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Application of paleostress analysis for the identification of potential instability precursors within the Benue Trough Nigeria

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Abstract

Background: Structures such as faults, joints and fractures of diverse patterns have acted as precursors of several slope instability cases within the Benue Trough Nigeria. In some cases, the structures by their nature weakened and also created avenues that streams took advantage to further destabilize the rock slopes. In other cases, structure orientation played significant roles in the mobility and eventual runout distance of debris flow and avalanches in the region. Detailed field-based structural, fracture and paleostress analyses were therefore carried out to determine the fractural patterns that correlate to reported instability and landslide cases in the region; and to produce models that reveal areas with heightened risk.

Results: Three fracture sets were isolated from analysis of fracture orientations and field relationships: Pre-folding (JT), Syn-Folding (JS) and Post Folding (JC) fracture systems. Paleostress analysis carried out on these fracture systems using the TENSOR™ software tool yielded three paleostress tensors corresponding to transtensional stress tensor with ENE-WSW direction of maximum extension (S_{HMIN}), oblique compressive (transpressional) tensor with NW-SE direction of maximum shortening (S_{HMAX}), and transtensional tensor with WNW-ESE direction of maximum extension (S_{HMIN}).

Conclusion: These tensors are related to the prevailing plate tectonic stress regimes affecting the entire Benue trough and the West and Central African Rift System (WCARS). Our pre- and post-tectonic models have revealed the reasons for instability and the likely places where future failures may be located. This is the first such analyses in the region and it is hoped that the results can broaden the use and applicability of paleostresses in failure-prone terrains for future risk and disaster reduction/assessment within the Trough and in other areas prone to structure-controlled landslides disaster.

Keywords: Paleostress, Instability, Landslides disaster, WCARS, Transtension, Transpression

Background

Geologic structures have been reported as precursors and control of several medium to large-scale rainfall-induced landslides within the Benue Trough Nigeria (Fig. 1) and the Cameroon Line (Igwe 2015a,b; Igwe et al 2015; Igwe et al 2016). These and other slope movements cause considerable loss of resources in a country where poverty and sundry socio-cultural circumstances rarely permit the implementation of disaster/risk reduction strategies.

In 2010, a rock-debris avalanche, unprecedented in scale and form, occurred on the hillslopes bounding Nigeria and Cameroon. Igwe et al (2015) reported the avalanche (Fig. 2) initiated as distinct slides on two slopes weakened by ubiquitous fractures. The observed surface displacements and predicted mechanisms of movement indicated that the slides started from different blocks at speed between 8 and 20 km/h. Soon after however, a structurally-controlled coalescing of the two slides, the subsequent movement of the coalesced mass slope along an expanded fracture surface, and the flow of water along the same fracture system aided a quick transformation to a highly mobile mass movement that attained speed between 55 and 80 km/h. Half way down

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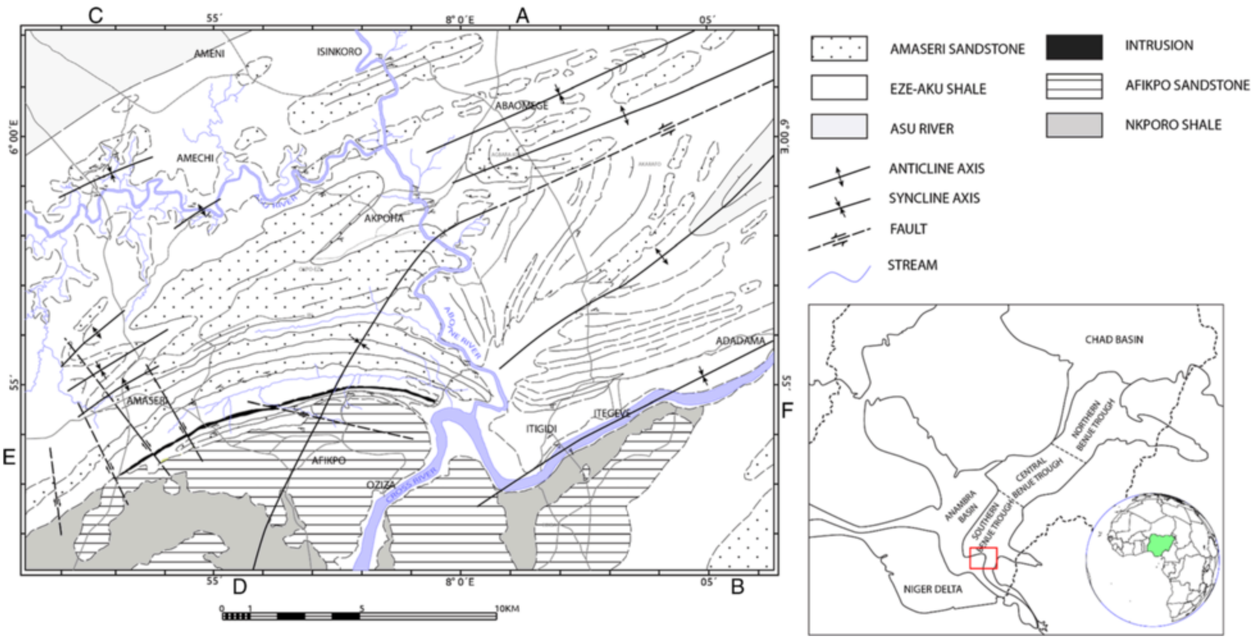

Fig. 1 Location and geological attributes of the Benue Trough

the slope, the moving masses were transferred to a surface with numerous foliations that were perpendicular to the direction of movement which enhanced mobility (>110 km/h) until reaching a distance of over 2.5 km where gradual deposition commenced. Several lives, acres of land, farms, trees and economic treasures were lost during the episode.

Similarly, Igwe (2015b) described a fractured slope in which streams took advantage of discontinuities to trigger a landslide in an area without any previous history of failure. It became obvious afterwards that this particular case was clearly a case of a disaster waiting to happen because researchers had not observed the myriad of fractures in the basal lithologic units comprising the slopes. The occurrence of fractures and their study are therefore important not only in slope stability risk assessment but also in disaster reduction and management. The understanding of the stress orientation will improve the knowledge of deformation mechanisms, which is crucial for the implementation of a viable monitoring system.

Fig. 2 The 2010 rock-debris avalanche showing the source and a part of the landslide toe where the researcher is standing

Irfan (1999), Revellino et al (2010), Grelle et al (2011), Aucelli et al. (2013), Prakash et al (2015) have reported structurally-controlled landslides. Investigation of the landslides revealed that the geo-structural settings predisposed the slopes to factors triggering mass movements, which is consistent with Fookes and Wilson (1966), Zaruba and Mencl (1969), and Varnes (1978). A structurally-controlled landslide is also documented in Luzon et al (2016) where it was reported that the 2006 rockslide-debris avalanche in Southern Leyte, one of the largest known landslides in the Philippines in recent history, occurred on a weakened slope at an area where there was continuous movement along the Philippine Fault. The characteristics and mechanisms of the Leyte landslides reported in Sassa et al (2004) and Catane et al (2008) are similar to those of the Nigeria-Cameroon border avalanche.

Brittle fractures are the consequences of the action of stresses on a macroscopic scale. A rock body subject to a known stress regime (that produces fractures) has an unambiguous relationship among the fracture planes and the orientations of the stresses. This concept can then be used to reconstruct the orientation of forces that created the fractures that were active in the past based on present day orientations. To fully understand the applicability of paleostress technique in risk assessment, it is necessary to analyze ancient stress regimes in the context of their role as potential precursory agents. Kayen et al. (2011) noted that stress analysis is a useful and popular tool for structural and seismological elements. Kaymakci (2006) reported that the state of stress in rocks is generally anisotropic and is defined by stress ellipsoid axes, which characterize the magnitudes of the principal stresses. The paper determined Paleostress orientations and relative paleostress magnitudes (stress ratios) using the reduced stress concept for the purpose of improving the understanding of the kinematic characteristics of a Basin.

At the moment, there is no previous paleostress study of the study area, which has in part hindered knowledge of the potential instability precursors in the zones of frequent slope failures. Even though a century of geological study has enabled an extensive understanding the geology of the Benue Trough, it was only in the later part of the 20th century that a picture of the structural framework, within which the trough evolved, began to emerge. The controversies surrounding the tectonic evolution of the Benue trough have been largely resolved; with the overwhelming evidence leaning towards the interpretation of the Benue trough as a collection of wrench related pull apart basins related to transcurrent movement along deep-seated oceanic transform faults (Benkhelil 1982, 1989; Guiraud et al 1989; M. Guiraud 1993). The evolution of the basin has also been incorporated into a framework of genetically related basins in west and central Africa: The West and Central African Rift System (WCARS) (Binks and Fairhead 1992; Genik 1992; Guiraud et al 1992; Guiraud and Maurin 1992; Fairhead et al 2013;). There is only limited field based structural studies especially in the central and southern parts due to the nature of the units which do not allow for preservation, and the tropic climate which makes for a difficult terrain to carry out detailed structural studies necessary to obtain information which could be used to deduce structural regimes that can be correlated to the precursor factors reported in several slope failures within the trough, and data required for the various methods of stress inversion (Benkhelil 1986).

Geologic and stratigraphic setting

The Afikpo synclinorium, forming a part of the Southern Benue Trough (Fig. 1), offers a unique opportunity to study and understand the deformational processes and to determine the tectonic stresses active in the southern Benue trough as the highly indurated nature of the sediments allow for a relative abundance of outcrops where structural data useful for inversion could be collected.

The study area falls within the southern part of the Benue trough (Fig. 1) a 1000 km long northeast trending intracontinental structure stretching from the beneath the Niger Delta and Anambra Basins to the south to the Chad Basin in the North (Benkhelil 1989; Ofoegbu and Onuoha 1990; Ojoh 1992; Nwajide 2013). It forms a part of the eastern flank of the Abakaliki synclinorium which forms the major structural unit in the Southern Benue trough. The synclinal structure is formed by Albian to Coniacian sediments folded in the Santonian (Fig. 3). The folds are generally open to gentle and asymmetrical with a southwest plunge. In the core of the synclinorium to the south are deposited Campanian and younger clastic sediments belonging to the Anambra basin formed after the Santonian folding episode (Nwajide and Reijers 1996; Obi and Okogbue 2004).

The stratigraphy of the Afikpo synclinorium is similar to the southern Benue trough as a whole (Fig. 4). With predominantly clastic shallow marine deposition with cycles of transgressions and regressions. Detailed descriptions of the stratigraphy of the Benue Trough have been addressed by Ojoh (1992) and Nwajide (2013).

Methods

Fracture analysis

Fracture data were obtained from 844 fractures from ten locations (Table 1). The area sampled was kept small enough (1000–2500 m2) in order to guarantee homogeneity of results (Delvaux and Sperner 2003). Data type obtained include attitude (Strike, dip and dip direction) of the fracture plane as well as nature of fracture surface, cross-cutting relations, mean separation between the fractures, bedding orientation and relationship and others which may be of use in determining the relative age relationships between the fractures and dividing them into fracture sets and systems. Three sets of fractures were observed a steeply dipping NNW-SSE pre-Fold system of fractures (JT), a NE-SW syn-folding fracture set with lower dips (JS), and a WNW-ESE set of post folding fractures predominant in the Post-folding sediments (JC). These fracture systems were used to define the initial subsets used in paleostress inversion of the fractures to obtain the reduced stress tensor.

Paleostress inversion

The most common and extensively used method of stress inversion typically involves use of faults with slickenlines that record the direction of slip relative to the fault plane (Hancock 1985; Angelier 1994; Ramsay and Lisle 2000). Their use is based on the Wallace-Bott hypothesis which states that the slip on a planar

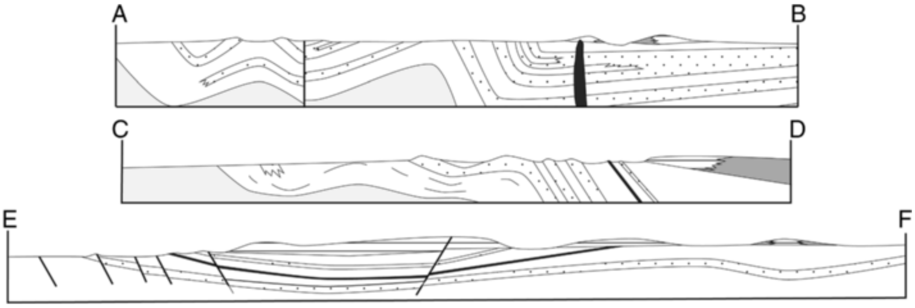

Fig. 3 Cross sections taken in different directions across the study area showing rock history and arrangement

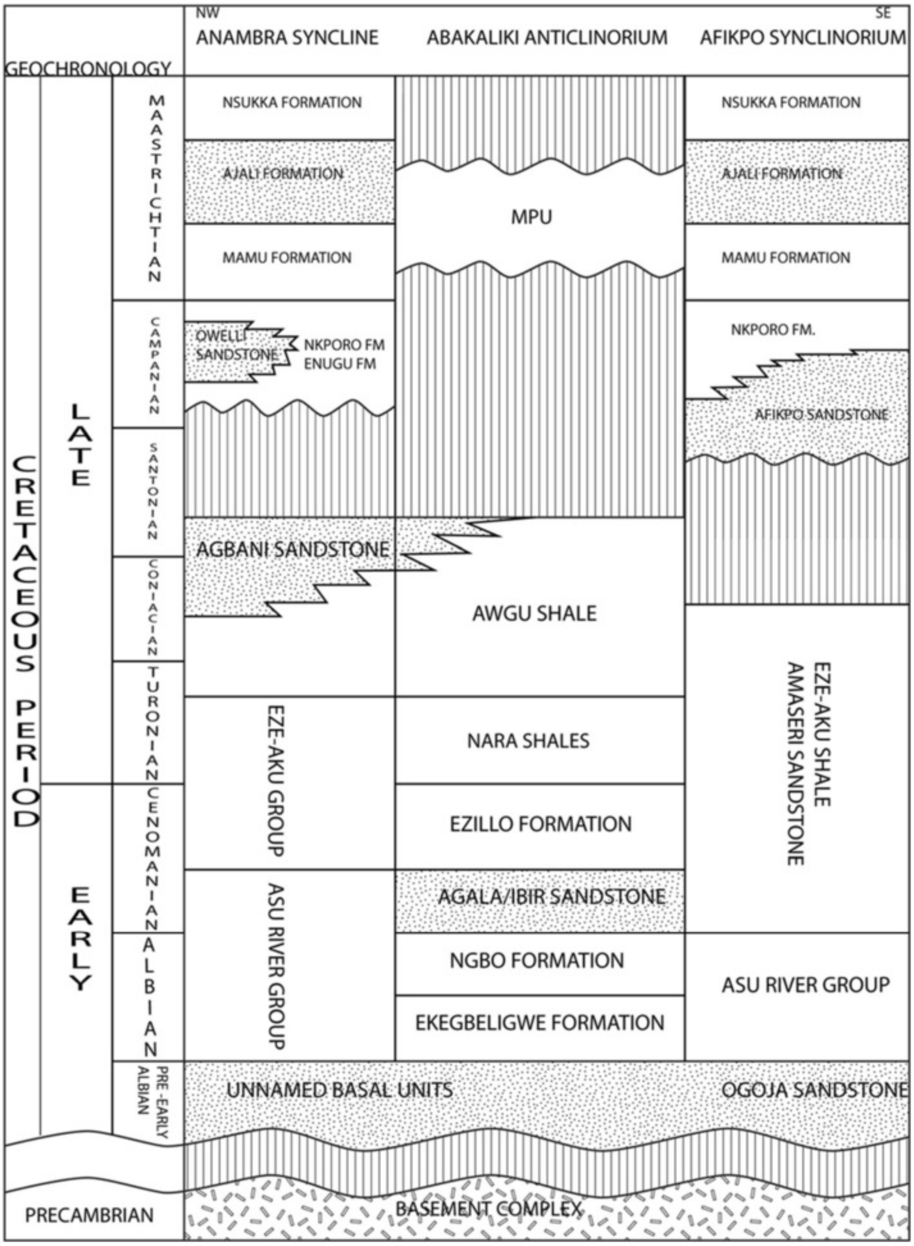

Fig. 4 Stratigraphic synopsis of the Southern Benue Trough and Anambra basin (After Ojoh 1992 and Nwajide 2013)

Table 1 A summary of discontinuities' characterization in the study area

Site ID	Locality	Rock type	Fracture set	No. of fractures	Strike	Dip	Average fracture spacing (m)	Fracture infilling
002	Itigidi	Sandstone	JC-1	30	300–310	80–90	1.5	Ferruginized
006	Aboine River Akpoha	Shale	JT-1	38	340–355	80–90	0.1	None
			JT-2	8	310–320	85–90	0.3	
			JT-4	3	260–270	80–90	2.0	
008	Amaseri Ridge	Sandstone	JT-1	5	330–360	80–90	0.7	None
			JS-1	9	045–060	45–60	1.5	
012	Ohaozara	Sandstone	JT-1	40	330–350	85–90	0.15	None
013	Asu River Ohaozara	Shale	JT-1	156	330–360	70–90	0.1	None
			JT-2	50	300–330	55–80	0.1	
			JT-3	3	290–300	85–90	0.1	
			JS-1	11	040–060	25–30 45–60 70–75	0.6	
			JS-2	10	060–080	60–65 80–85	0.55	
014	Asu River Akpoha	Shale	JT-2	100	310–330	70–80	0.05	None
			JS-1	13	40–50	30–35 55–60	2.0	
			JS-4	29	280–300	40–45 55–60	1.6	
017	Aboine River Isinkoro	Shale	JT-1	18	355–050	90	0.2	None
			JT-2	51	310–340	70–75	0.2	
			JT-3	1	290–300	75–80	0.5	
021	Aba-Omega Ugep Road	Sandstone	JT-1	12	350–360	70–75	0.2	None
			JT-2	9	320–330	80–85	0.2	
026	Asu River	Shale	JT-2	28	330–340	70–80	0.2	None
			JT-2	57	320–340	75–80	0.3	
			JS-6	55	340–350	45–50	0.3	
			JS-5	59	310–320	30–35	0.2	
			JT-1	35	330–340	60–65	0.2	
027	Afikpo Road	Sandstone	JS-3	5	020–030	40–45	1.0	Ferruginized
			JC-1	8	280–290	55–60	1.0	

structure is assumed to occur parallel to the greatest resolved shear stress (Bott 1959). Similar assumptions can be made for extension fractures (e.g. Joints) and contractional (e.g. Stylolites) fractures -that they form perpendicular or at a high angle to the minimum (σ_3) and maximum (σ_1) principal stress direction respectively- or for conjugate shear fractures where the maximum principal stress (σ_1) bisects the acute angle between the conjugate planes while the minimum principal (σ_3) stress bisects the obtuse angle between the fracture planes. The structures can be used separately or collectively to constrain the stress field that led to their formation. The assumption being that the fractures formed in the same homogenous stress field i.e. related to the same deformational event, that the rocks themselves are fairly homogenous, the fractures do not significantly perturb the stress field in their vicinity and also that the structures have not rotated significantly since their initiation (Ramsay and Lisle 2000).

The aim of paleostress inversion is to characterize what is known as the reduced stress tensor. The reduced stress tensor has four parameters of the six needed to define the full stress tensor: the principal stress axes σ_1 (maximum), σ_2 (intermediate) and σ_3 (minimum) and the ratio of principal stress differences, $R = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_1)$. The parameter R defines the shape of the stress ellipsoid. Only the directions of the principal stresses (known as Euler angles) can be determined for the stress tensor from inversion. Their relative magnitudes are represented by the fourth parameter *R*. The two additional parameters of the full stress tensor arc the ratio of extreme principal stress magnitudes (σ_1/σ_3) and the isotropic component of the stress tensor (the Mean stress), but these cannot be determined from fracture data only.

The methods of paleostress inversion are numerical and currently involve the use of computer programmes to statistically analyse fracture data in order to characterize the stress field responsible for them (Etchecopar et al 1981; Angelier 1994; Ramsay and Lisle 2000; Delvaux and Sperner 2003; Célérier et al. 2012). This study makes use of TENSOR™ program (Delvaux 1993; Delvaux et al. 1997; Delvaux and Sperner 2003). This program is a tool for controlled interactive separation of fault slip or focal mechanism data and progressive stress tensor optimization using successively the Right Dihedron method and the Rotational Optimization method. Detailed explanation of how these methods are utilized in TENSOR can be found in Delvaux et al. (1997) and Delvaux and Sperner (2003).

The stress regime is determined by the nature of the vertical stress axes: extensional when σ_1 is vertical, strike-slip when σ_2 is vertical and compressional when σ_3 is vertical. The stress regimes also vary, within these three main types, as a function of the stress ratio *R* : *Radial extension* ($\sigma_1$vertical, $0 < R < 0.25$), *Pure extension* (σ_1 vertical, $0.25 < R < 0.75$), *Transtension* (σ_2 vertical, $0.75 < R < 1$ or σ_2 vertical, $1 > R > 0.75$), *Pure strike-slip* (σ_2 vertical, $0.75 > R > 0.25$), *Transpression* ($\sigma_2$vertical, $0.25 > \mathrm{R} > 0$ or σ_3 vertical, $0 < \mathrm{R} < 0.25$), *Pure* compression (σ_3, vertical, $0.25 < \mathrm{R} < 0.75$) and *Radial compression* (σ_3 vertical, $0.75 < \mathrm{R} <$ I) (Delvaux et al. 1997; Delvaux and Sperner 2003). The type of stress regime can be expressed numerically using an index R', ranging from 0.0 to 3.0 and defined as follows:

$R' = R$ when (σ_1 is vertical; extensional stress regime)

$R' = 2 - R$ when (σ_2 is vertical; strike-slip stress regime)

$R' = 2 + R$ when (σ_3 is vertical; compressional stress regime).

The index *R'* defines the stress regime completely and is convenient for computing the mean regional stress regime from a series of individual stress tensors in a given area (Benkhelil et al 1989). On structural maps, the stress tensors are displayed with the orientation of both horizontal principal stress (*SHmax*) and horizontal minimum stress axes (*SHmin*) as recommended by Guiraud et al (1989) (Fig. 5).

Results

The stress fields were determined for the three joint systems based on field-based age relationship criteria. The tensors were determined after applying the Right Dihedron and Rotational Optimization described above.

At a location named Aboine River, Akpoha, two tensors were determined. The first tensor was calculated from 46 Joints belonging to the JT fracture system, giving a Strike-slip extensional regime with parameters σ_1 =12/150, σ_2 = 12/150 and σ_3 = 00/060 with an NNW-SSE direction of maximum shortening and a stress regime value of 1.00 (Fig. 6a). A single conjugate shear fracture yielded a pure compression tensor with parameters σ_1 = 00/337, σ_2= 20/067 and σ_3 = 70/247 with a stress regime index of 2.50 and a NNW-SSE direction of maximum shortening. Being the only shear fracture data it is considered unreliable and ranked E (Fig. 9a).

At a location named Amaseri Ridge, analysis was carried out on 14 joints (extension fractures) with two tensors determined. A strike-slip extensional tensor characterized by σ_1 = 76/008, σ_2 = 13/163 and σ_3 = 07/254 and a stress regime index of 1.00 and a NNW-SSE direction of maximum shortening, characterized the JT fracture system (Fig. 6b). An oblique radial compressive tensor with σ_1 = 47/348, σ_2 = 19/237 and σ_3=37/131 and a stress regime index of 3.00 and a NE-SW direction of maximum shortening, characterized the gently dipping JS fracture system (Fig. 9b). Similarly at another location called Amichi, analysis was carried out on 40 joints (extension

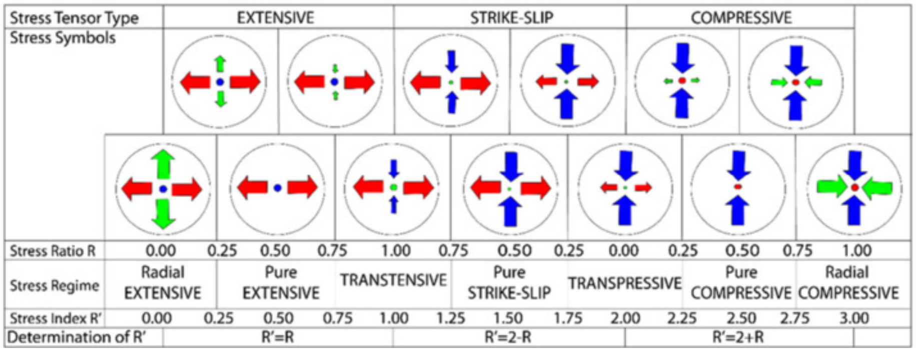

Fig. 5 Stress tensor representation for different stress regimes. After Guiraud et al (1989)

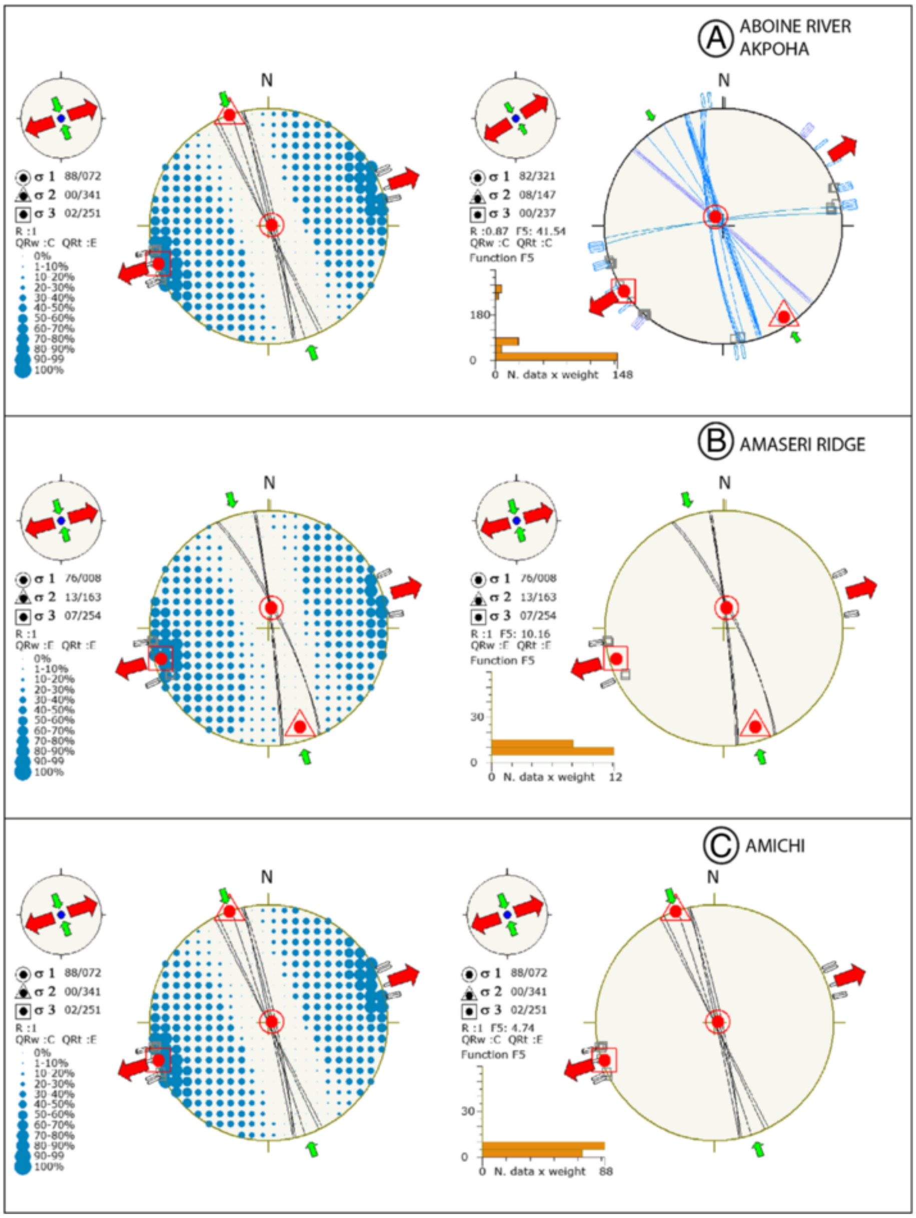

Fig. 6 Cenomanian to Turonian tensors for calculated for three locations in the study area (a) Aboine River Akpoha (b) Amaseri Ridge (c) Amichi

fractures) with a single strike-slip extensional tensor characterized by σ_1 = 88/072, σ_2 = 00/341 and σ_3 = 02/251 and a stress regime index of 1.00 and a NNW-SSE direction of maximum shortening, determined for the JT fracture system (Fig. 6c).

Within the Asu River, Okposi Road, a single tensor was determined. The first tensor was calculated from two hundred and nine (209) Joints giving a Strike-slip extensional regime with parameters σ_1 =78/295, σ_2 = 09/152 and σ_3= 07/061 with an SSE-NNW direction of maximum shortening and a stress regime value of 0.99 (Fig. 7a). At an adjacent location (Asu-River Akpoha), two tensors were determined. The first tensor was calculated from 100 Joints giving a Strike-slip extensional regime with parameters σ_1 =73/023, σ_2 = 07/136 and σ_3= 16/228 with a NW-SE direction of maximum shortening and a stress regime value of 1.00 (Fig. 7b). The second tensor was calculated from all the JS system joints combined together (43 planes). The tensor parameters are σ_1 =42/343, σ_2= 21/094 and σ_3= 41/204 with a WNW-ESE direction of maximum shortening and a stress regime value of 1.91 (Oblique radial compressive) (Fig. 9c).

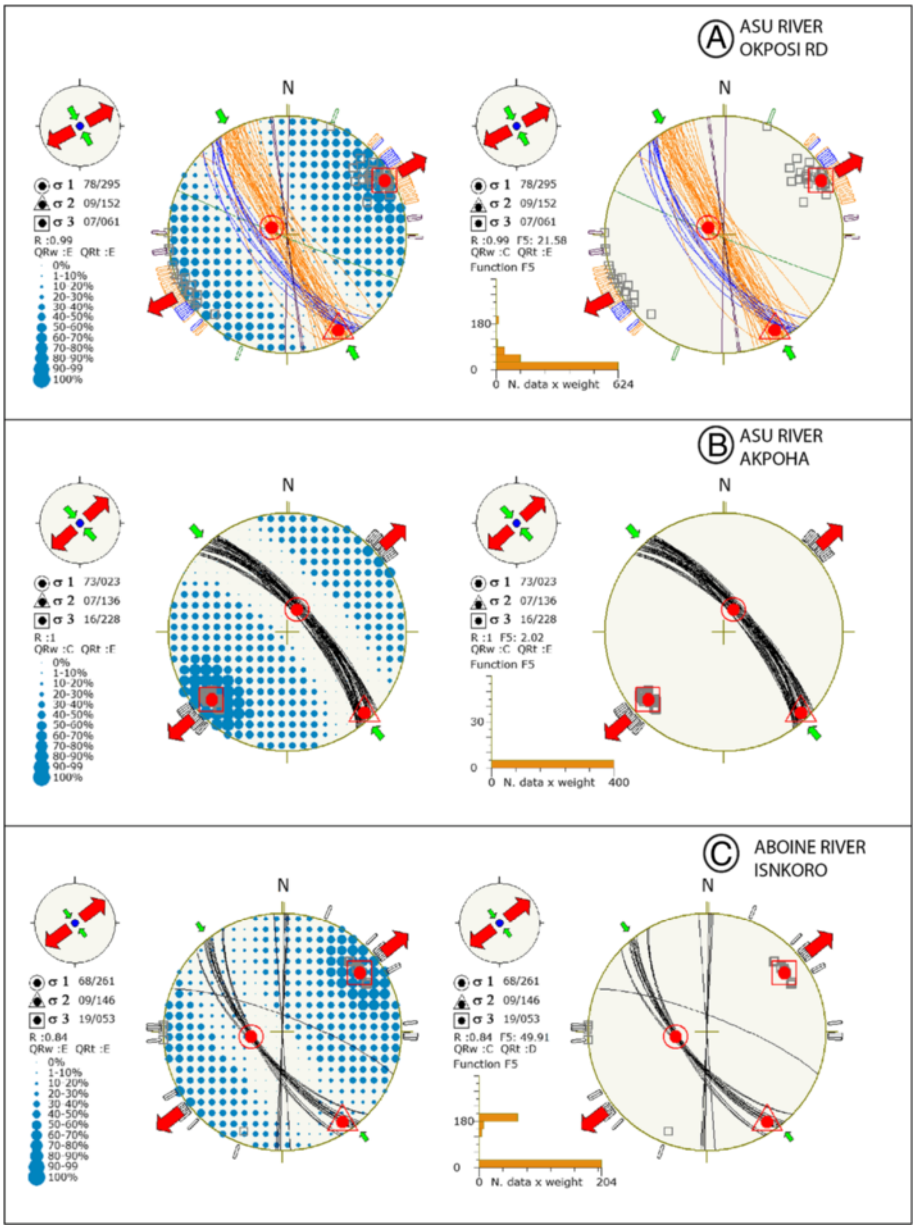

Fig. 7 Cenomanian to Turonian tensors for calculated for three locations in the area (a) Asu River Okposi RD (b) Asu River Akpoha (c) Aboine River Isinkoro

Analysis was carried out at Aboine River, Isinkoro on 70 joints with a single tensor determined with the parameters σ_1= 68/261, σ_2 = 09/146 and σ_3 = 19/053 and a stress regime index of 0.84 and a NW-SE direction of maximum shortening representing a Strike-slip extensional regime (Fig. 7c). At Abaomege-Ugep road, analysis was carried out on 22 joints with a single tensor determined with the parameters σ_1 = 69/305, σ_2 = 18/160 and σ_3 =11/066 and a stress regime index of 1.00 and a NNW-SSE direction of maximum shortening representing a Strike-slip extensional regime (Fig. 8a). At Asu-River, two tensors were determined from a total of 234 joints. The first tensor, determined from 120 joints gave the following parameters: σ_1 = 64/280, σ_2 = 15/155 and σ_3 =20/060 and a stress regime index of 1.00 and a NNW-SSE direction of maximum shortening representing a Strike-slip extensional regime (Fig. 8b).

The second tensor belonged to an oblique radial compressive regime with parameters σ_1 = 42/225, σ_2 = 07/321 and σ_3 =47/058 with a stress regime index of 2.67 and a NNW-SSE direction of maximum shortening (Fig. 9a).

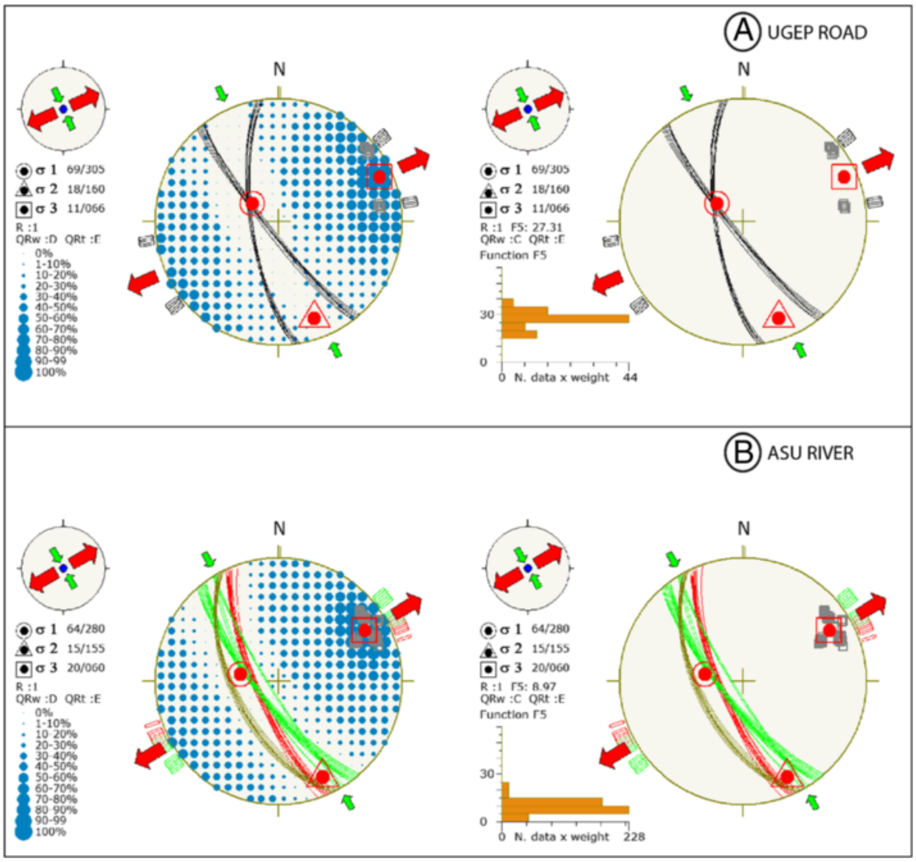

Fig. 8 Cenomanian to Turonian tensors for calculated for two locations in the area (a) Ugep Road (b) Asu River

Within Afikpo Road area, two tensors were determined from a total of 13 joints. The first tensor gave the following parameters: σ_1 = 33/072, σ_2 = 21/176 and σ_3 =21/176 and a stress regime index of 2.30 and a NNE-SSW direction of maximum shortening representing an oblique radial compressive regime (Fig. 9b). The second tensor belonged to an oblique strike-slip extensional regime with parameters σ_1 = 42/225, σ_2 = 07/321 and σ_3 =47/058 with a stress regime index of 1.37 and a WNW-ENE direction of maximum shortening (Fig. 10b). Finally, at Itigidi, analysis was carried out on 29 joints (extension fractures) only one tensor was determined for the JC fracture system found in the area. This tensor is characterized by σ_1 = 66/310, σ_2 = 22/107 and σ_3 =08/200 with a stress regime index of 0.96 and an ESE-WNW direction of maximum shortening (Fig. 10a). The tensor type is Strike-slip extensional or Transtensional.

Discussion

For a long time now, paleostress inversion techniques have been successfully applied to various tectonic settings despite some existing limitations. This work is all the more useful because there is very little information about the link between instability and discontinuities in the unstable regions of the country.

From the results three major tensors can be characterized for the study area. They are directly related to the three fracture systems earlier described, with indications that these directions are a manifestation of stress permutations in the region which are contemporaneous. Shearing along these fractures leads to deformational pathways that may be similar to the mechanisms espoused in Scheidegger (1998) and Grelle and Guadagno (2010). Interestingly, the dominant fracture orientations can be correlated to the general trends of the fractures that have created instability and predisposed the unstable slopes in the region to several failures. The knowledge gained from the unambiguous relationships among the fracture planes and the orientations of the stresses can be applied for the analysis of risks at specific areas of high instability such as the Iva valley in Enugu and the Nigerian-Cameroon mountain range.

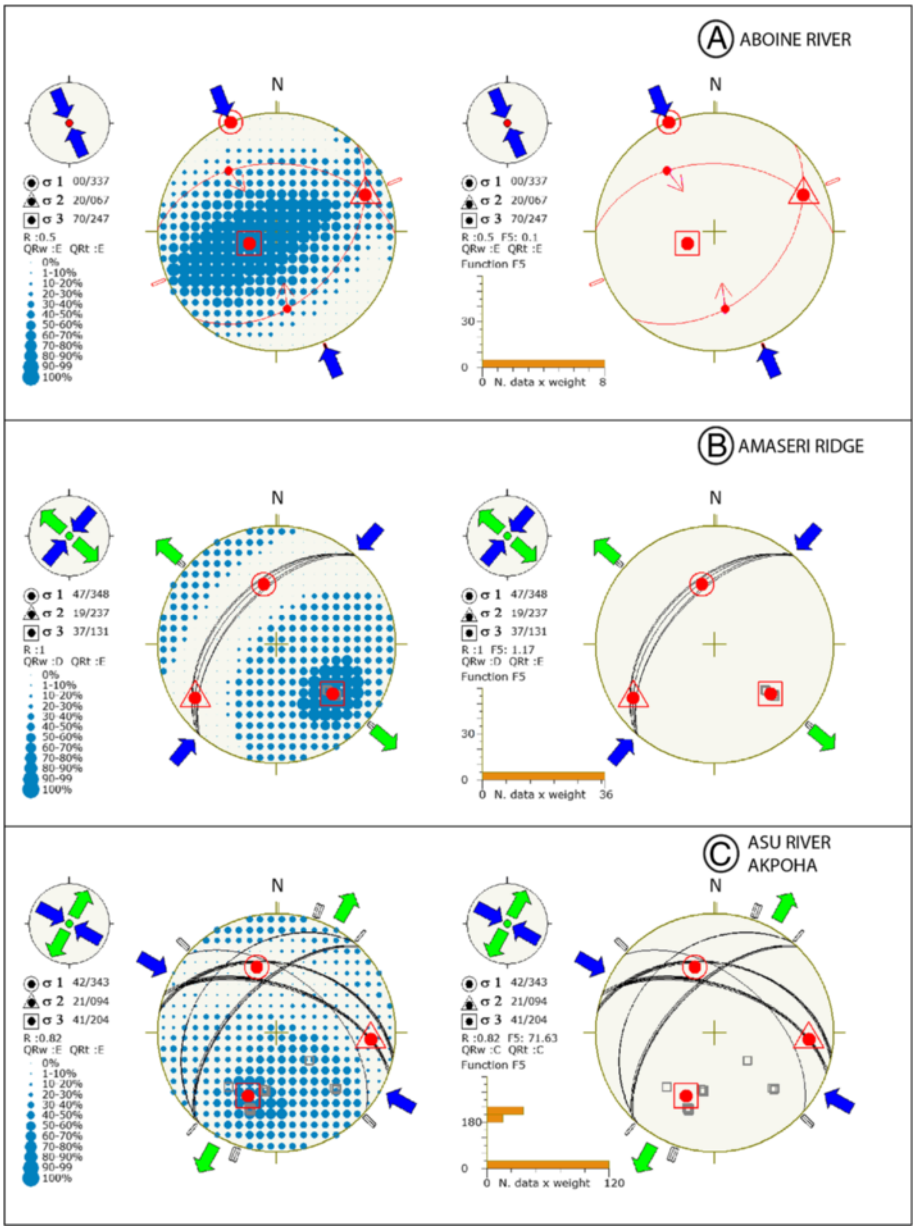

Fig. 9 Santonian tensors for calculated for three locations in the area (a) Aboine River (b) Amaseri Ridge (c) Asu River Akpoha

Cenomanian-Turonian transtension

A most prominent strike-slip extensional or transtensional tensor is found in the pre-folding fractures (JT) which are dated Cenomanian- Turonian (Fig. 11), with a general NE-SW maximum extension (SH_{MIN}). The period was a general period of rifting in the Benue trough and the other basins of the WCARS (Genik 1992; Guiraud and Maurin 1992; Fairhead et al 2013). The Turonian was also a time of maximum basin subsidence rates (Ojoh 1992) and eustatic sea levels leading to a connection between the equatorial atlantic (Petters 1980; Benkhelil et al 1989) and the Tethys through the Benue trough and the Termit basin (Petters 1980). This dominant transtensional stress regime is also likely related to Lead-Zinc and Barite mineralization characteristic of the Benue trough. The mineralization has been established to have occurred from the Albian to the Turonian, possibly related to magmatic activity in that period. Most significant though is that the structural trend of these vein mineralization is strikingly similar the fractured trend related to this stress regime (NNW-SSE and N-S) (Ezepue 1984; Etim et al 1988; Benkhelil 1989).

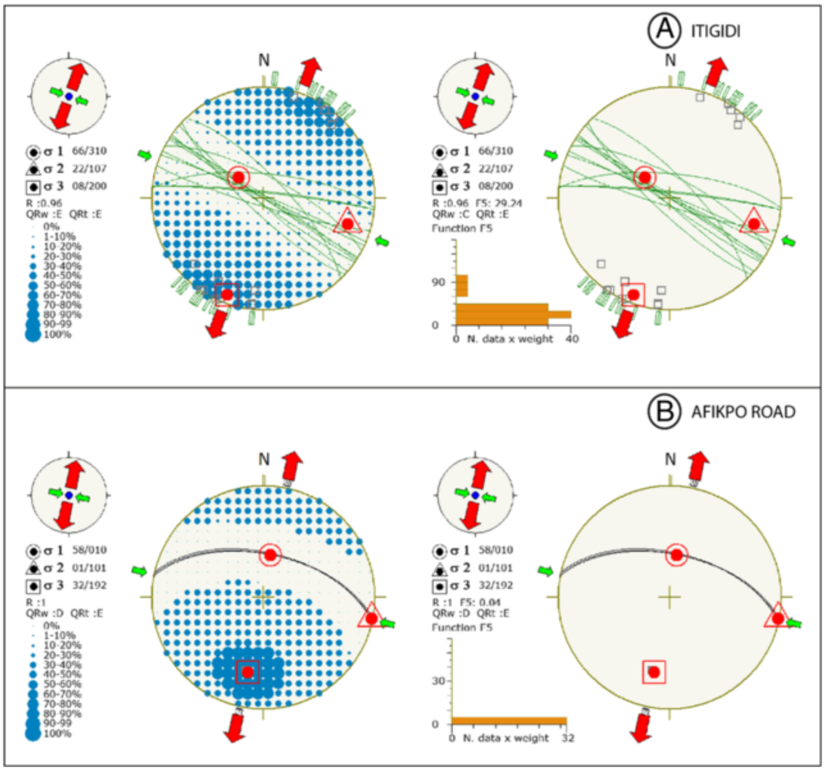

Fig. 10 Campanian to Maastrichtian tensors for two locations in the study area (a) MGIDI (b) Afikpo Road

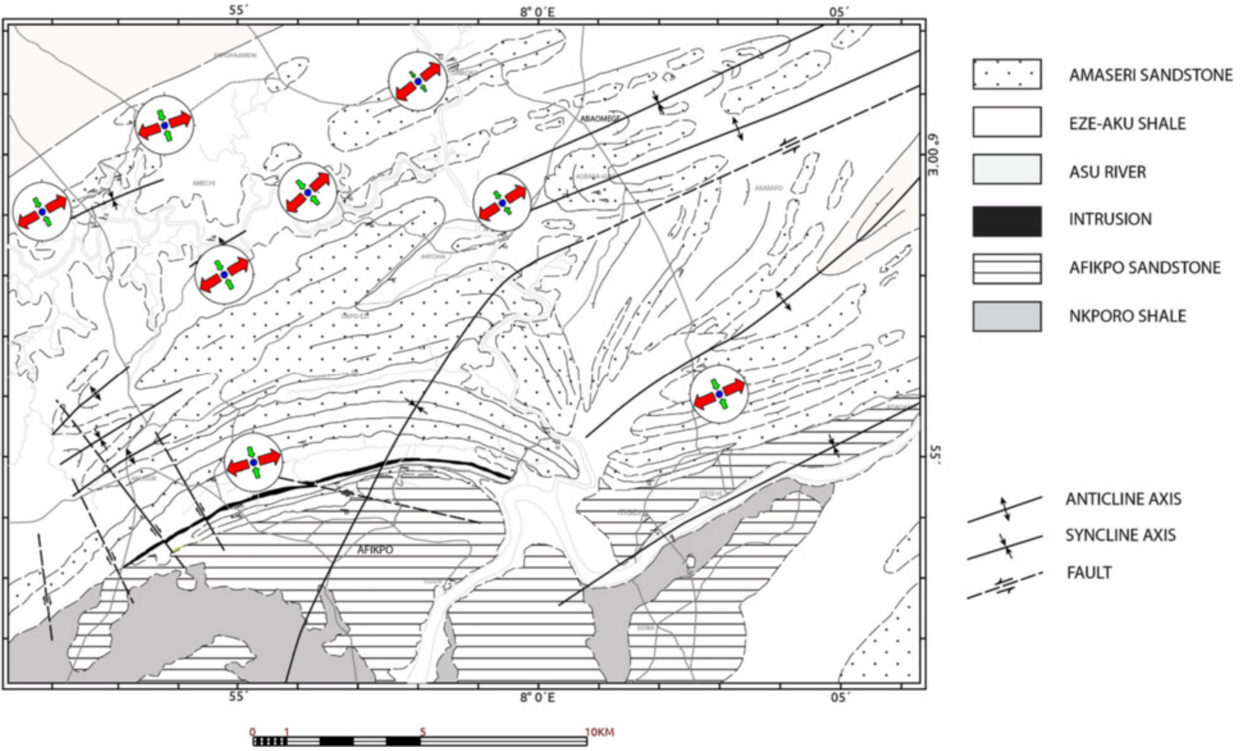

Fig. 11 Geologic map with Cenomanian to Turonian tensors

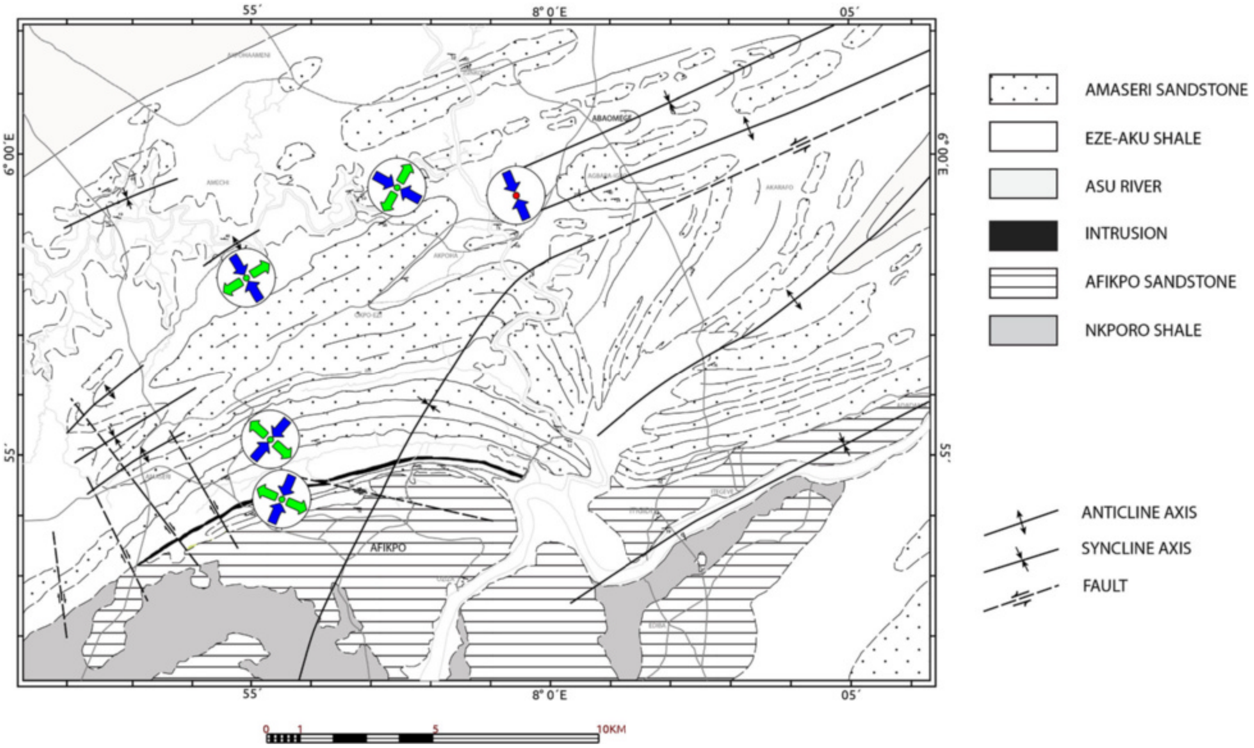

Fig. 12 Geologic map of the study area with Santonian tensors shown

Santonian transpression

The second tensor is an oblique radial compressive regime with a slight strike-slip (transpressive) component (Fig. 12). This tensor is related to the folding (SH_{MAX} directions are perpendicular to the fold axes) and probably to the weakly develop sub-vertical axial fracture cleavage seen in some of the shales. The Santonian phase is one of compression and structural inversion In other parts of the southern Benue trough the Santonian phase is marked by intense folding and low grade regional metamorphism with the development of sub-vertical axial cleavage which is poorly developed in the study area as NE-SW fracture cleavage (Benkhelil 1989; Guiraud 1993).

Campanian-Maastrichtian transtension

The third tensor is also transtensional but with a change in direction from the typical NE-SW (Fig. 13) to NNE-SSW maximum extension (SHMIN). This tensor was calculated from fractures that are seen to post-date the folding episode and are the youngest system of fractures (JC). This fracturing is related to the major lineament directions of the Anambra basin and significantly the trend of the major dolerite sill intruding the Eze-aku shale which is Campanian-Maastrichtian in age (Benkhelil 1986). The fractures are also seen to be related to deformation bands and probably to nearby faulting. These normal faults have been already established to post-date the folding episode. The post santonian was one of a return to tension stress regimes (Benkhelil 1986; Guiraud et al 1992; Guiraud and Bosworth 1997). This could be attributed to the flexuring of the south-eastern and western flanks of the folded and uplifted southern Benue trough into the Afikpo and Anambra Synclinoria and also stress release which followed the santonian inversion stage. The tension fractures therefore show transtensional tensors with a NNW-SSE direction of maximum extension. The tensional regime is also marked by a peak in magmatic activity and intrusion of Campanian to Maastrichtian sills and minor intrusion in the Afikpo to Ugep region. A set of Normal faults also cut into the Turonian to Campanian Sandstones and shales with evidence of synsedimentary deformation. The pre- and post-santonian tectonic models of the area created from the study indicate the zones of potential instability (Figs. 14 and 15). It is understood that areas of increased instability are the areas that have probably experienced faulting, folding, and has several discontinuities. Using this knowledge therefore, it will be possible to predict that the areas of frequent landslide activity within the Trough.

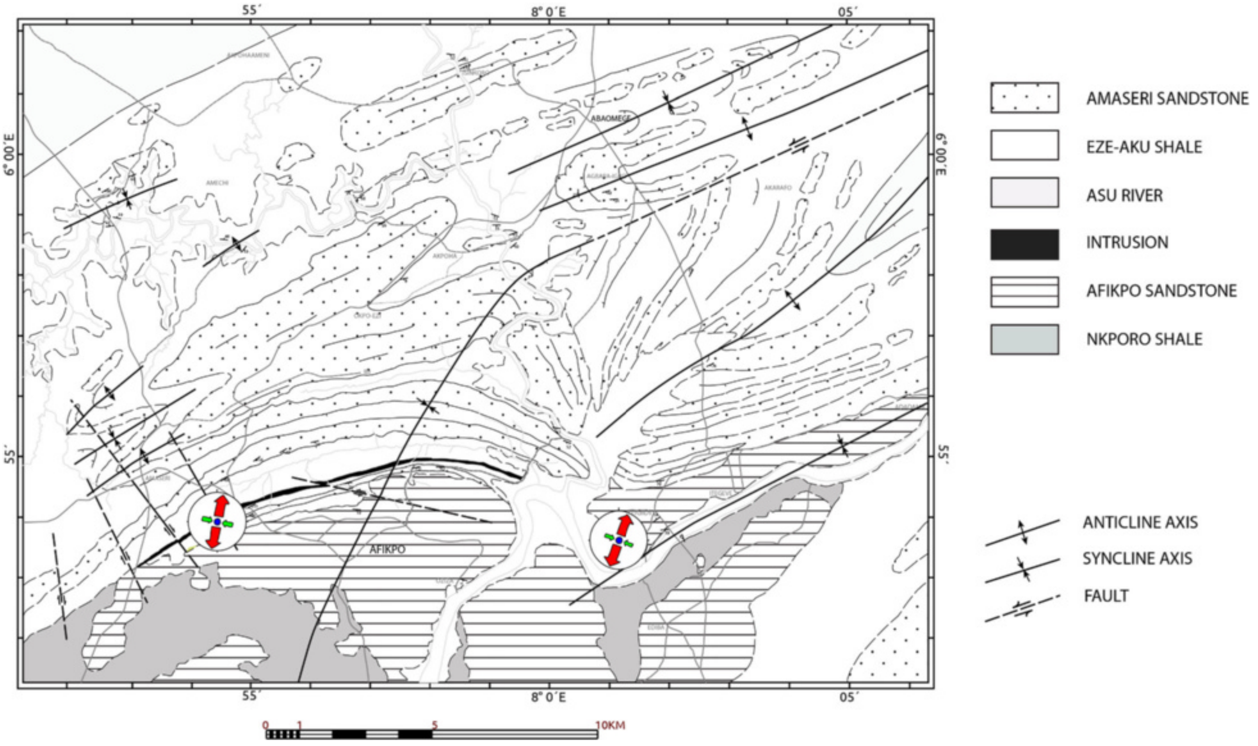

Fig. 13 Campanian to Maastrichtian tensors on the geologic map of the study area

Conclusions

This research undertook the structural characterization of small and large-scale discontinuities to properly understand their roles as potential precursors of instability. Detailed field-based structural and paleostress analysis using the software TENSOR™ have enabled three stress regime phases to be characterized for the study area from the Cenomanian to the Maastrichtian. A cenomanian to Coniacian transtensional phase, a Santonian transpressional phase and a Campanian to Maastrichtian

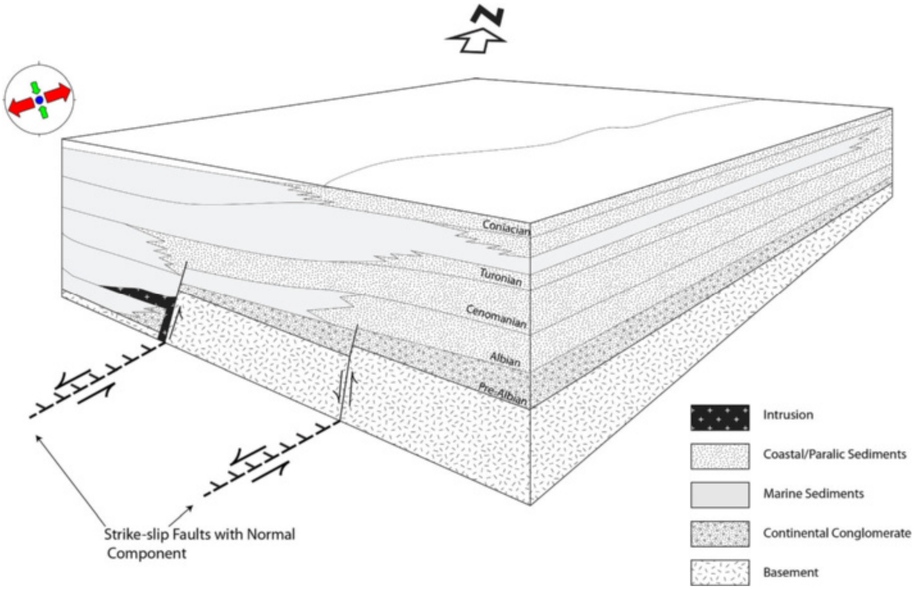

Fig. 14 Pre-Santonian schematic model for the study area

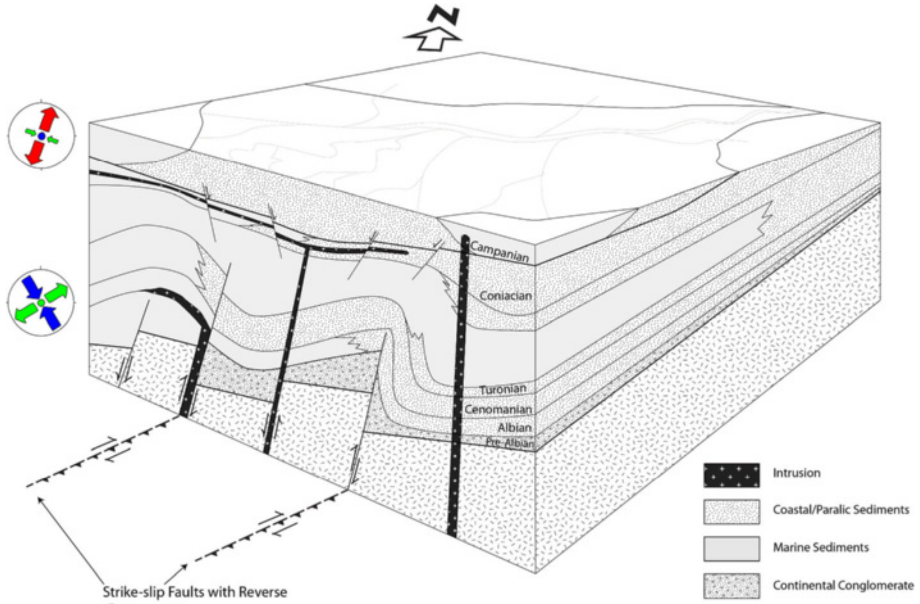

Fig. 15 Post tectonic schematic model for the study area

transtensional phase. These stress regimes are related to regional plate scale tectonics affecting the Benue Trough as a whole. Interestingly, the dominant stress orientations correspond to the reported orientations of the fractures predisposing slopes to catastrophic failures in the region; which are indications that the fractures origin is related to the regional paleostress history of the Benue Trough.

A most prominent strike-slip extensional or transtensional tensor, with a general NE-SW maximum extension (SH_{MIN}) is strikingly similar the fractural trend related to major episodes of landslide activity in the region. Additionally, The third tensor which is transtensional but with a change in direction from the typical NE-SW to NNE-SSW maximum extension (SHMIN) are fracture orientations related to deformation bands and probably to nearby faulting, which are all signs of instability.

Furthermore, the paleostress analysis has aided the production of accurate pre- and post- tectonic models of the area which can be used as a reference in future stress analysis and interpretation. It is understood that areas of increased instability are the areas that have probably experienced faulting, folding, intrusions, and are criss-crossed by several discontinuities. Using this knowledge therefore, it will be possible to predict the areas of frequent landslide activity within the Trough are the areas. Before the tectonic activities, the Trough seemed generally stable. This stability appeared to have been lost following the Santonian tectonic activity which created instability pathways. These pathways not only weakened the rocks but are also now being exploited by factors aggravating failure tendencies.

Finally, this work will enable the prediction of the likely fractural trends in any area within the Trough, and may aid the development of sustainable disaster management and risk reduction strategies.

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Authors' contribution
OI conceived, designed, modified and approved the research project. OI also examined the data, validated the results of analysis, interpreted the data, and drafted the manuscript. IAO was my MSc, and Ph.D student. This manuscript was part of IAO MSc and Ph.D work under the supervision of OI. IAO collected the field data, made substantial contribution in data analysis and interpretation, created the maps and Figures, was involved in the design and scoping of the project, edited the draft manuscript. Both authors read and approved the final manuscript.

Competing interests
The authors declare that they have no competing interests.

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