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Systematic Seismic Events Discrimination Methods at the Kenya National Data Centre (N090)

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Research Article

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SYSTEMATIC SEISMIC EVENTS DISCRIMINATION METHODS AT THE KENYA NATIONAL DATA CENTRE (N090)

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Abstract [WORD LIMIT 150 TO 250 words]

The International Data Centre (IDC) routinely applies event screening or discrimination using a multi-technology approach in order to characterize events as either natural or anthropogenic. Various event discriminants are presented in literature. At the Kenya National Data Centre (KE-NDC or N090), a systematic and step-by-step procedure of SEISMIC events discrimination is applied. Results from the discriminants adopted are obtained within a short time and the discriminants are relatively easy and fast to use. The discriminants used at KE-NDC (N090) are ranked in a hierarchy based on results obtained from one discriminant being applied in subsequent dsicriminants and ease of returning results within the shortest time possible to allow for events discrimination and dissemination of results. The discriminants applied and their hierarchy at KE-NDC include:- (i) event location (epicenter/hypocenter parameters) (ii) hypocenter parameters based on events relocation using HYPOCENTER, (iii) magnitude determination, (iii) m_b:Ms criteria and (iv) focal mechanism determination. Two seismic events are used as case examples to demonstrate how events discrimination is achieved based on the discriminants presented herein. The two seismic events are the 20190324 and 20200503 seismic events in the southwestern and northern Kenya respectively. The choice of these two events is based on the fact that they were strong enough to be recorded by a number of global seismic stations and their magnitudes are comparable to the 2009, 2013 and 2016 but slightly lower than the 20170903 DPRK announced tests. Based on the discriminants used and presented herein, the two seismic events were categorized as being due to natural earthquakes.

Key words: Discriminants, Seismic events, Natural, Anthropogenic, KE-NDC.
[4 to 6 keywords]

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Author contribution statement

The results of seismic event discrimination at KE-NDC were presented during the Comprehensive Nuclear Test-Ban Treaty (CTBT) Science and Technology Conference 2023 (SNT2023) which was held from 19-23 June 2023 at the Hofburg Imperial Palace in Vienna, Austria. The author's contribution is outlined below:-

Josphat Kyalo Mulwa (JKM)
JKM is the sole author of this paper and is involved in routine analysis of seismic events at the Kenya National Data Centre (KE-NDC). IMS data from four seismic stations is received on continuous basis at KE-NDC. Additional data was requested by JKM from the IDC in Vienna, and these together with the continuous data forms part of the data used in this and other studies at KE-NDC. Waveform data from non-IMS seismic stations is requested from either IRIS or FDSN in SAC format. The analysis of waveform data, application of the seismic event discriminants and the write-up of this paper were done solely by JKM. JKM presented the results of this work during the CTBT Science and Technology conference (SNT2023) in Vienna, Austria. Based on the SNT2023 presentation, JKM was called upon and requested by the Provisional Technical Secretariat (PTS) to prepare and submit a full paper for publication in Pure and Applied Geophysics (PAGEOPH) Journal Topical Issue on "Nuclear Explosion Monitoring and Verification: Scientific and Technological Advances". On the basis of this call for papers, JKM has written this manuscript based on his expertise seismology and taking into consideration the mandate of the CTBTO and the obligations of CTBT member states.

KEY MESSAGE (WORD LIMIT 30).

This manuscript presents a hierarchy of seismic events discriminants used at KE-NDC, which enable the NDC to effectively advise the Kenyan government through the National Authority as to the nature of seismic events.

1 Introduction

The Comprehensive Nuclear Test-Ban Treaty (CTBT) is multilateral treaty that prohibits all nuclear weapon test explosions or any other nuclear explosion for both civilian and military purposes in all environments. The Comprehensive Nuclear Test-Ban Treaty Organization (CTBTO), established through adoption of a resolution (CTBT/MSS/RES/1) by State Signatories during their first meeting on November 19, 1996, oversees the CTBT. The objective of the CTBTO is to prepare for the entry into force (EIF) of the Treaty. Further, the CTBTO is charged with ensuring object and purpose of the CTBT (e.g. its monitoring which requires seismically discriminating between earthquakes, mining activities and any potential clandestine nuclear explosion tests), implementation of its provisions such as those for international verification of compliance, and to provide a forum for consultation and cooperation among states parties (CTBT, 1996). Where else it is not obligatory for member states to designate an NDC, the CTBTO assists States Parties to develop the capability to receive process and analyse International Monitoring System (IMS) data and IDC products at an institution designated as a National Data Centre (NDC) by a member state. The NDC has the sole responsibility of advising their governments, through the National Authority, of any cases of Treaty violations in addition to using the data for training, research, civil and scientific applications. The NDC is therefore expected to have the capacity to receive, process, analyse and interpret data from IMS facilities, as well as receiving additional processed data from IDC in Vienna according to a member state's need and subsequently utilizing these data and products to advice their governments on any Treaty violations.

The Kenya National Data Centre, domiciled in the Department of Earth and Climate Sciences of the University of Nairobi, is the national entity charged with receiving, processing, and analyzing International Monitoring System (IMS) data and IDC products. Continuous data is forwarded from four of the 337 IMS facilities (i.e. KMBO, BOSA, DBIC and TORD) on 24/7 basis. Additional data and products are received at KE-NDC upon request from the IDC through any of four IMS data request methods (CTBTO Prep Comm., 2015). The four methods include:- (i) IDC Secure Web Portal (an interactive graphical web-based server interface that allows the user to browse, view, download and retrieve IMS data and IDC products online using the CTBTO's secure web portal, (ii) Requests (on demand one-time requests of IMS data and IDC products of special interest submitted either via email or through a command line client software). Data and products access using this method require a preformatted text message in IMS2.0 format (CTBTO Prep Comm., 2015). Email requests are also known as automated data request manager (AutoDRM) requests, (iii) Subscription (standing requests of IMS data and IDC products forwarded continuously once available at IDC until cancelled by the subscriber). Subscriptions also require a preformatted text message in IMS2.0 format (CTBTO Prep Comm., 2015). (iv) IDC External Database Service or Virtual Data Messaging System (VDMS) (a timely and direct data access method to replicas of the CTBTO/IDC operational and archival databases and parameters. This method requires the use of SQL statements. Access rights are required for all the four data and products access methods and such rights are granted by the Provisional Technical Secretariat (PTS) on recommendation by the Point of Contact (PoC) at the National Authority.

In order to factually and effectively advise the Kenyan National Authority of any cases of treaty violations, it is critical that event discrimination, which entails distinguishing between explosions and earthquakes, is undertaken at KE-NDC. The problem of distinguishing man-made from natural seismicity using seismic data has been studied for a long time. Since the cold war, development of methodologies to discriminate natural seismicity from man-made events began for the purpose of monitoring nuclear tests. The discrimination methods have since become important components of national verification regimes of nuclear treaties. At present, man-made versus natural earthquakes discrimination using regional seismological data is an emerging research topic and a variety of these regional discriminants have been proposed (Pameroy et al. 1982; Taylor et al. 1989).

The aim of this manuscript is, therefore, to present a background of various seismic event discriminants and provide a systematic and step-by-step approach of the seismic event discriminants used at the Kenya National Data Centre (KE-NDC).

2 Materials and methods

The following sub-sections 2.1, 2.2 and 2.3 outline the hierarchy of seismic event discriminants used at the Kenya National Data Centre (KE-NDC). Sub-section 2.4 presents other discriminants, which may potentially be used but are only occasionally used at KE-NDC.

2.1 Surface wave Rayleigh (Rg) phase as depth discriminant

Shallow source seismic events at local distances are often characterized by large amplitude of the Rg seismic phase. For such events, fundamental mode Rayleigh (Rg) waves with periods between about 0.4 and 2.5 sec and P-wave energy dominates in the observed seismograms of explosions and very shallow-focus earthquakes. The Rg seismic phase is not identifiable for depth >5 km and is particularly prominent on seismograms of explosions. Kafka (1990) observed that the strongest Rg signals recorded by New England Seismic Network (NESN) are generally in the period range of 0.5 to 1.5 sec. The Rg displacement in the period range of 0.5 to 1.5 sec is confined to the upper 5 km of the crust, with most of the Rg wave energy in the upper 2 or 3 km. Seismic sources deeper than about 5 km would potentially not generate strong Rg signals at these periods. Identification of Rg seismic phase in a seismogram is an indicator of a shallow seismic energy source. Observed Rg waves at short epicentral distances of 100-200 km can therefore be used to discriminate very shallow-focus events from deeper events, provided that Rg can be identified and distinguished from other phases ((Bath 1983; Kafka 1990). In using this method as a discriminant, it has to be recognized that short period Rg waves, which travel as guided waves through the crust across continental paths with velocity of 3km/s or slightly higher, are more effectively attenuated compared to crustal body waves. Their range of propagation is therefore limited to distances of less than about 600 km. Thus, the absence of Rg phase in seismic records does not necessarily indicate deep seismic source (Båth, 1983). Owing to the lack of a comprehensive local seismic network and the sparse coverage of the seismic stations by other networks (e.g. USGS/NEIC, IMS, GEOFON and AF), seismic event discrimination using the Rg method as a depth discriminant is not applicable. At KE-NDC, seismic event depth is determined using the global seismic velocity models and travel times (Jeffreys and Bullen 1967; Kennett and Engdahl, 1991) and conventional waveform analysis techniques (CTBTO, 2013). The depth is further refined using HYPOCENTER (Lienert 1994; Lienert et al. 1986; Lienert and Havskov 1995; Havskov and Ottemoller, 1999). Depth as a discriminant is based on the maximum possible depth limit at which a clandestine nuclear explosive device can be placed as per the current drilling technology where boreholes exceeding 10 km are not feasible. Upon this basis, for event focal depths >10 km with 95% certainty, the seismic energy source is likely to be natural e.g. earthquake (Blandford 1977).

2.2 Body wave magnitude (mb) versus Surface wave magnitude (M_s)

Proceeding from the method discussed in 2.1, Rg seismic phase from shallow sources often has the largest amplitude at local distances. The ratio of the body wave and surface wave magnitudes (m_b:M_s) is recognized as one of the most successful discriminator between natural and anthropogenic events e.g. nuclear explosion (Douglas at al. 1974; Pomeroy et al. 1982). The m_b:M_s discrimination method has proven to be the most robust teleseismic event-screening procedure for shallow seismic events. However, effectiveness of the method to discriminate natural versus anthropogenic events diminishes at local and near-regional distances. The effectiveness of the method as a discriminant is based on the well-documented observation that m_b-M_s is typically less than one for crustal earthquakes and greater than one for underground explosions. Fisk et al. (2002) notes that the m_b-M_s relation is based on the classical m_b and M_s values published in various earthquake catalogues such as the U.S. National Earthquake Information Center (NEIC) and other agencies. A trade off as to the use of this method is therefore envisaged since the Rg phase rapidly attenuates with distance and would be expected to be completely missing in seismograms at the regional and teleseismic distances.

2.3 Focal Mechanism Solution

Another method of seismic event discrimination is used to analyze the characteristics of explosions and tectonic events using the theoretical differences between the source mechanisms. The source mechanism of tectonic earthquakes consists of shear dislocation, so S-wave energy dominates, whilst in the case of explosions isotropic pressure pulse occurs, and the P-wave and fundamental mode Rayleigh waves Rg energy dominates. Earthquake focal mechanisms provide critical in-situ insights about the subsurface faulting geometry and stress state (Li et al 2023). For naturally occurring seismic events, focal mechanism (FM) or source mechanism displays double-couple earthquake mechanism. For explosions, non-double-couple mechanism (isotropic) pressure pulse occurs. This however does not necessarily imply such non-double couple (isotropic) events are purely due to explosions. Cheng et al (2021) investigated 224 $M \geq 3$ non double-couple events in Ridgecrest, California and attributed the isotropic radiation to motions normal to the faults caused by complex fault geometry, transient fluid pressure effects, and generation of microcracks in the rapture zone.

2.4 Other seismic events discriminants

Other seismic event discriminants, which may potentially be used but are only occasionally used at KE-NDC include:-

(i) **Short period discriminants** with the most popular discriminator being the regional amplitude peak ratio of the S to P waves versus the logarithm amplitude peak of the S wave in the time domain of the seismogram (Baumgardt and Young 1990; Taylor et al. 1988; Wüster 1993; Horosan et al. 2009; Yılmaz et al. 2013). Allmann et al. (2008) undertook a comparative analysis of P-and S-wave amplitudes and found that, moderately smaller average S amplitudes for the explosions compared to the earthquakes occurred in southern California. Other short period discriminants include Complexity, Spectral ratio and Third Moment of Frequency (TMF) (CTBTO 2020).

(ii) **Pn/Sn and Pn/Lg amplitude ratios:** The excitation of compressional and shear wave energy is considered as a possible discriminant between explosions and earthquakes (Dysart and Pulli 1990). The frequency dependent ratios for Pn/Sn and Pn/Lg for incoherent beams are characterized by higher amplitude ratios for quarry blasts than earthquakes. Elsewhere, Pn/Sn and Pn/Lg amplitude ratios on incoherent beams for 8-16 Hz filter were found to exhibit significant differences between blasts and earthquakes groups among other amplitude pair ratios. The Pn phase is however not visible in the low frequency (2-4 Hz) filter band for the earthquake, whereas it is apparent in both the 2-4 Hz and 8-16 Hz bands for the explosion. The discriminatory capability of Pn to Sn and Lg ratios increases with frequency (Dysart and Pulli, 1990).

(iii) **The cepstrum analysis**, a non-linear analysis method, is used as a discriminant by detecting echoes and other reverberations in a signal. Mathematically, cepstrum or C-parameter, is defined as the Fourier transform of the logarithm of the power spectrum of a signal (Wei and Li 2003). The C-parameter (denoted as "C") measures the variability of the cepstrum of the recorded waveforms, where explosions show an approximate linear variation and earthquakes display significant variations (Wei and Xu 2009).

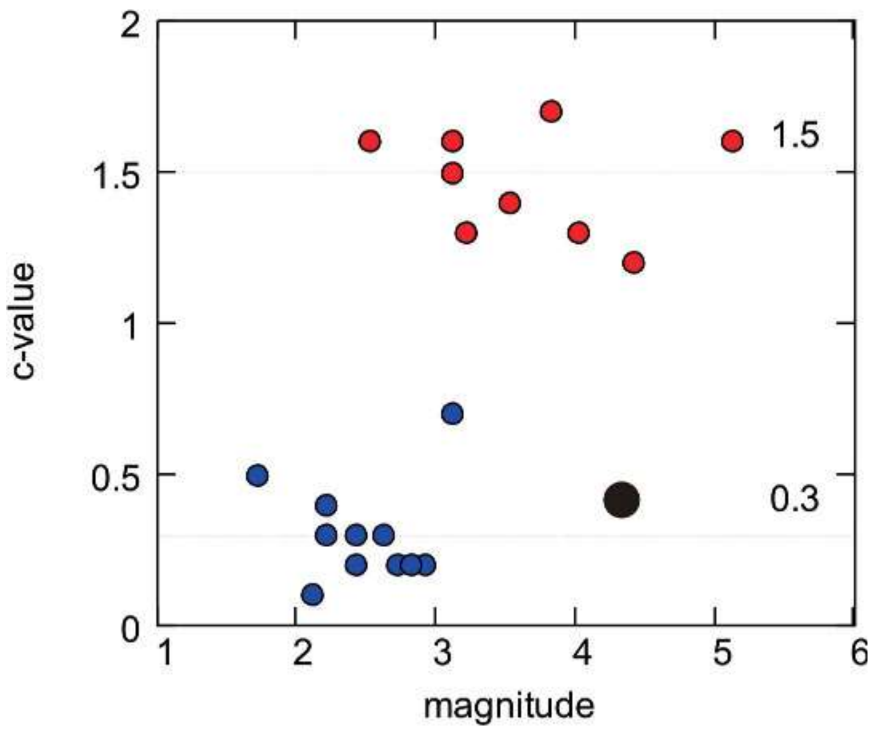

Fig 1 Plot of C-parameter versus local magnitude for earthquakes (denoted by red dots) and chemical explosions (denoted by blue dots). Black dot represents the 2006/10/09 DPRK nuclear test (after Wei and Xu 2009)

(iv) **Spectral amplitude ratios for Lg**

Based on studies conducted in Germany, Lg spectra for events at comparable distance ranges of 40-60 km from a seismic station BFO exhibited impulsive and higher frequency Lg signals with positive and negative slopes in the spectra for earthquakes and explosions respectively (Koch 2002). Further, the earthquake records showed considerable energy in the higher passband, while the explosion data showed negligible amplitudes for the upper band. Since geometrical spreading can be regarded as independent of the frequency considered (at least to first order when considering far-field terms), it becomes imperative to take into account attenuation of the seismic waves along the propagation path. Attenuation was accounted for through a distance correction for the observed amplitude ratio, which has since proven to be essential for regional discrimination work in many different geological settings. The spectral amplitude ratios, corrected for propagation path effects, were then used to define station-dependent spectral ratio thresholds for classification of the spectral characteristic of each measurement as explosion or earthquake (Koch 2002). The shortcoming of the spectral amplitude ratio for Lg method is a rather narrow gap between earthquakes and explosions at certain spectral amplitude ratios, which makes proper event discrimination impossible. In spite of this shortcoming, the spectral Lg ratios from 1-2 Hz and 6-8 Hz frequency bands as a measure for identification of earthquakes and mining or quarry explosions has potential as a seismic event discriminant (Koch 2002).

(v) **Coda Decay Rates**

Seismic coda wave analysis has been used as potential quarry blast – earthquake discriminant method**.** Coda decay rates (Q_c^{-1}) can be compared for different frequency values and a significant rate difference between earthquakes and quarry blasts deduced. It may also be necessary to apply attenuation correction in order to obtain a power spectrum $P_0(\omega)$ from same stations, which could be compared for earthquakes and quarry blasts in order to find a significant difference in the spectral shapes between these two data sets. The different frequency dependence of power spectrum $P_0(\omega)$ between quarry blasts and earthquakes can be attributed to their different source properties and therefore can be used for seismic discrimination of quarry blasts from earthquakes (Su et al, 1991)**.**

3 Results and Discussion on hierarchy of discriminants applied at KE-NDC

The discriminants presented in sections 2.1, 2.2 and 2.2 are routinely applied at KE-NDC in the same order. Examples are hereby presented of two seismic events, which occurred in northern and southern western Kenya as shown in fig. 2.

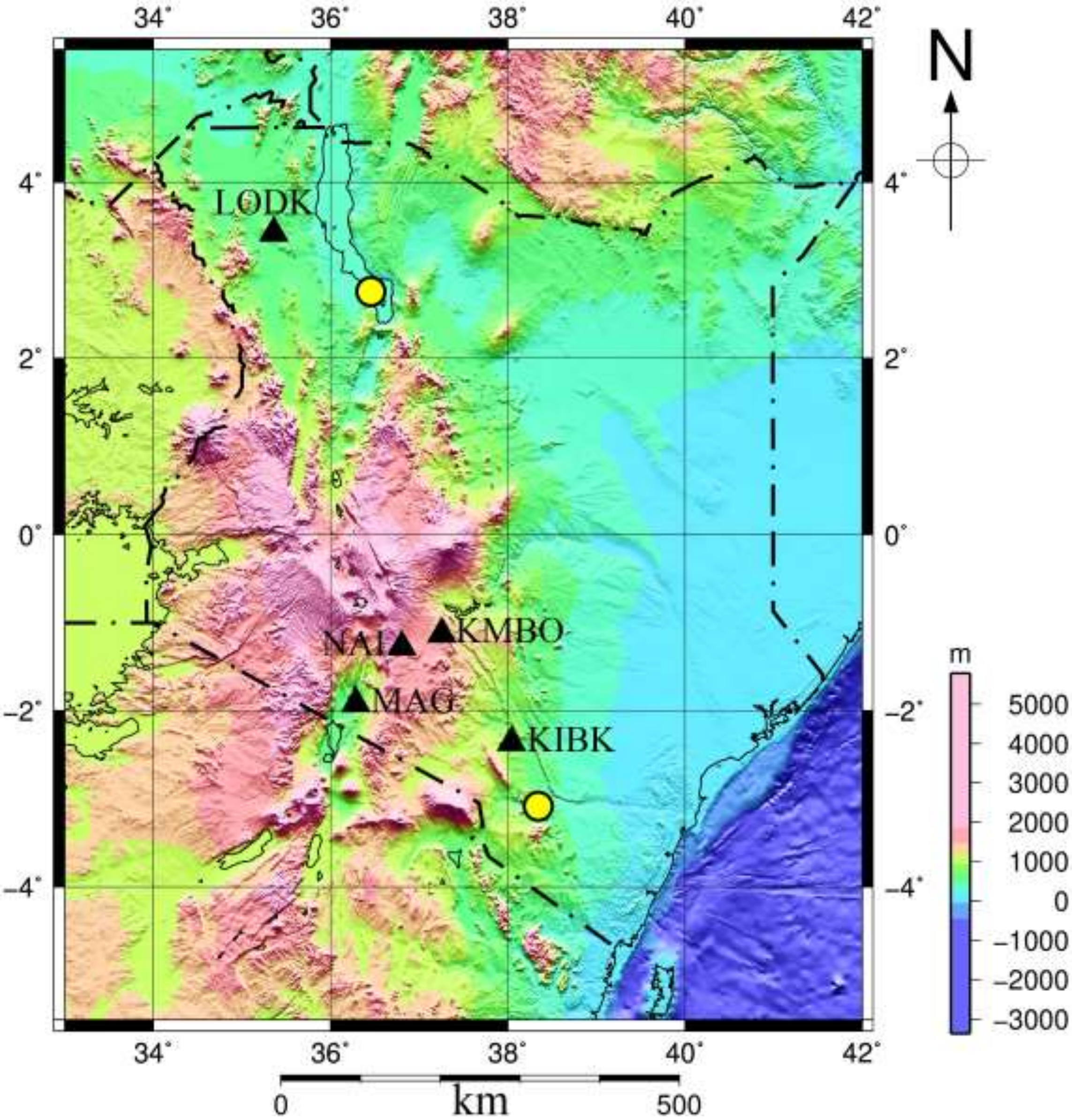

Fig 2 Seismic events used in this study indicated by yellow circles. The black triangles are seismic stations that constitute the Kenya National Seismic Network (KNSN): LODK-Lodwar (GE), NAI-Nairobi (AF), KMBO-Kilimambogo (IMS), MAG-Magadi (KNSN) and KIBK-Kibwezi (GE)

In order to determine the focal depth and use it as a discriminant as per the criteria presented in sub-section 2.1, the earthquakes epicenters, focal depths and origin times were determined using the conventional waveform analysis techniques in Geotool (Vers.2.4.1), which incorporates the global seismic velocity models and travel times (Jeffreys and Bullen 1967; Kennett and Engdahl 1991). The events waveforms were requested from the IDC in IMS2.0 format, loaded into geotool and preliminary seismic phases picked on three component (3C) seismograms with good signal-to-noise ratio (SNR). The seismic events were located to obtain preliminary events parameters (epicenters, focal depths, origin time). The waveforms were then sorted by distance and aligned by time minus predicted P phase arrival (CTBTO 2013). Additional seismic phases were then picked on all other 3C seismograms and the events located to obtain refined epicenter parameters. Seismic arrays enhance the signal by reducing noise and beam forming is a basic technique to improve signal-to-noise ratio (Ogiso pers.comm.). For array stations, the frequency-wavenumber (FK) analysis tool was used to create common beams for waveforms of same sampling rate and channel by defining a time window of about 3 sec around the predicted P arrival (CTBTO, 2013). Seismic phases were then picked from the common beams. Seismic arrays have an additional advantage of determining azimuth of the events and slowness of the P- seismic phase. The azimuths were used during the third stage of events location as an additional constraint to the events parameters other than just using time as the only constraint. Bowers and Selby (2009) however caution that depth estimates using only teleseismic P onset times tend to trade off with the origin time. Further, depths estimated using onset times from regional distances are unreliable for depths < 50 km and have large uncertainty (Fisk et al. 2002 cf. Bowers and Selby 2009). Magnitudes were determined by measuring the amplitudes of P-phases and then computing both the stations and network magnitudes. Tables 1 and 2 summarize the epicentral parameters while figs. 3 and 4 show the locations from geotool and plot in GMT for the two seismic events.

Table 1 Epicentral parameters of the 20190324 seismic event in southwestern Kenya

Latitude	**Longitude**	**Date and Origin time (UTC)**	**Depth (km)**	**Magnitude ml mb**	**Number of seismic stations**	**Region**
-3.0807	38.3428	20190324 16:21:13	0.0	4.9 4.2	54	Chyulu hills in southwestern Kenya

Table 2 Epicentral parameters of the 20200503 seismic event in northern Kenya

Latitude	**Longitude**	**Date and Origin time (UTC)**	**Depth (km)**	**Magnitude ml mb**	**Number of seismic stations**	**Region**
2.7577	36.4563	20200503 19:36:53	0.0	4.8 4.8	33	Turkana depression, Northern Kenya

Based on the epicentral parameter results obtained from the conventional waveform analysis, the two seismic events are categorized as resulting from explosions as depth (0 km) is less than 10 km (Yoshida pers. Comm.).

HYPOCENTER (Lienert 1994; Lienert et al. 1986; Lienert and Havskov 1995; Havskov and Ottemoller, 1999) was used to refine the epicentral parameters initially obtained as described in the preceding paragraph. P-wave polarities, characteristics (compression versus dilatation) and phase arrival times were used as input parameters in HYPOCENTRE. The seismic stations coordinates (xyz) were updated in the STATION0.HYP file. In addition to the IMS stations, HYPOCENTER has an additional advantage of utilizing data (P-wave polarities, characteristics (compression versus dilatation) and phase arrival times) from waveforms of non IMS stations. Tables 3 and 4 summarize the refined hypocentral parameters (latitude, longitude and depth) obtained from HYPOCENTER.

Based on the HYPOCENTER results, the 20200503 seismic event in northern Kenya is screened out as being a natural earthquake. The 20190324 seismic event would require to be subjected to further discriminants as focal depths obtained from conventional waveform analysis (d=0 km) and HYPOCENTER (d=9.1 km) are indicative of explosion (d < 10 km).

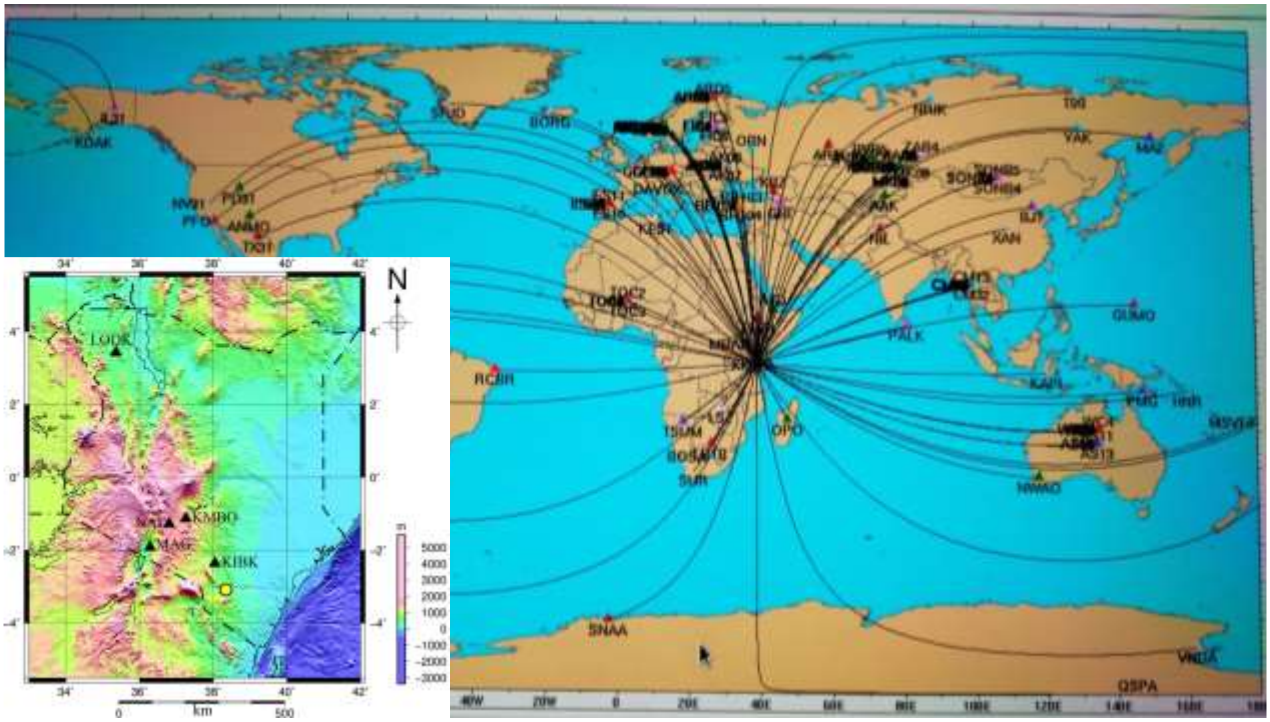

Fig 3 Geotool location solution and plot in GMT (yellow circle in inset map) of the Chyulu hills seismic event in southwestern Kenya

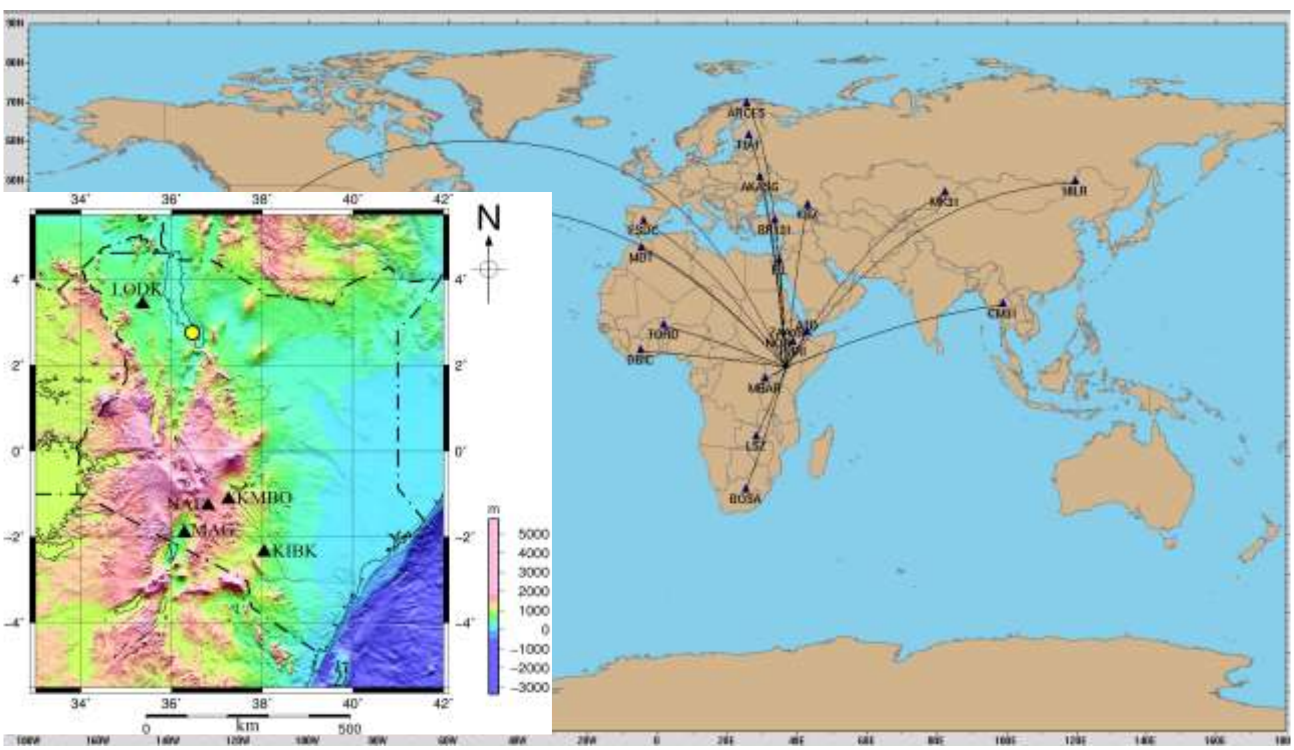

Fig 4 Geotool epicentral solution and plot in GMT (yellow circle in inset map) of the Turkana depression seismic event in northern Kenya

Table 3 Hypocenter parameters of the 20190324 seismic event in southwestern Kenya

Latitude	Longitude	Date and Origin time (UTC)	Depth (km)	Magnitude ml mb	Number of seismic stations	Region
-3.117	38.362	20190324 16:21:11	9.1	4.9 4.2	57 (3 non IMS)	Chyulu hills in southwestern Kenya

Table 4 Hypocenter parameters of the 20200503 seismic event in northern Kenya

Latitude	Longitude	Date and Origin time (UTC)	Depth (km)	Magnitude ml mb	Number of seismic stations	Region
2.855	36.254	20200503 19:36:55	14.1	4.8 4.8	35 (2 non IMS)	Turkana depression, Northern Kenya

The m_b: M_s criteria presented and discussed in section 2.2 was further used to characterize the nature of the two seismic events. For this purpose, the regression equation by Bowers and Selby (2009) (equation 1) was used to convert mb to M_s. Further the m_b: M_s relationship based on the 2006 IDC REB Eurasian events (Fig. 5) was used to characterize the events based on the relative sizes of mb and M_s (Bowers and Selby 2009 and references therein).

$$1.25m_b(IDC) - M_s(IDC) = 2.20 \quad \textbf{Eq. 1}$$

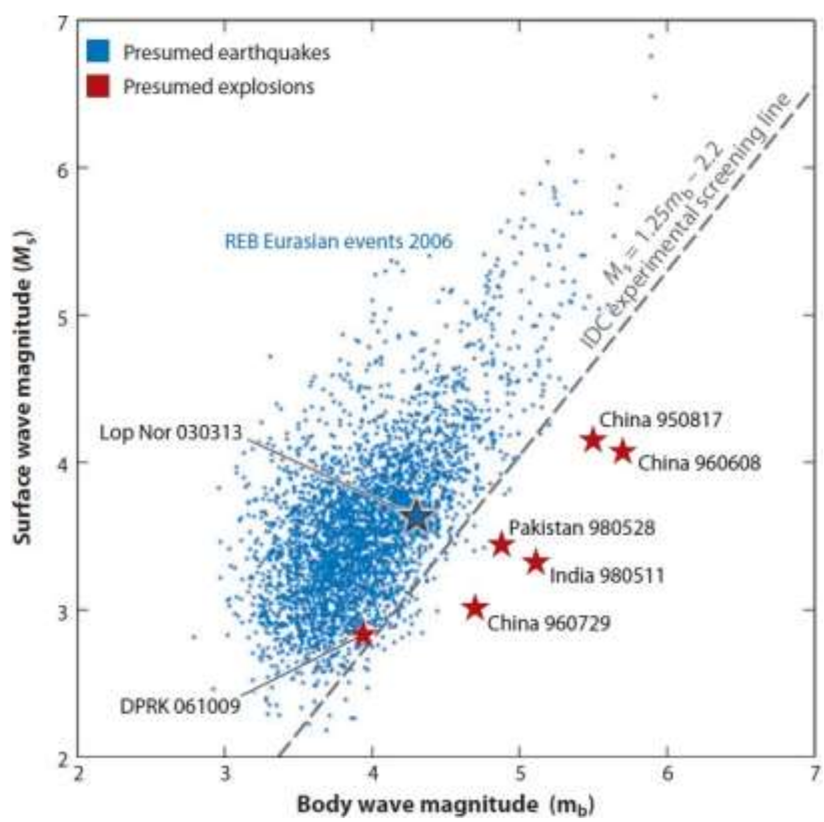

Fig. 5 IDC REB Eurasian underground explosions and earthquakes showing m_b: M_s regression relationship (After Bowers and Selby 2009)

The surface wave magnitudes obtained for the two earthquakes in Kenya using the regression equation by Bowers and Selby (2009) and the corresponding body wave magnitudes are presented below:-

m_b = 4.2; M_s = 3.1 (20190324); m_b = 4.8; M_s = 3.8 (20200503)

Based on m_b: M_s relationship, the two earthquakes may pass as explosions despite the 20200503 seismic event having been determined to be earthquake by virtue of its focal depth (14.1 km). The IDC m_b: M_s regression relationship gives far much lower surface wave magnitude (M_s) than would otherwise be obtained using other magnitude conversion formulae e.g. Scordilis (2005). In any case, the m_b value is still greater than M_s implying possible explosive source of the seismic event.

Discriminant 2.3, which is the last discriminant in our systematic seismic events discrimination methods at KE-NDC is based on focal mechanism using FOCal MEChanism (FOCMEC). FOCMEC performs an efficient and systematic search of the focal sphere and reports acceptable solutions based on selection criteria for the number of polarity and/or amplitude errors (Snooke 2003, 2017). The input parameters in FOCMEC are first arrival P-phase picked on the vertical component seismometers, its polarity (U or +, D or -) and characteristic (impulsive, i or emergent, e), and the seismic stations coordinates (latitude and longitude). The results of focal mechanism solutions obtained using FOCMEC for the two seismic events are presented in Fig. 6.

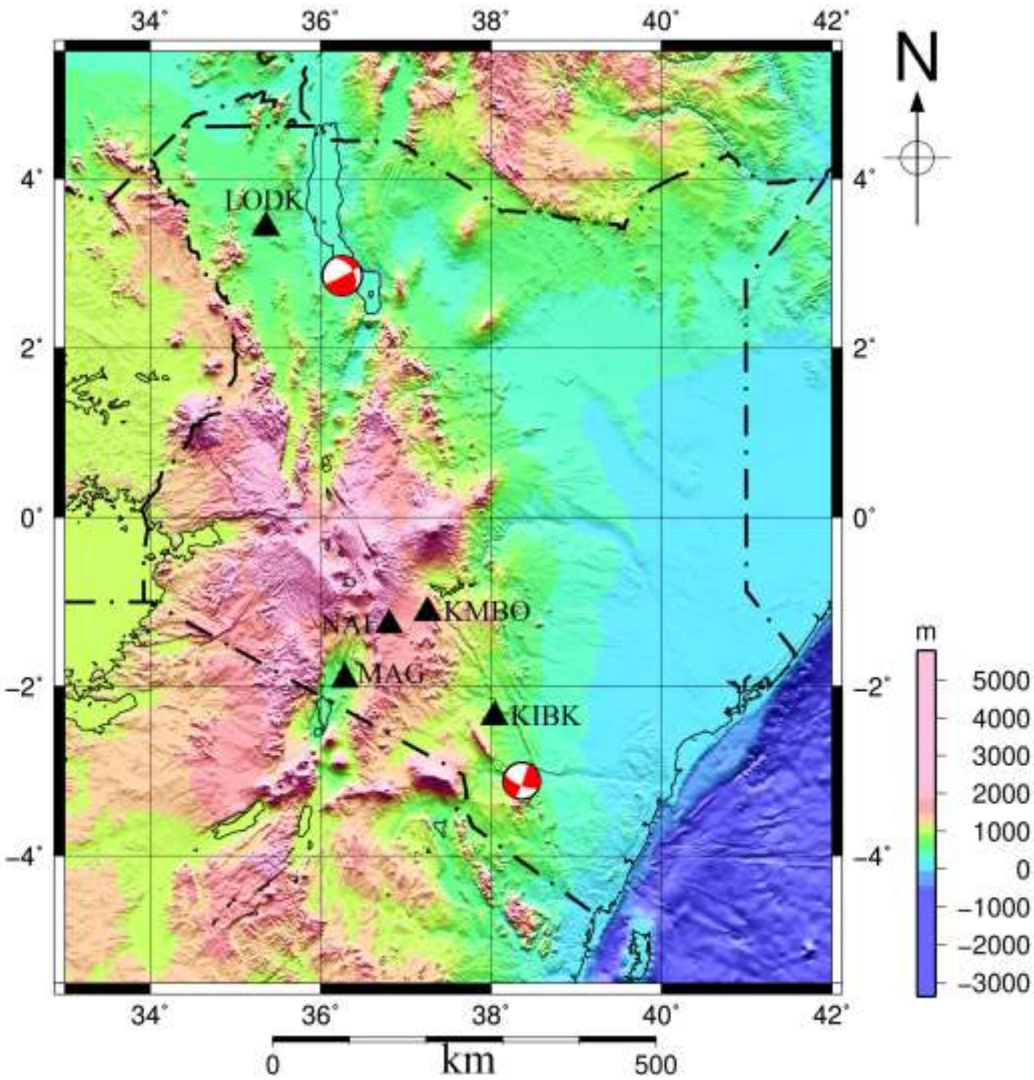

Fig. 6 Focal mechanism solutions for the 20190324 and 20200503 earthquakes in southwestern and northern Kenya respectively

4 Conclusion

Four methods of seismic events discrimination and the results from these methods have been presented. The choice of the methods at KE-NDC is because of the fact that they complement each other and are also intertwined. During routine phase picking on waveforms, the seismic phases arrival times are obtained as well as the polarity and characteristic of the first arrival P-phase. Depth and magnitude determinations a part of the routine analysis of waveforms of seismic events. The depth and other epicentral parameters are further refined using HYPOCENTER. Using the regression equation by Bowers and Selby (2009), the body wave magnitude (m_b) obtained is used to compute the surface wave magnitude (M_s). An assessment of the m_b: M_s relationship is further undertaken to judge if the nature of the seismic event is natural or anthropogenic. The final discriminant applied is the determination of focal mechanism of the seismic events. The method utilizes first arrival P-phase picked on the vertical component seismomograms, its polarity (U or +, D or -) and characteristic (impulsive, i or emergent, e), and the seismic stations coordinates (latitude and longitude).

Based on the discriminants presented herein, the 20190324 southwestern and 20200503 northern Kenya seismic events are hereby categorized as resulting from natural earthquakes due to strike slip faulting mechanism.

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