspond to cracks, i.e. 34%, of which: 40 affected the buildings made from cement and 34 in clay material;
- 140 structures are in the state of fractures , i.e. 64%: 91 affected buildings made from cement and 49 affected the buildings made from clay material;
- 6 structures correspond to the faults, i.e. 3%, of which 2 affected the clay buildings and 4 cement buildings.

Based on percentage of the structural data, out of 100 buildings affected by fractures, about 3% are at risk of faulting, 64% undergo a risk of fracturation, and 34% are affected by simple cracking, which represents a lower risk of collapse.

Data analysis has shown as well that rheology (nature of the material) influences the buildings fracturation. Indeed, the buildings made with cement and reinforced concrete (made from sandstone material) are more easily fractured than buildings made with clay materials. For example, in 220 measured fractures, 135 affect the buildings made from cement, and 85 the buildings made with clay materials (Table 1), or 61.36% against 38.64%.

According to the results obtained by microtectonic study [10], this is due to the difference on rheological behavior between clay which is a plastic and ductile material and sandstone and concrete which are brittle materials.

These observations are in agreement with the results obtained in the Franklinian Basin [11] where, considering the rheology of the materials, the sandstone strata was qualified as a "competent level" for brittle deformation and the clay strata as "incompetent level".

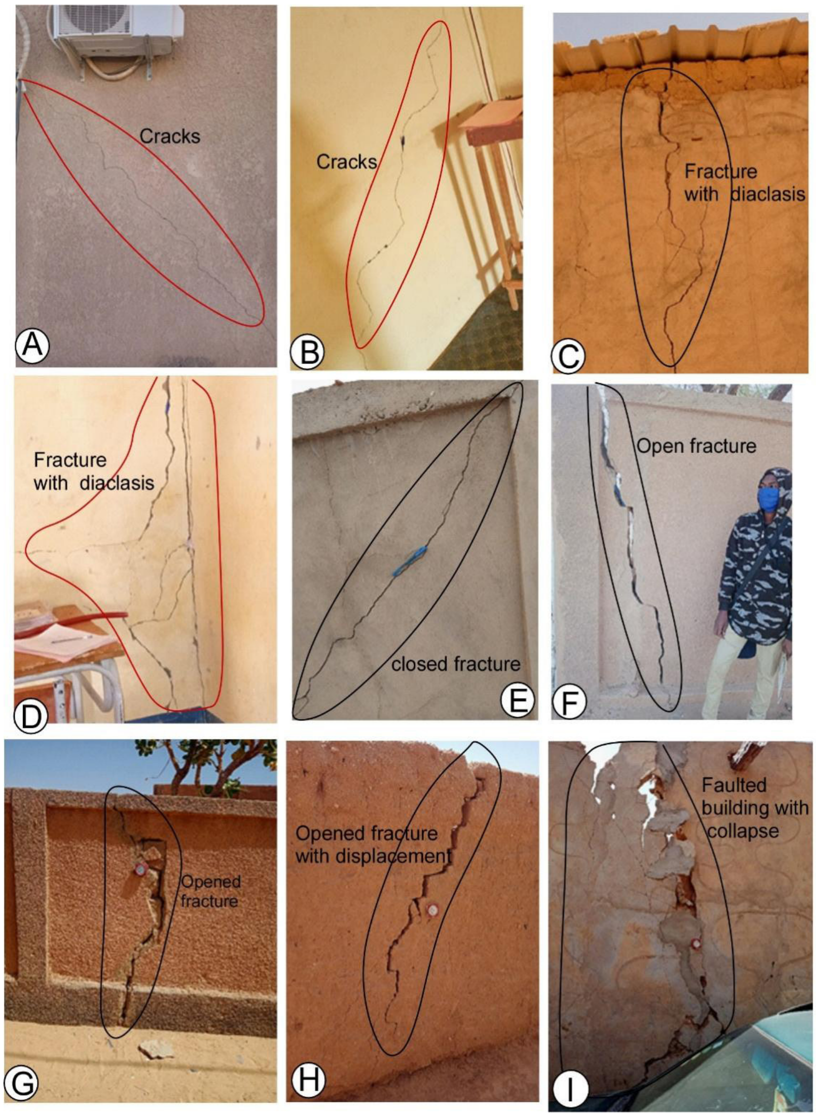

Figure 4. In situ photographs of deformation structures showing the impact of hazards on homes. (A and B) cracked buildings (low risk), (C, D, E, F) fractured buildings (medium risk of collapse), (G, H, I) fractured and faulted buildings (high risk of collapse).

Table 1. Statistic of measured structures in number and by type of material.

State of structures	Number	Percentage (%)	Type of building	
			From cement	from Clay material
Cracks	74	34%	40	34
Fractures	140	64%	91	49
Faults	6	3%	4	2
Total	**220**	**100%**	**135**	**85**

3.3 Risk Assessment According to the Directions and Dip Sectors of Risk

Analysis of geotechnical risks related to fracturation is based on both the determination of direction and dip sectors of fractures planes. Thus, the directions and dip sector of measured fractures (Table 2) were statistically analyzed.

3.3.1 Directional Analysis of Fractures

To determine the major direction of risk propagation, 220 measured planes of fractures are classified by direction interval of 45° from the North (Table 2 and Figure 5). The results of statistical analysis by the percentage of directions are as follows:

- the N0°-N45° directions: 25%,
- N45°-N90° directions: 30%,
- N90°-N135° directions: 12.73%; and

- N135°-N180° directions: 32%.

According to these observations, the directions ranging from SE-NW (N135°) to SSE-NNW (N175°) are the majority with 32%, followed by NE-SW (N45°) to E-W (N90°) directions with 30%. Therefore, the geotechnical risk related to the buildings fracturation has a stronger propagation component according to the mean direction NW-SE (N135°).

Table 2. Directional distribution of measured fractures.

Direction intervals	Effective	Percentage (%)
[N0°-N45°]	55	25.00
[N45°-N90°]	66	30.00
[N90°-N135°]	28	12.73
[N135°-N180°]	71	32.27
Total	220	100.00

3.3.2 Analysis of Fractures According to the Dip Sectors

The risks related to a fracture plane of buildings are not only associated with their propagation directions but also with their dipping sectors. For this, the statistical analysis of 220 fractures planes by their dipping sector was carried out. Thus, among these 220 planes measured:

- 24.55% are dipped toward the Northeast sector,
- 22.27% toward the Southeast,
- 19.09% toward the Southwest, and
- 34.09% toward the Northwest (Table 3 and Figure 6).

This analysis shows that the fracture planes of buildings are dipping mainly (34.09%) in the northwest sectors (zones) of the Agadez city.

Table 3. Statistic of fractures according to their dipping sectors and associated graph.

Dip sectors	Effective	Percentage (%)
North-East	54	24.55
South-East	49	22.27
South-West	42	19.09
North-West	75	34.09
Total	220	100.00

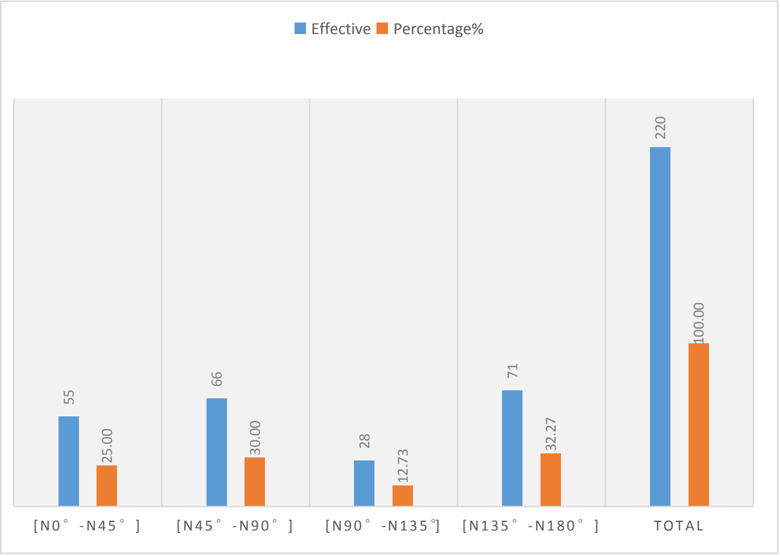

Figure 5. Histogram of 220 measured fractures planes according their directions.

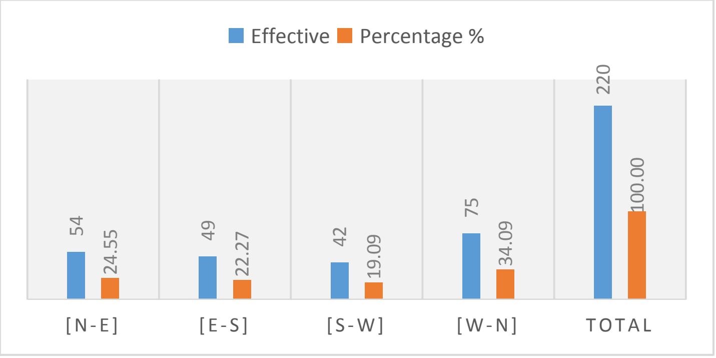

Figure 6. Histogram of 220 measured fracture planes according to the dipping sectors.

Riposte and reducing measures of risks

Despite the damages caused by this geotechnical risk of fracturation, preventive and riposte measures remain still classic. These measures involve the filling of open fractures with cement, which are not yet collapsed (Figures 7A-7B). In some cases, processed fractures continue to widen despite clogging, leading to the definitive abandonment or reconstruction of the building.

This is the case of the buildings of the Regional Direction of Hydraulic (HRD, Agadez, Figure 7C) and some blocks of the Regional Centre of Mother and Child (CRME, Agadez, Figure 7D).

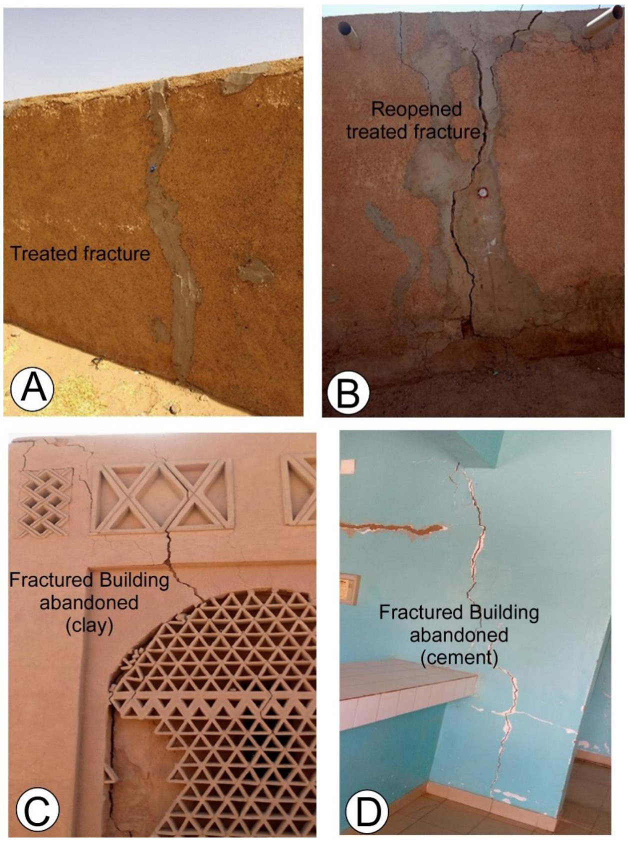

Figure 7. Mitigation and riposte measures against the risk of fracturation of houses in the city of Agadez. (A) Treated fracture, (B) reopened treated fracture (with post-compaction operation), (C) abandoned block in clay material (Dagmanet Town hall, Agadez), (D) abandoned block in final material (Maternity, Agadez).

3.4 Origin of Buildings Fracturation

The phenomenon of buildings fracturation in Agadez city can be interpreted as resulting from the effects of seismic movements occurring within the earth. These seismic movements can be tectonic in origin (natural) or anthropogenic (dynamite blasting at mining sites).

Geological Origin

To better understand and explain the origins of seismic movements causing building fracturation, the investigations focused on: (i) local and regional geological data [4,12-14], (ii) geophysical data (magnetic and seismic) combined with the field observations. The analysis of these data shows that the Agadez city is located on a tectonically active zone corresponding to a major N-S trending lineament belonging to the Arlit In-Azaoua fault system (Figures 1, 2, 8).

According to the geophysics interpretation map [15], the N-S faults affecting the Agadez region (Figure 8) were the focus of three seismic events. The satellite fault of the In Azaoua-Arlit lineament, located to the west of the Agadez city (Figure 8), has been the focus of two seismic events (on May 19, 1967 and on January 18, 2017) according to the African seismic map [7]. In seismology, these three seismic events are considered to be a recurrence phenomenon (in this case every 50 years). Unfortunately, the data did not allow us to know the activity of this fault during the period 1907. If this recurrence is correct, another seismic event should affect this fault in 2067. The Raghane shear system, passing to the eastern part of Agadez city (Figure 8, was the focus of a seismic event on 4th July 1969 from geophysics interpretation map [15]. There is also a potential seismic zone corresponding to a system of strike slip faults oriented ~N75° (Figures 1 and 8), called “Agadez Lineament” [16] or the Guinean-Nubian Lineament (GNL) [17,18] that passed through the southern part of Agadez city [19,20].

A structural study carried out on the Agadez sandstones and the underlying basement (Figure 9), showed that faults and fractures oriented N120° to N165°, affect both the basement of the Aïr Mountains and the sandstone formations on which the city of Agadez is built (Figure 9D**)**. These observations indicate a close relationship between the seismic events affecting the Aïr Mountains and the cracking of buildings in the Agadez city.

These faults and fractures oriented N120° to N165° have been identified on the pseudo-geological map of the southern edge of the Aïr Mountains, produced from the interpretation of Mag/Spectro and Mag/EM airborne geophysical data [15] (Figure 10).

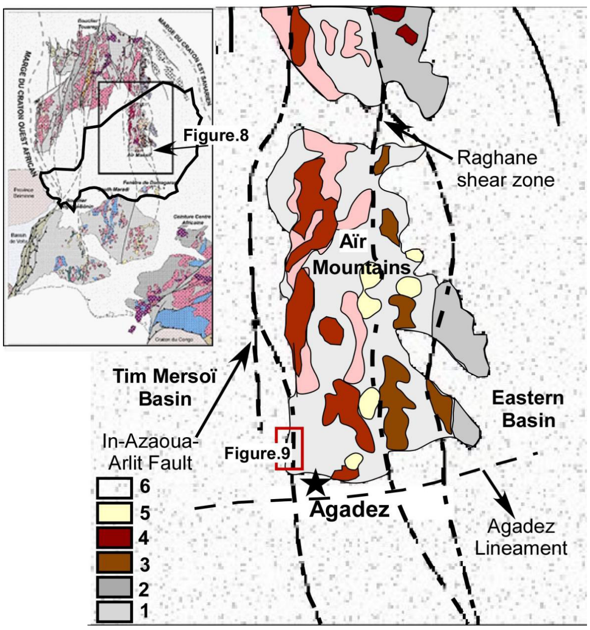

Figure 8. Trans-Saharan regional structures through Aïr Mountains: Raghane shear zone passing to Eastern part of Agadez city and In-Azaoua-Arlit Fault to Western Aïr Mountains [15], modified.

Note: 1. Remobilized Paleoproterozoic Crust, 2. Pan-African Juvenile Crust, 3. Calcaline Granites, 4. Anatectic granites, 5. Younger Granites, 6. Sedimentary Rocks. Original language: French.

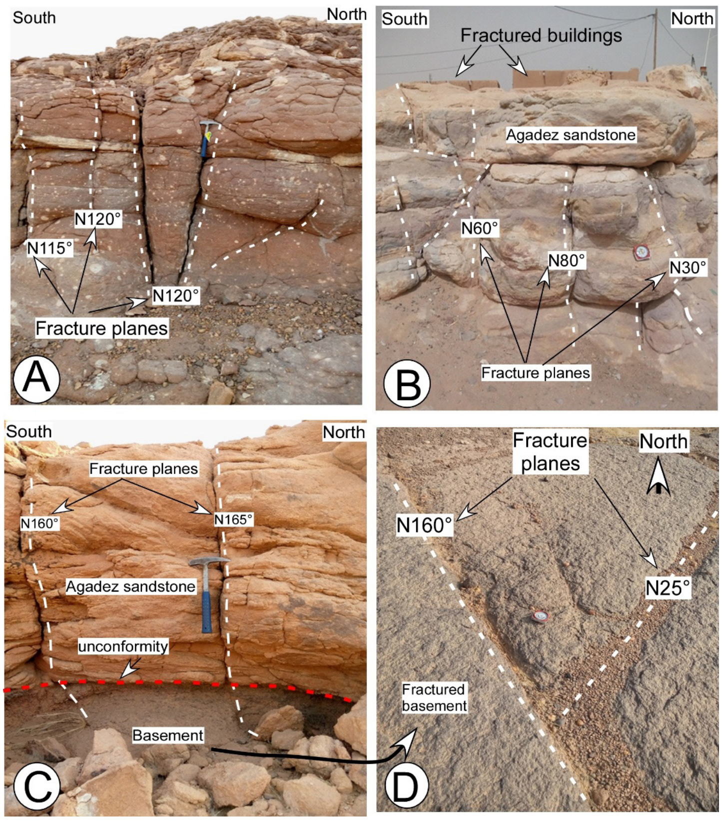

Figure 9. In situ photographies showing the narrow-relations between building fracturation and those affecting the underlying sandstones and basement. (A) Tchibbinnitan fractured sandstones, (B) buildings and their underlying fractured sandstones, (C and D) respectively Agadez sandstones and its underlying basement, all affected by the same directions of fractures.

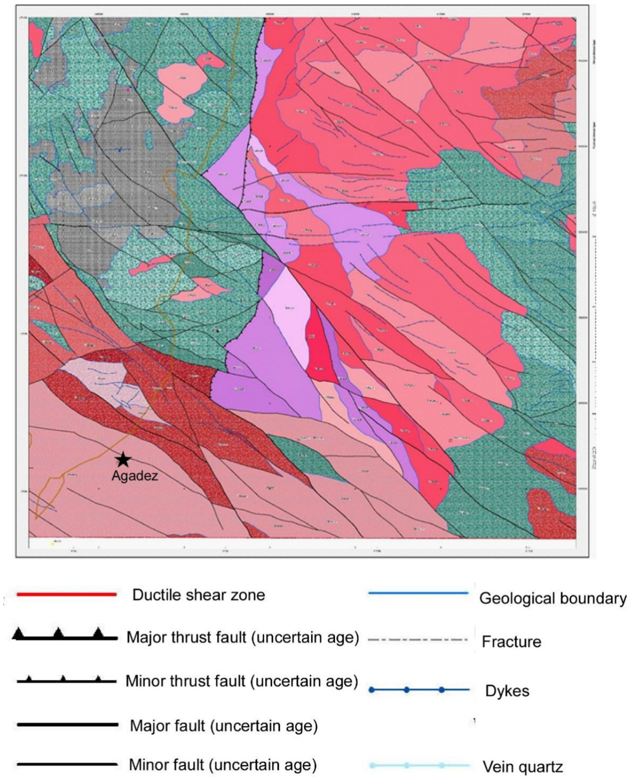

Figure 10. Interpretation of the geophysical map from Mag/Spectro and Mag/EM [15], showing the major directions of fractures affecting the crystalline basement of the Aïr, the Tim Mersoï basin sandstones and the Agadez city buildings.

Note: The original language is French.

Anthropogenic origins

The use of dynamite during the mining of sites such as the Somaïr, Cominak, Sonichar, and Imouraren projects are the anthropogenic activities that create seismic waves that can promote the fracturation of buildings in the city of Agadez. In addition, the vibrations of airplanes during take-off and landing would induce fracturation of the surrounding buildings. Thus, it is imperative to install seismic observation stations using portable seismometers to study fracturation related to seismic waves.

4. Conclusions

According to this study, out of 100 fractured buildings, about three (3) are at major risk of collapse, sixty-four (64) are at risk of fracturation and thirty-four (34) are at risk of cracking. The results also showed that the rheology of the materials strongly influences the fracturation of the building. Indeed, cement buildings fracture more easily than clay buildings.

The kinematic analysis showed that building fracturation has a higher propagation tendency according to the SE-NW direction (N135° on average) in the city of Agadez.

The origin of the fracturation of the buildings was attributed to seismic waves whose origins can be natural (tectonic) or anthropogenic (blasting at mining sites and aircraft vibrations).

4.1 Recommendations

Based on the causes of building fracturation identified by this study, the following recommendations can be made to avoid or reduce the fracturation risks:

- **For tectonic and geological causes**
  - to promote the construction of buildings in clay materials rather than in cement and concrete. Indeed, clay materials with a plastic rheology are less exposed to the fracturation,
  - to consider minor directions of fracture propagation for construction,
  - to study the geological and geotechnical characteristics of the soil before building,
- **For Anthropogenic effects**
  - to avoid the building along or around the fault zones and on basement with predominantly fractured rocks,
  - by acting on the power of the explosives, which should not exceed the energy required to fragment the rocks in the mine,
  - by relocating the airport so that the vibrating waves produced by the aircraft do not impact the social accommodations,
  - to avoid building in the high-vibrating zone (around airports) and or nearby mining sites.
- **For geotechnical measures**
  - the geotechnical standards of civil engineers should take into account the effects of seismic events,
  - for the buildings made from cement, respect the geotechnical construction standards (correct cement dosage and well-reinforced concrete).

4.2 Research Perspectives

In order to accurately determine the causes of the fracturation of buildings in the Agadez city, we aim, together with the mining operators on the one hand and the civil engineers on the other hand:

- to install at least three seismometers at specific locations to identify the seismic focus that is causing the building fracturation,
- to carry out the mechanical tests on the underlying formations (Agadez clay and sandstones) to understand their rheological properties before constructions.

Author Contributions

Baraou Idi Souley: Chief of Investigation, fieldworks, data analysis, cartography and writing manuscript leader,

Abdoulwahid Sani: Permanent assistant during fieldworks, data analysis and cartography operations,

Abdoul Wahab Djibo Maïga: Contributes for geophysical data acquisition (seismic and magnetic maps) and their interpretation,

Moussa Konaté: Research supervisor and permanent assistance during manuscript writing.

Conflict of Interest

No conflict of interest.

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Appendix A1

Form of structural data **Site name…………………………………………….**					
Station N°…..	**Latitude……………………..… Longitude…………..…………….** **Altitude………**				
Planes N°	**Direction**	**dip**	**Dipping sector**	**State of structure (crack, fracture fault?)**	**Type of building (from clay material, from cement?)**
1					
2					
3					
4					
5					
6					
7					
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9					
10					
11					
12					
13					
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15					
16					
17					
18					
19					
20					

Appendix A2

Sites	GPS Coordinates (Degree decimal)	
	Longitude	Latitude
Aéroport/Obitar1 (AO1)	7.99010	16.96467
Aéroport/Obitar2 (AO2)	7.98839	16.96846
Emair/Sabon Gari1 (ES1)	8.00276	16.97216
Emair/Sabon Gari2 (ES2)	8.00746	16.97509
Misrata1 (MIS1)	7.971305	16.94694
Misrata1 (MIS2)	7.953611	16.93472
Tadalanf/Alaghsass1 (AL1)	8.00444	16.990555
Tadalanf/Alaghsass2(AL2)	8.011805	17.008055
Katanga/Amarewat1 (KA1)	7.9857	16.97828
Katanga/Amarewat2 (KA2)	7.99021	16.97749
Amarewat Amdite1 (AA1)	7.99142	16.97699
Amarewat Amdite2 (AA2)	7.98885	16.97261
Dagamanet1 (Dag1)	7.96933	16.95983
Dagamanet1 (Dag1)	7.967777	16.96375
Dagamanet2 (Dag2)	7.96561	16.954666
Dagamanet2 (Dag2)	7.96919	16.95966
Sabon Gari1 (SG1)	8.00715	16.97709
Sabon Gari1 (SG1)	8.00408	16.97994
Sabon Gari2 (SG2)	8.00745	16.997705

Appendix/Supplementary materials available

Checklist is presented as stand-alone including simplified supplementary materials in the shape of appendix C. This table is the original creation of the author and all sources are acknowledged and appreciated for its contribution to knowledge and building maintenance. The checklist (table) covers 220 measured fracture planes on the buildings and has too much content (including direction, dips, dip sectors, state of fractures and type of affected building) to display herein. Please contact the journal editorial office if you require.