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ORIGINAL ARTICLE

An assessment of the performance of the geophysical methods as a tool for the detection of zones of potential subsidence in the area southwest of Nakuru town, Kenya

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Abstract The area to the southwest of Nakuru town in Kenya located within the Kenya Rift Valley is prone to incidences of ground subsidence especially toward the end of the heavy rain season. The zones affected by subsidence are typically linear, trending approximately north–south conforming to the structural trend of the Kenya Rift Valley. These ground subsidence incidences have in the past led to collapse of houses and damage to roads that happen to be located above the affected linear zones. This study set out to investigate the potential of geophysical methods to delineate these linear zones. Two profiles of lengths 2,430 and 2,850 m, respectively, were selected for this purpose. The study was conducted immediately after one major incidence of subsidence when the zones affected were still fresh and observable. Magnetics, very low-frequency electromagnetics (VLF-EM), and gravity methods were used in the study. The choice of these methods was dictated by their widely known applicability in the detection of linear structures, especially faults. The results of the study have shown that the linear zones affected yield good response to magnetic and VLF-EM methods. Anomalies similar to those detected across fresh subsidence zones were also detected at locations where there was no surface expression of subsidence, suggesting that the latter locations are potential zones of future subsidence. Further, there were locations along the profile that were without any anomalies. The relatively low sensitivity of the zones to the gravity method is attributed to the very narrow nature of these zone and hence limited low-density material to generate appreciable negative gravity anomalies. It is concluded from this study that geophysics permits identifying the potential areas to develop surficial collapse and to identify sectors that are potentially dangerous because they present similar signatures as the sectors with surficial evidence and sectors without anomalies. The sectors without anomalies are interpreted as having a different subsoil structure to that with sinkholes.

Keywords Subsidence · Kenya Rift system · Geophysical methods · Sinkhole detection

Introduction

Several linear north–south trending zones in the area to the immediate southwest of Nakuru town (Fig. 1) show a high level of instability in the overburden layers. This behavior has been attributed to a high intensity of faulting and presence of highly unconsolidated silts and pumaceous material constituting the overburden layers (Ngecu and Nyambok 2000).

Several incidences of soil collapse which, in places, have resulted in houses being destroyed are reported nearly every year. Most of these incidences usually occur toward the end of the long rain season (May/June).The worst cases of ground subsidence in the area occurred in 1985 and destroyed a number of houses and roads. Ngecu and Nyambok (2000) suggested a number of mitigation measures to assist in reducing the extent of subsidence consequences. These measures include channeling of drainage, proper engineering practices and appropriate land use.

At the practical level, in the subsequent years, most developments around Nakuru town have focused on the east of the town with the southwest part being shunned as less favorable.

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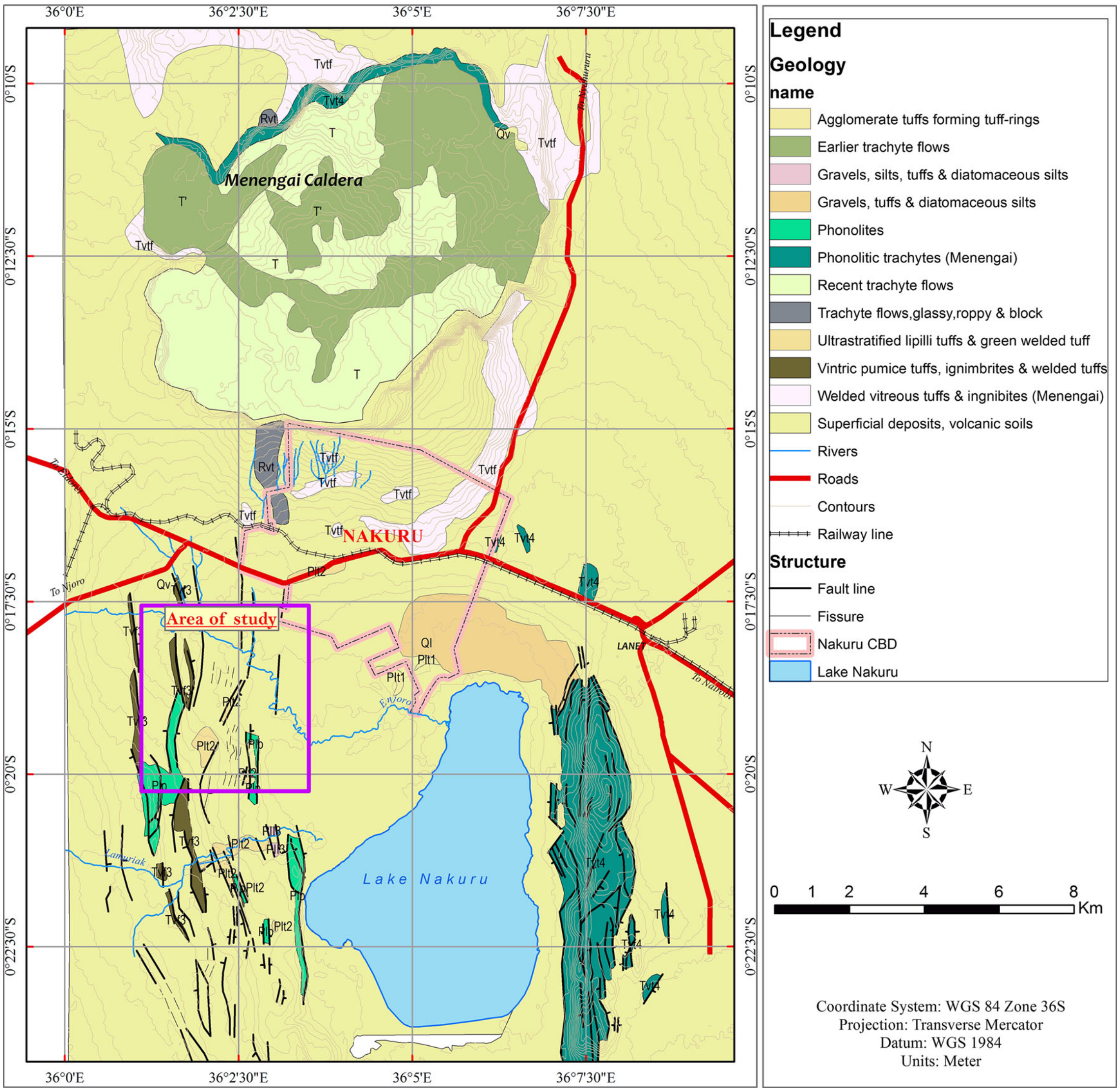

Fig. 1 Location and geology (after McCall 1967)

Having worked in the area and observed the pattern and distribution of zones affected by subsidence, the author has been of the view that with good site investigation prior to any development, the risk of structures being located on potential zones of subsidence can be substantially minimized. It is in this context that the author has been interested in critically evaluating the possibilities of using geophysical methods to identify hidden weak zones. Although the aim of this paper is to depict a picture of the region southwest of Nakuru town, the application of the methods in the detection of faults is of broad interest and similar investigations have been carried out in other parts of the Kenya Rift Valley and elsewhere (Babu et al. 2007; Barbosa et al. 2007; Komolafe et al. 2013; Kuria et al. 2010) This paper presents the results of the geophysical work carried out to investigate the feasibility of the use of geophysical methods and discusses the potential of the methods for locating potential collapse zones.

Study area

Figures 1 and 2 show the geological and structural setting of the wider Nakuru area. The location of the study area is shown (boxed area) on the two maps. The wider area (bound by longitudes 36°0′E to 36°10′E and latitudes 0°9′S to 0°24′S) constitutes a part of the graben structure of the Kenya Rift Valley and lies at an elevation of between 1,500 and 2,000 m above sea level. The topography is uneven in places due to the minor displacements caused by grid faults which are fairly numerous in the area. The land rises westward toward the Mau Escarpment located on the

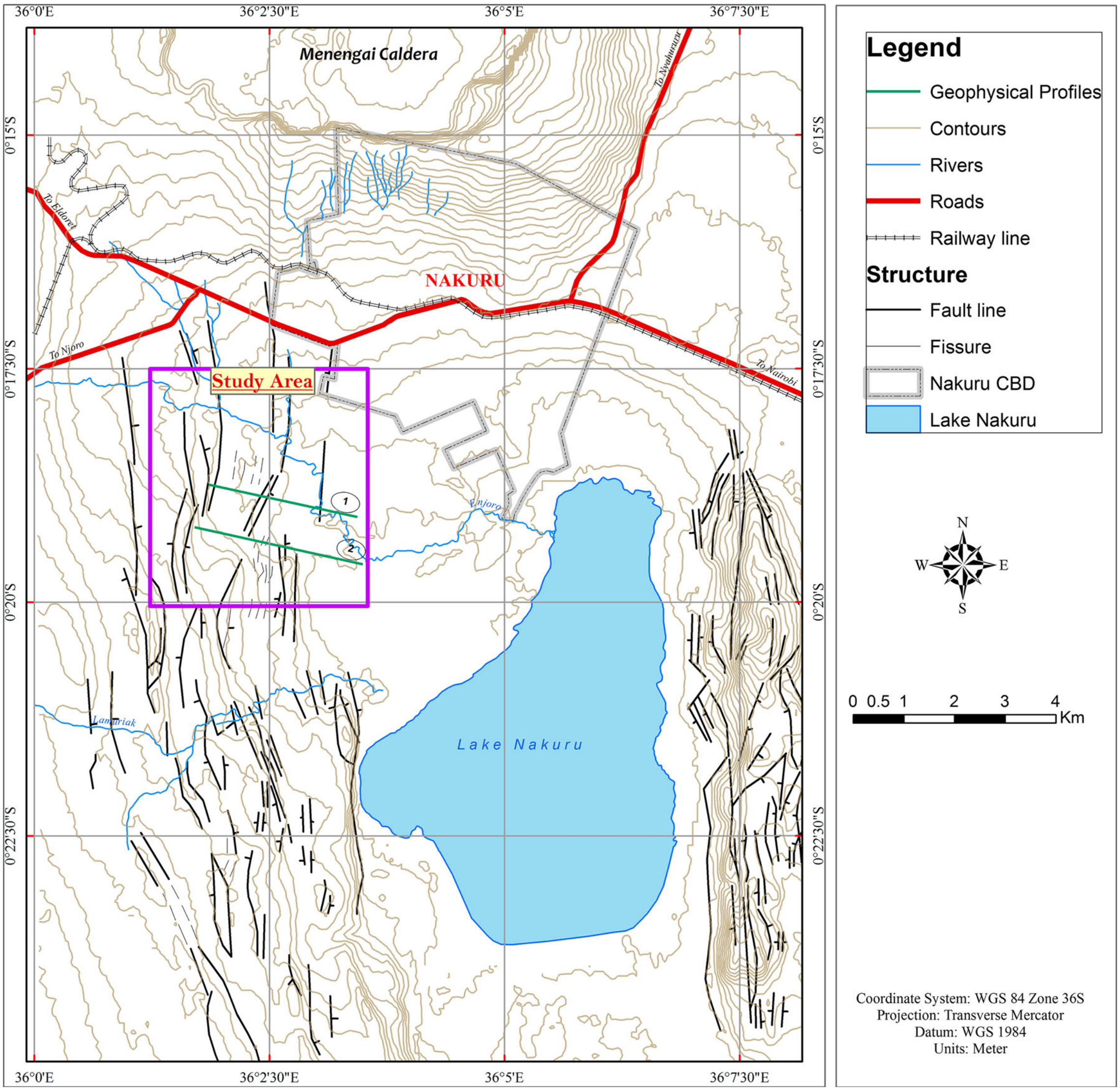

Fig. 2 Distribution of faults and fissures in the study area (updated from McCall 1967)

western shoulder of the Kenya Rift Valley. The escarpment has a marked control on the drainage pattern in the area. The two main rivers Larmudiac and Njoro originate from the escarpment and traverse the study area eventually draining in Lake Nakuru (Fig. 2). The water levels in the rivers are however generally low. This is attributed to the high porosity of the pumiceous material which mantles the older rock surfaces and the high intensity of fissuring in the area.

Geological setting

The area covered by this study was mapped by McCall (1967). The rock types consist of lavas, pyroclastics and sediments, mainly lacustrine (Fig. 1). Rocks constituting lava flows are seen only where they have been exposed through block faulting along the scarps. The lava flows comprise mainly of phonolites and trachytes. Otherwise a greater part of the area is covered by pyroclastics and lake sediments. The pyroclatsics are due to explosive episodes associated with the development of the rift and the Menengai crater located on the northern outskirts of Nakuru town (Fig. 2). The area is considered to have been under an extensive lake at various times during the Pleistocene. The porosity of the rocks in the area is very high. It is because of the high porosity that pools of water after the rain are rare. This also explains the loss of flow of rivers in this section. McCall (1967) suggested that the percolating waters in the area go to fill an aquifer located below Lake Nakuru. Stratigraphically, the Ronda trachytes were emplaced in the Middle Pleistocene. More sediments and pyroclastics accumulation took place in the Upper Pleistocene. These were followed recently with superficial deposits such as soil and alluvium.

Structural setting

Most of the structures found in the area are those associated with the development of the Kenya Rift Valley. Three major phases of faulting are recognized in the structural development of the Kenya Rift Valley in this section (Baker and Wohlenberg 1971). The first major phase represents the development of the boundary faults in Late Miocene. The second phase is related to rifting within the rift resulting in faults steps, horst and graben structures at Late Pliocene. The third major phase constitutes the so called grid faults in the Quaternary. The features in the current area are mainly representative of the third major faulting episode characterized by closely spaced faults (Fig. 2). These faults are of normal type, with small throws and are near vertical. Most of these grid faults trend NNW and NNE, although a few are oblique to this trend. Surface observations suggest that the intensity of faulting is not as high as in other areas of the rift such as in the Lake Magadi and Lake Natron areas (about 80 and 100 km south of the study area, respectively). However, the actual intensity of faulting in the area is not exactly known, as some of the faults here are concealed below the unconsolidated deposits. This is supported by the fact that sediments in the area are very young, having been deposited after the faulting phases. Faulting in the area is believed to have closely followed the Middle Pleistocene eruptions.

Some of the young faults are however as a result of renewal of movement along older faults. Fissures also occur in the area. The grid faults give rise to small horsts and graben structures. Interestingly, most zones of subsidence are not along fresh scarps, but along zones where no scarps exist, i.e., where peneplanation is complete and the ground surface is almost flat except for minor depreciations in places.

Causes and dangers of subsidence

Several theories have been proposed to explain the phenomena of subsidence in the area to the southwest of Nakuru town. These are:

(a) Rejuvenation of older faults.
(b) Influence of earth movement-related tremors.
(c) Subterranean erosion.

Although existing records show that the local seismicity in the country increases during the long rains, (period April–June), an earthquake monitoring station set on Ronda Hill located in the study area by the University of Karlsruhe for 6 months during the 1985 incident showed no unusual increase in seismicity. No movements with lateral displacement were observed along the zones of subsidence. Thus, there are no evidences so far to support the first two theories. The theory of subterranean erosion has however found much support (Ngecu and Nyambok 2000). It has been suggested that flow along the faults is ever present and that it is merely speeded up during the rains. This implies that the zones should be ideal for locating boreholes if they are water saturated throughout the year. However, McCall (1967) suggested that depending on how deep the faults are, such zones may depress the water table and should be avoided when siting boreholes. An alternative view is that there are no permanent rivers, but that water flows through these zones vertically into geothermal zones. Whether permanent rivers exist or whether the zones merely represent conduits activated during heavy rains, several evidences are in support of subterranean erosion. The model (Fig. 3a, b, c) is a pictorial illustration of the concept of subterranean erosion in this context. This model envisages a fault that has displaced the beds B and C, but has since been covered by superficial materials (A) so that at the surface there is no evidence of any fault. In Fig. 3a, sub-surface erosion continues along a fault zone with water moving along and down into the fault carrying away unconsolidated material in its way (the horizontal white cylindrical shape represents a horizontal sinkhole that develops). As erosion eats away

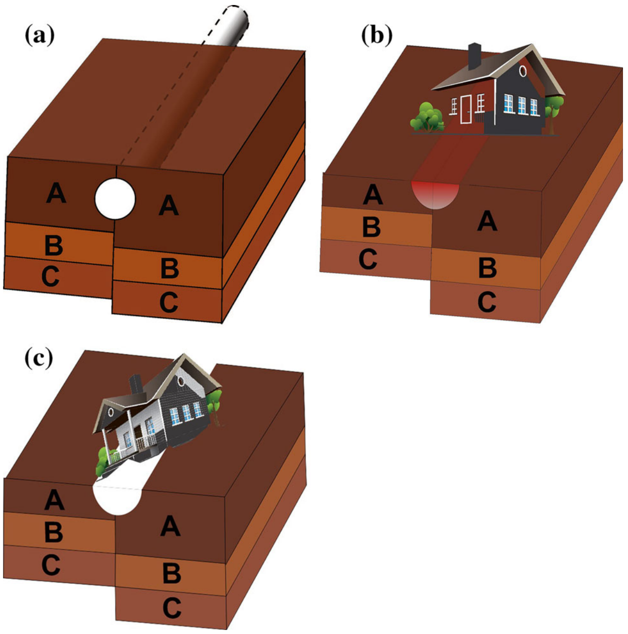

Fig. 3 Schematic representation of subterranean erosion caused by fissures: **a** before, **b** during and **c** after erosion

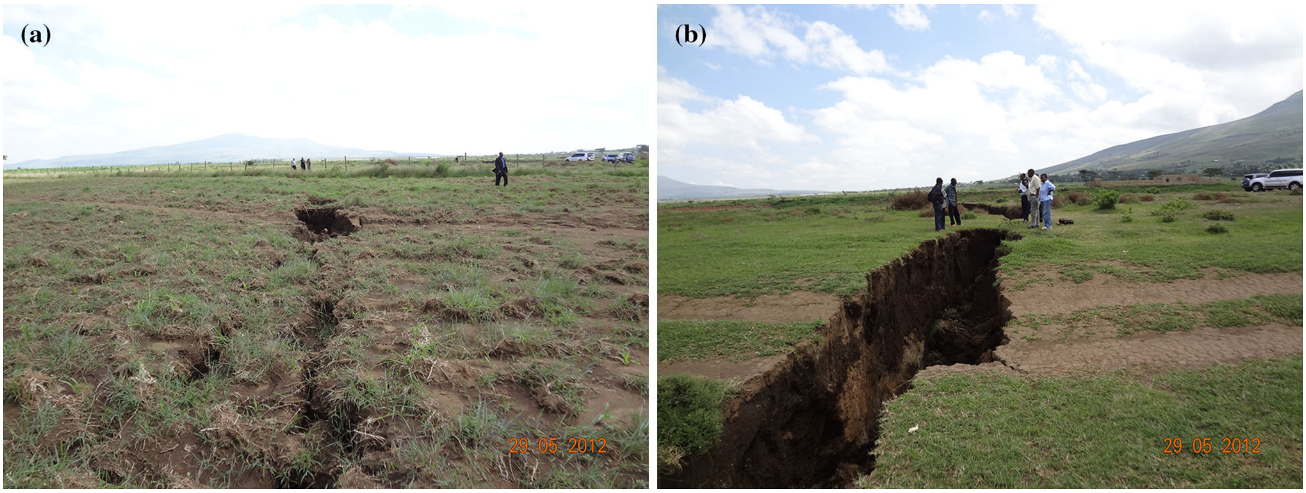

Fig. 4 **a** A ground subsidence event at Mai Mahiu, some 50 km south of the present area taken at the end of the rain season in May 2012. **b** A ground subsidence event at Mai Mahiu, some 50 km south of the present area taken at the end of the rainy season in May 2012. This section is the northern part of the same zone seen in Fig. 4a

unconsolidated material in the subsurface, the linear horizontal sinkholes keep on enlarging. This causes the overlying overburden materials to become unstable and eventually collapse into the linear sinkhole (Fig. 3b, c). Observations supporting the third theory are as follows:

- In a number of cases, some dams formed and eventually all the water disappeared suddenly, implying that there is a sudden development of cavities at depth most likely caused by the sinking water.
- The events correlate well with the heavy rain period when water flow would be fast and chances of hollow spaces being created high.
- If permanent rivers existed, one would not expect the subsidence incidences to be aggravated after the rain but to also occur at other times of the year.

Figures 4a shows the aftermath of a subsidence event in Mai Mahiu area located some 50 km south of the study area. The picture was taken at the end of the rainy season in late May 2012. Figure 4b is the northern section of the same lineament that had widened due to the collapse of the gully walls.

Hazards arising from ground subsidence have been in the form of destroyed residential houses or damage to railways lines and roads. No loss of life has so far been reported and losses through structural damage have been low. This is partly because the area is not yet built up and the population is low. Further, the structures in the area are simple and the number of grid power supply lines is still relatively small. Unless appropriate measures are taken, cases of deaths due to sudden subsidence of houses, falling objects when houses are collapsing with the foundation, short-circuiting of electrical lines or sudden collapse of sections of the road in the area in future cannot be ruled out.

Purpose of the study

The purposes of the present study were as follows:

(a) To test the responses of the zones of subsidence to the different geophysical methods.
(b) To detect any similarities in the types of responses from the zones to the geophysical methods used.
(c) To evaluate the possibility of using the results to locate potential locations of subsidence.
(d) To make recommendations on how to cope with the problem of subsidence in the area southwest of Nakuru through careful site investigations before construction.

Survey methods

The geophysical methods used in this study were very low-frequency electromagnetics (VLF-EM) method, ground magnetics and gravity. The choice of the geophysical methods was based on their widely known applicability in the detection of linear structures, especially faults. Examples of application of these methods in similar studies are briefly described below.

Past and recent studies on the use of VLF-EM for the detection of concealed faults include Paterson and Ronka (1971), Phillips and Richards (1975), Gürer et al. (2009) and Tijani et al. (2009). Studies on the use of magnetics include Benson and Mustoe (1991), Ten Brink et al. (2007), Adagunodo and Sunmonu (2012), Kuria et al. (2010) and Komolafe et al. (2013). The use of gravity methods for fault detection has been reported by Benson and Mustoe (1991) and Barbosa et al. (2007).

Benson and Mustoe (1991) used seismic refraction, gravity and magnetic survey data to delineate shallow concealed faulting in Utah, USA. Field observations coupled with interpretation of geophysical data facilitated identification of a number of probable faults.

Ten Brink et al. (2007) using magnetic data over the Dead Sea Fault were able to delineate the fault clearly in areas characterized by the absence of surface exposure. The fault was characterized by negative magnetic anomalies of between 10 and 20 nT where the fault cuts magnetic basement and less than 5 nT in other areas. The magnetic expression was attributed to alteration of magnetic minerals due to fault zone processes and groundwater flow.

Barbosa et al. (2007) used gravity data to detect and locate in-depth normal faults in the basement relief of a sedimentary basin. They acknowledge the challenge of detecting such faults using gravity data only, but point out that this may be possible from strong gravity gradient if the fault produced a sharp discontinuity in the density distribution and had a large vertical throw. In their study they used gravity to map several faults whose locations and plane geometries were already known from seismic imaging.

Adagunodo and Sunmonu (2012) used ground magnetics to investigate fault patterns in Ogbomoso SW Nigeria. The study revealed fault zones and relatively mineralized zones.

Kuria et al. (2010) have used magnetic method among others to detect and study faults in Magadi area of the Kenya Rift Valley. They used four traverses, each 2.3 km long and running E–W. The field data show a highly disturbed distinct magnetic signature across the fault zone.

Komolafe et al. (2013) working in Magadi area of the Kenya Rift Valley found the magnetic method to be very effective in studying structures. Their study reaffirmed that lithology controls magnetic properties through mineralogy and that variation in rock properties generally coincide with lithological contrast. They state that the existence of faults and fractures in geological units creates magnetic variations which generate magnetic anomalies. Because most magnetic rocks must have been altered and converted to others, this in turn results in lower magnetic anomaly than unaltered zones. According to Komolafe et al. (2013), the presence of fluids within faults and fractures would in general reduce or have no magnetic response. Kuria et al. (2010) report fault zones containing fluids (hot springs) that lack magnetic response.

Geophysical field investigations, results and interpretation

Geophysical investigations were carried in two periods, both falling immediately after heavy rain periods when the zones affected by subsidence were still fresh and observable. The first phase was conducted in the months of June to September 1985 and the second in June to August 2011. The methods applied were magnetics, very low-frequency electromagnetic (VLF-EM) and gravity.

To investigate any correlation between the subsided zones and the geophysical response, two profiles 2,430 and 2,850 m long and spaced 1 km apart were cut running WNW–ESE (as shown on Fig. 2). Positions where the profile crossed fresh zones of subsidence or conspicuous fault scarps were recorded to facilitate comparison with geophysical data. All the three geophysical methods were applied to Profile 1. Profile 2 was investigated using magnetics and VLF-EM methods only.

Magnetics

Magnetic measurements were made using two proton precession magnetometers that measure the absolute value of the total magnetic field strength. A base station was located within the area of the traverses at a site free from any magnetic noise for the purpose of carrying out drift correction due to diurnal effects on the recorded magnetic data. One of the magnetometers was kept at the base station and the other was used for field measurements. A station spacing of 30 m was used with three measurements being taken at each station. The data were then corrected for drift before plotting. The magnetic and gravity stations coincide.

Profile 1

The plot of the magnetic data for Profile 1 is shown in Fig. 5a. The magnetic field is not noisy, so that the positions of anomalous zones (represented by short bold vertical lines) can be located easily. Five anomalies can be observed on the profile located at 1,440 W, 1,260 W, 750 W, 0BL and at 180 E. The first four anomalies (location of vertical bars) correlate well with positions where disturbances were actually observed on the ground. The fifth anomaly is interpreted to be related to variation in the magnetic properties of the rocks on the scarp east of 0BL. The negative amplitude of 300nT at 0BL was a point negative. This negative amplitude could have easily been dismissed as an error but for its persistence despite several repeat readings. The sharp rise at 180E is interpreted to represent displacement along a fault located east of the one

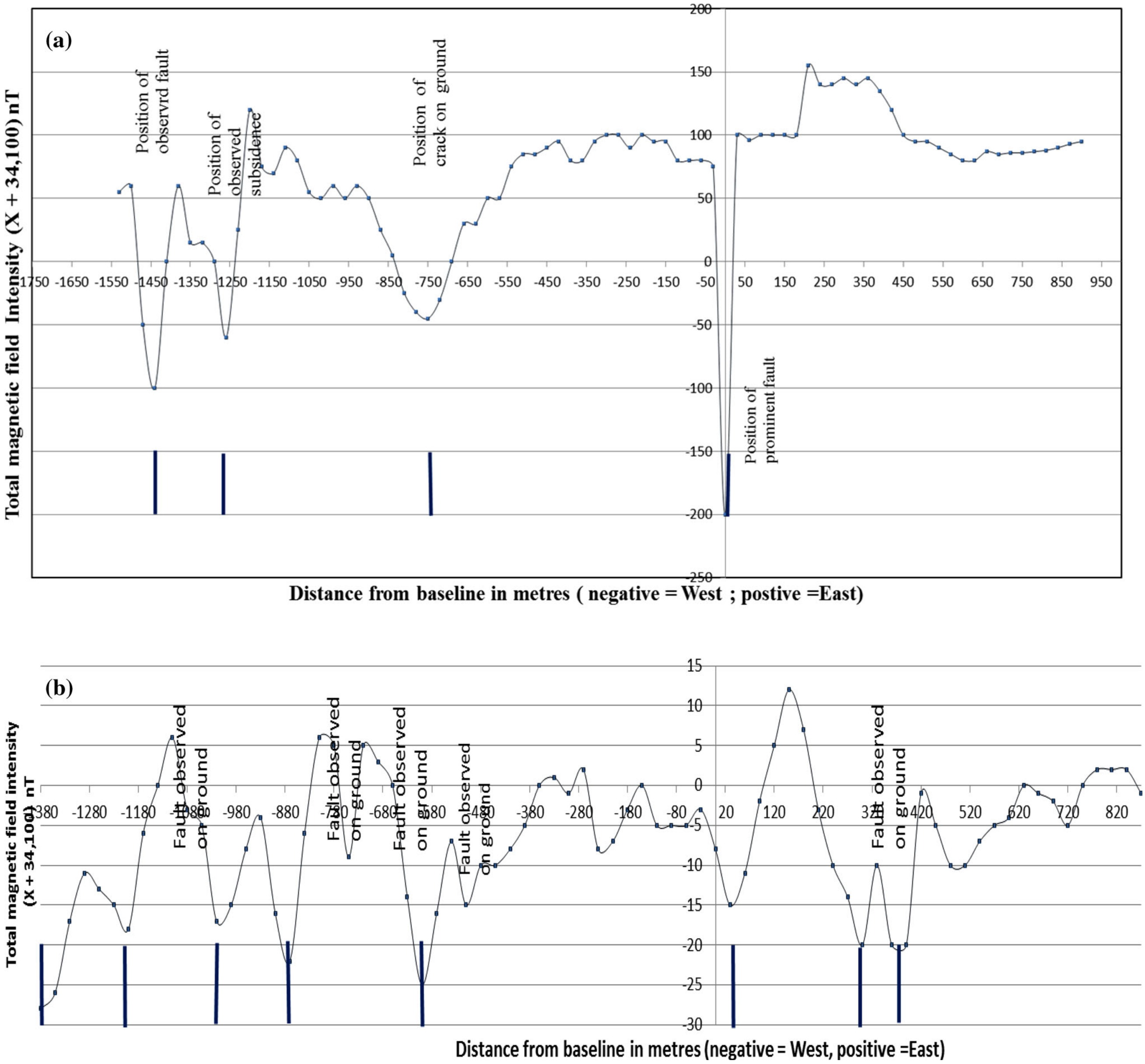

Fig. 5 **a** Total magnetic field anomaly along Profile 1. **b** Total field magnetic anomaly along Profile 2

at 0BL. The observations from this profile show that zones affected by subsidence as well as fault zones in this area are characterized by negative amplitudes relative to the background of 34,100 nT.

Profile 2

The magnetic field for Profile 2 is shown in Fig. 5b. In this case the field is relatively noisy. The profile shows two anomalous zones. The first zone lies between 500 W and 1,380 W with negative amplitudes observed at 1380W, 1,200 W, 1,000 W, 880 W and 600 W. The second zone lies between 0BL and 420E with negative amplitudes at 50E, 250E and 370E.

VLF- EM

VLF-EM method is a passive geophysical method that uses radiation from military navigation radio transimitters operating in the VLF band (15–30 kHz) as the primary EM field to generate signals for various applications (Babu et al. 2007). Conductivity contrasts associated with shear zones, brecciated and mineralized faults normally produce VLF-EM anomalies and hence the method is useful for geological mapping and in particular for locating fault zones. However, narrow fault zones particularly under a conductive overburden may not have a sufficient effect on apparent resistivity measurements to allow their detection by this method. This problem was however not experienced

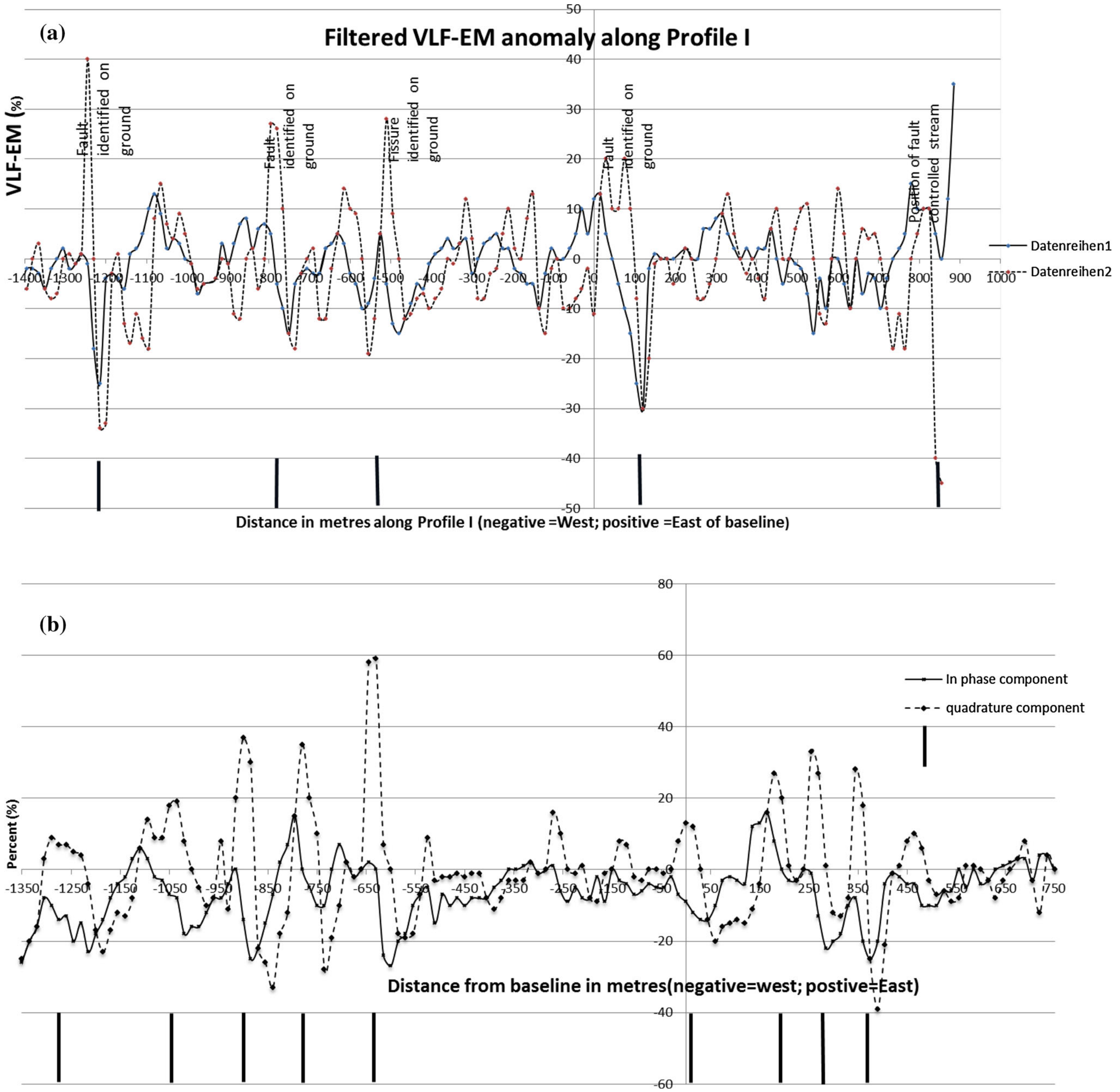

Fig. 6 **a** Filtered VLF-EM anomaly along Profile 1. **b** Filtered VLF-EM anomaly along Profile 2

in the present area. In the present study FUO station located in Bordeaux, France, was used as the transmission station. The measurements were carried out using the device EM-16 manufactured by Geonics Ltd. A spacing of 15 m of measurements was maintained.

The raw VLF-EM data were difficult to interpret because the relatively high transmitter frequency gives rise to secondary fields from many geological features. A simple filter technique (Frazer 1966; Jeng et al. 2007) which transforms crossovers and inflections into peaks and also removes regional gradient was used. In a sequence of consecutive readings, M_1, M_2, M_3, and M_4, the plotted function is $f_{2,3} = (M_3 + M_4) - (M_1 + M_2)$, but it is important to remember that the filtering process must be done in the direction from negative to positive peaks on the profile. Because of the method of calculation, only the positive filtered values are significant. Another advantage of the method is that when plotted, the filtered data are more easily correlated with the data obtained by other geophysical methods. In the case of this study, the perceived cause of the anomalies is the weathering effects along the fault zones. The disadvantage of the VLF-EM method is that metal conductors, such as fences, may give rise to prominent anomalies, although these may to some extent be distinguished from their erratic nature.

Profile 1

The filtered data (Fig. 6a) show a few prominent clear peaks located at 1,230 W, 765 W, 510 W, 60 E and 870 E. The peaks at 1,230 W, 765 W, 510 W and 50 E coincide with the location of cracks that had developed during the 1985 subsidence. The VLF-EM also contains some smaller peaks which have been regarded as insignificant.

Profile 2

VLF-EM for profile II (Fig. 6b) contrasts substantially with that of profile I, as in this case the peaks can be grouped into two. There is a disturbed zone between 500 W and 1,350 W with peaks at 900 W, 780 W and 630 W. Another disturbed zone occurs between 0BL and 420 E with specific peaks at 150 E, 270 E and 370 E. The disturbance at about 100E coincides with the scarp marking the western end of the Ronda Hill horst feature. This seems to mark a zone of faulting that extends to 370 E.

Gravity measurements were made using a Worden Gravity Meter of resolution 0.01 mGal at a spacing of 30 m. Height measurements were done using a level and stuff achieving an accuracy of 0.1 m. As no known base stations could be located, a local base was set up on the respective profiles. The gravity data were corrected for instrument drift and the combined elevation and Bouguer effects. A reduction density of 2,300 kg/m^3 which corresponds to the measurements on the unconsolidated overburden material in the rift (Swain 1979) was used in the reduction.

Efforts were then made to correlate any discontinuities which may imply faults with the exposed zones of subsidence. The results for profile I are shown in Fig. 7 (short thick lines show the positions where gravity data show anomalous behavior).

It runs approximately WNW–ESE and traverses five faults characterized by clear lineaments at the surface. The main lineament having a very sharp scarp and bounding Ronda Hill to the west is located at 50 E on this profile. Faults to the west of this are located at 950 W, 480 W and 0BL. The abrupt change of trend at 150 E is related to rock displacement on a fault east of that at 0BL. On the ground, soil subsidence zones were observable to the west of 1,260 W, 75 W and 0BL. A small depression probably representing an earlier subsidence zone occurs at 510 W.

Discussions

It can be seen from the results of the study that nearly all faults occurring on the ground can be observed on the magnetic data. Further, all zones of subsidence lie at or close to faults identified on the magnetic data. The magnetic data also delineates other lineaments (most probably buried faults) which are not observed on the ground.

The recognition that distinct magnetic anomalies are associated with faults in Nakuru area was first reported by McCall (1967). To test this, they made traverses across zones where faults were known to exist. At the time this was in connection with the siting of boreholes where faults were to be avoided, as they caused a depression of the water table. Results were in the form of one sharp peak or several sharp peaks interpreted in terms of buried valleys and disturbed zones. Point highs of significance were also noted in the study. He concluded that the magnetic method provided the easiest means of determining positions of hidden faults and those strong anomalies imply the presence of water channels (Table 1).

Filtered VLF-EM data have shown a close correspondence to magnetic data, in that it reveals nearly all known faults. In all, three cracked zones have been located on gravity, magnetic and VLF-EM data. Further, four zones showing similar characteristics but not cracked yet have been revealed by these methods. One method worth investigating but which was not applied in the present study is the electrical resistivity profiling (electrical tomography). Work done in Subukia area by the author (some 50 km to the north but within the Kenya Rift Valley setting) in connection with groundwater showed that VLF-EM anomalies across faults are almost always accompanied by resistivity anomalies.

The good response to VLF-EM and magnetics can be attributed to the weathering processes related to long periods of interaction of materials along these zones with water. Also, since fracture zones are conduits for migration of fluids, a contribution from mineralization of these zones cannot be ruled out.

The results of this study show that geophysics permits identifying the potential areas to develop surficial collapse, to identify sectors that are potentially dangerous because they present similar signatures to those sectors with surficial evidence and sectors without anomalies. In the sectors without anomalies, the probability of collapse/sinkhole phenomena will be lower than the sectors with anomalies. However, it does not indicate that they are safe zones. It just indicates that the subsoil structure is different from that of the sector with sinkholes. It is clear that the areas without anomalies will have a lower probability to perform sinkhole phenomena than the neighboring areas. In this sense this area should be safer than others or the sinkhole

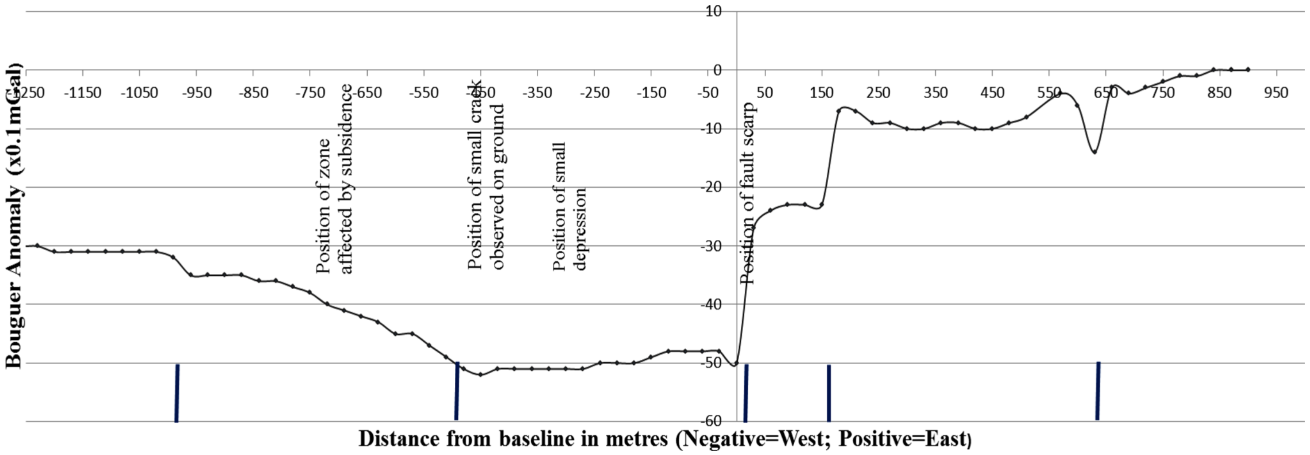

Fig. 7 Bouguer anomaly along Profile 1

Table 1 A summary of the responses of the method to known zones in the case of Profile 1

Location	1,440 W	1,230–1,260 W	950 W	750–780 W	510 W	0BL-90E 1	180 E	870 E
Data source								
Cracks on the ground due to subsidence	Yes		–	Yes	Small depression seen (earlier subsidence?)	–	–	–
Faults/fissures observed		Yes. Fault		Yes. Fault	Yes. Fissure	Yes. (fault scarp)		Yes. Fault controlled stream
Magnetics	√	√	–	√	–	√	√	–
VLF-EM	No data	√	–	√	√	√		√
Gravity	–	–	√	–	√	√	√	–

It can be seen that wherever a crack was identified on the ground, magnetic and VLF-EM anomalies were invariably associated with the cracks, but gravity anomalies were not always associated

susceptibility lower than other neighboring areas with anomalies.

Conclusions and recommendations

The VLF-EM and magnetics showed good response to zones affected by subsidence. Zones with surface evidence of collapse were associated with clear VLF-EM and magnetic anomalies. Similar anomaly signatures were observed at locations where there was no surface evidence of collapse. These zones are considered to be potential zones for future subsidence.

There were sections of the profiles where both magnetic and VLF-EM data were not anomalous. These sections are deemed to be less susceptible to collapse.

Although gravity responded positively to some of the anomalies detected by VLF-EM and magnetics, it failed to respond to others. The relatively low sensitivity of the zones to the gravity method is attributed to the very narrow nature of these zones and hence limited low-density material to generate appreciable gravity lows.

Based on the findings of this study, it is recommended that the area to the southwest of Nakuru requires careful site investigations before any constructions are made. Careful site investigations involving both geological and geophysical investigations as discussed above will ensure that areas considered of higher risk are avoided. Since cultural and geological noise are the major challenges in these types of investigations, integrated geophysical investigations should be encouraged as these increase the confidence which can be attached to the interpretations. It is important that those intending to construct in the area are made aware of the foundation problems that exist and advised on how to cope with them through expert advice. Efforts should be made to prepare a risk map indicating locations of all known and suspected faults and fissures. All data emanating from various site investigations done for clients should be used to update the Foundation Risk map. To minimize accidents which may come about as a result of sudden collapse of roads, warning signs should be erected at the points where roads cross known weak zones.

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