Seismicity of the central Afar rift and implications for Tendaho dam hazards

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Abstract: Temporary broadband seismic networks deployed from 2007 to 2011 around the Afar triple junction of the East African Rift System provide insights into seismicity patterns of the actively deforming crust around the 1.86 km^3 impounded lake system behind the Tendaho dam. The observed seismicity correlates well with the active magmatic centres around central Afar. The area around the dam site is characterized by a network of intersecting NNE- and NW-trending faults. Seismicity clusters observed in the specified time interval indicate that both fault sets are active and are potential sources of seismogenic hazards. The dam neighbourhood is naturally active and it is a challenge to associate the observed seismic activity to either a change in magmato-tectonic conditions or attribute it to the influence of reservoir load. It is evident that the dam region experiences high levels of seismic and volcano-tectonic unrest, regardless of the origin of the activity. The spatial overlap of narrow zones of crustal seismicity and upper mantle low velocity zones observed in S-wave tomography models suggests that melt production zones guide the distribution of strain during continental rupture. Given its volcanically and seismically active setting, the Tendaho dam site and the surrounding region require continuous monitoring for the safety of downstream populations and development infrastructures in the Afar National Regional State of Ethiopia.

Dams can potentially cause post-impounding seismic activity even on faults that had previously been considered inactive (Allen 1982). Increased earthquake activity has been associated with the filling of a number of large reservoirs (e.g. Gupta & Rastogi 1976; Simpson 1976). The combined effect of increased vertical load and pore pressure will have the greatest tendency to increase seismic activity in regions where the maximum compressive stress is vertical. Globally, the level of dam-induced seismicity ranges from micro earthquakes (M_L $<$2.5) detectable only with nearby instruments of high sensitivity to destructive earthquakes of magnitude over M_W 6.3 (Gupta & Rastogi 1976; Simpson 1976), which are recorded well on the global seismic network (Gupta 2002). Some of the best studied examples are the Koyna Dam in India, the Kremasta Dam in Greece and the Kariba Dam on the Zambezi River in Africa (Gough & Gough 1970*a*, *b*; Tizdel 1972). One of the earliest reservoir studies recording induced seismicity is the Hoover Dam in Colorado that experienced increased activity after the loading of Lake Mead. The impoundment caused a downward movement of crustal rocks along pre-existing fault lines (Carder 1945). A destructive case resulted from loading the Xinfengjiang reservoir in China where a 6.1 magnitude earthquake struck in 1962 (Chen & Talwani 1998). In some cases, a direct correlation of pronounced increases in seismicity with the first filling of the reservoir makes the causal relationship obvious: however, there are many cases in which there remains doubt as to whether the reservoir was directly responsible for increased seismicity. The most conclusive cases for induced seismicity are those relatively rare instances where there are data available from detailed monitoring

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of the reservoir region prior to impounding and where there is a substantial increase in seismicity on first filling of the reservoir (e.g. Nurek reservoir; Simpson & Negmatullaev 1981).

Induced seismicity during reservoir filling is most common in areas of normal and strike-slip faulting (Simpson 1976; Packer *et al.* 1977). Therefore, dams under consideration for construction within predominantly extensional regimes (e.g. East African Rift System (EARS)) need extensive pre-construction evaluation, as well as real-time monitoring. Magmatically active rift zones pose additional challenges, since magma-induced ground deformation is not normally considered in building codes. Furthermore, detailed background seismicity studies prior to dam filling are poorly practised in much of the EARS, a requirement to properly document dam-induced seismicity.

Growing demand for hydroelectricity and arable land has recently resulted in an increase in the development of dams in Africa. The EARS hosts a long chain of seismically and volcanically active, fault-bounded topographic depressions that contain vast water resources and serve as corridors for human and animal migration. The Awash River Basin in Ethiopia is gifted with abundant surface and ground water resources with nutrient-rich soil fed by surface water runoff from the Ethiopian highlands. Sediments accumulate in subsiding rift segments, making much of the rift valley along the Awash River ideal for agriculture.

Noting the potential of the Awash River Basin for multi-sector development (Fig. 1), the then Imperial Government of Ethiopia established the Awash Valley Authority (AVA) in 1962 based on a feasibility study conducted by United Nations Development Program (UNDP) and Food and Agriculture Organization (FAO). A general survey of the river basin was completed by consultants (FAO/UNDP 1965) and thereafter several development projects in the fields of hydropower, irrigation and livestock were identified along the Awash River Basin, decades before the recognition of the seismic and volcanic hazards of the Afar triple-junction zone. The idea of constructing two water storage dams at the Tendaho Gorge and along the Kessem River for downstream irrigation schemes was conceived by this pioneering work, and it was later supported by reports of Halcrow & Partners (1989). The earlier assessments strengthened other development projects at the upper Awash, middle Awash and lower Awash cotton and sugar cane plantation sites that continue to expand.

Early studies were conducted on the feasibility of constructing the Tendaho dam (e.g. FAO/UNDP 1965), but the unique geothermal groundwater systems and potential threat of earthquakes (Fig. 1) and intrusive magmatic activity were never identified or quantified for the envisaged development activities. More recently, contractors provided site-specific evaluations of maximum ground accelerations, which are applicable only for reinforced concrete structures based on the relatively sparse earthquake database and without consideration of the rapid, metre-scale ground deformation associated with shallow normal faulting and dyke intrusions which are typical of this region (e.g. Abdallah *et al.* 1979; Sigmundsson 1992; Wright *et al.* 2006; Rowland *et al.* 2007).

The Dabbahu-Manda Hararo dyking sequence started in 2005, just a year after the Tendaho dam (Fig. 2) construction commenced, with active faulting occurring <40 km to the NW of the dam (Fig. 1). The onset of this rifting episode was marked by an initial *c.* 2.5 km^3 magmatic intrusion, volcanic eruption, and surface faulting that caused up to 3 m of surface deformation (e.g. Wright *et al.* 2006; Rowland *et al.* 2007; Ayele *et al.* 2009). In October 2005, a team from Royal Holloway University of London and Addis Ababa University deployed nine seismic stations in Afar to capture seismicity associated with the dyke intrusions. The network included a station in Semera, near the Tendaho dam, which was removed in October 2006. During March 2007–October 2009, the University of Rochester in collaboration with Addis Ababa University deployed 15 stations in Afar in order to continue monitoring dyke-induced seismicity. This network included a seismic station at the Tendaho dam site so that high resolution monitoring of the region could continue during and after impounding the lake behind the dam (e.g. Ebinger *et al.* 2008; Keir *et al.* 2009; Belachew *et al.* 2011). Data collected since 2007 provided an opportunity to investigate the seismicity in the dam neighbourhood. Though pre-impoundment monitoring was done in 2007 and 2008, the main focus was to study the intense Dabbahu tectono-magmatic rifting episode. The seismic station network distribution was not configured to fully evaluate background seismicity levels in the dam area. Our study uses new datasets (Fig. 3) and incorporates results with previous studies (e.g. Ebinger *et al.* 2008; Belachew *et al.* 2011) to illustrate the spatial distribution and kinematics of seismicity in the dam neighbourhood, regardless of the cause of the earthquake activity. Furthermore, by combining the earthquake locations with a detailed fault map of the region, we aim to identify structures that pose a potential seismogenic hazard.

Background

Dam history

The Tendaho dam fills the Awash River Gorge (Fig. 2). The gorge is incised across the

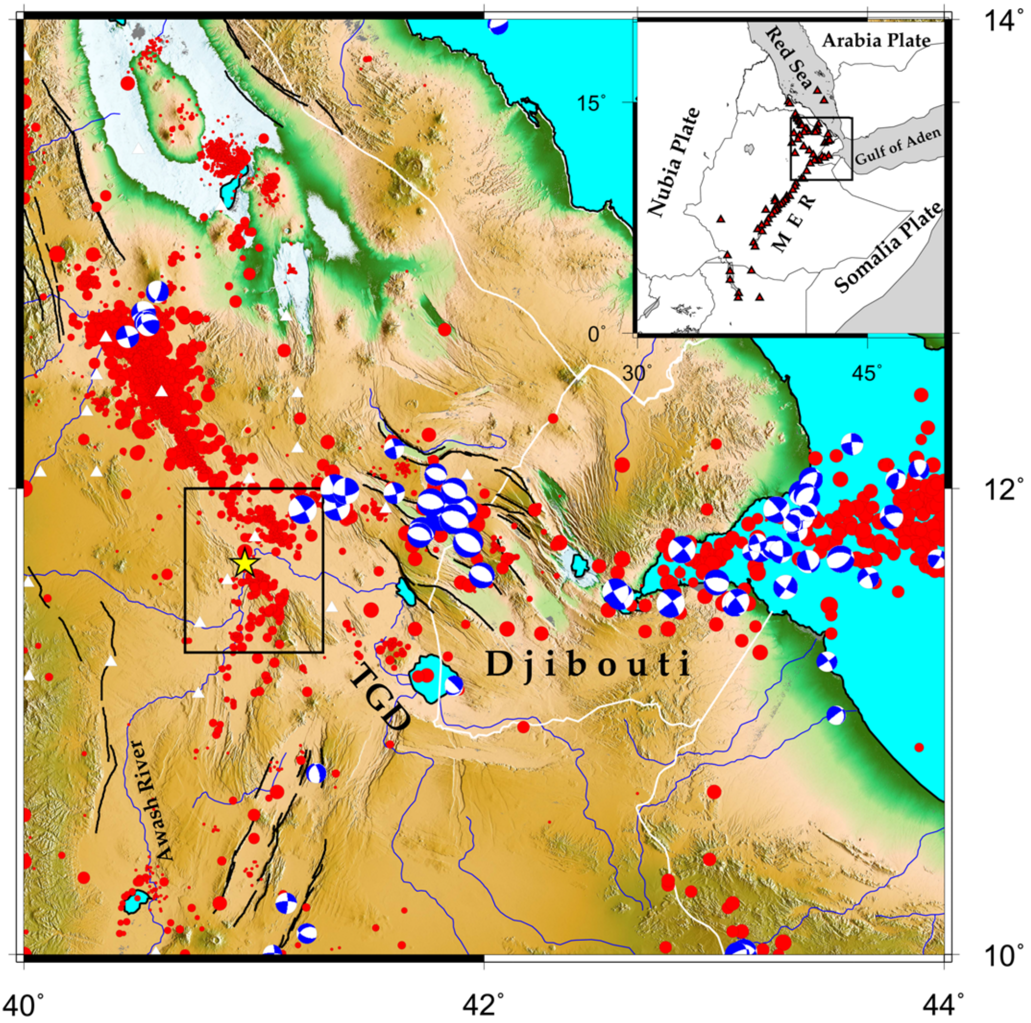

Fig. 1. Inset: Red Sea and Gulf of Aden oceanic rifts forming a triple junction with the Ethiopian rift in the Afar Depression where red triangles show distribution of active volcanoes in the region. Red dots show seismicity in the Afar Depression region with size of the circle being proportional to earthquake magnitude. The white and blue 'beach balls' show fault plane solutions of some major earthquakes from GCMT solutions. The black rectangle shows the location of the Tendaho Dam in the Depression with the yellow star showing the location of the earth filled Dam body. The black lines show fault traces while the white lines show national boundaries. MER, Main Ethiopian Rift; TGD, Tendaho Go'Bad Discontinuity.

Tendaho-Goba'ad Discontinuity (TGD), which marks the position of the Africa–Arabia plate boundary (Figs 1 & 4). Plans for the dam were initiated in the 1960s (FAO/UNDP 1965) prior to recognition of the existence of the multiple plate boundaries in the Afar Depression. After decades of delay, the Tendaho dam irrigation project was officially launched in 2004 and managed by the Ministry of Water Resources of Ethiopia. It is an earth-filled dam with a crest length of 412 m, maximum height of 53 m and a reservoir storage capacity of up to 1.86 billion m^3. The project was financed by the Government of Ethiopia with the aim to supply a 60 000 ha irrigation system to produce sugar cane and to create more job opportunities for the benefit of over 35 000 pastoralist families. The dam was completed after six years of construction and the first phase of reservoir filling started during the spring of 2009, two years after the installation of a temporary seismometer

Fig. 2. Reservoir view seen from the intake tower.

array encompassing the dam site (e.g. Keir *et al.* 2009; Hammond *et al.* 2011; Belachew *et al.* 2013). The dam construction was implemented without detailed subsurface geophysical and geological investigation and up-to-date information regarding volcanic and earthquake hazards. The supports for the earth-filled dam were drilled into hydrothermally altered mafic volcanic rocks along a zone of coeval NW- and NNE-striking normal fault systems, near hot water seeps and geysers of Allalobeda (Figs 1, 4 & 5a, b).

Tectonic setting

The Tendaho dam site is located close to the Afar triple junction where the EARS meets the Gulf of

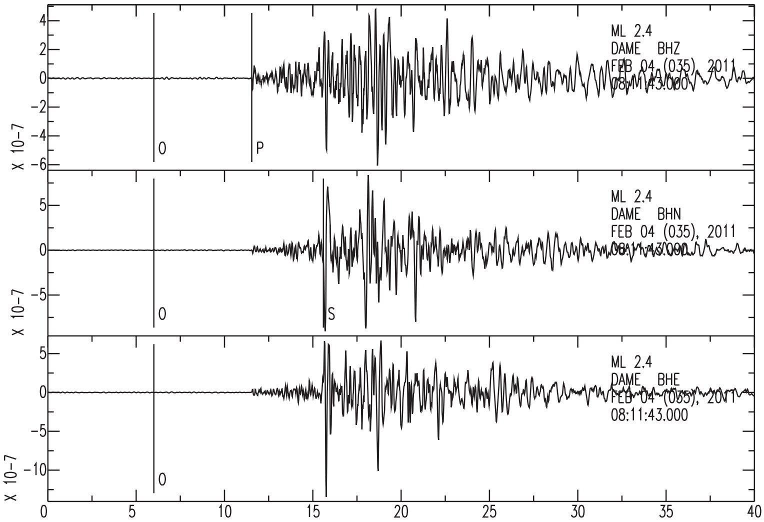

Fig. 3. Three component displacement seismograms recorded at DAME (located on the right abutment) station for an event located about 25 km SE of the dam body. The event occurred on 4 February 2011 at 08:11:49.57 GMT with magnitude M_L 2.44.

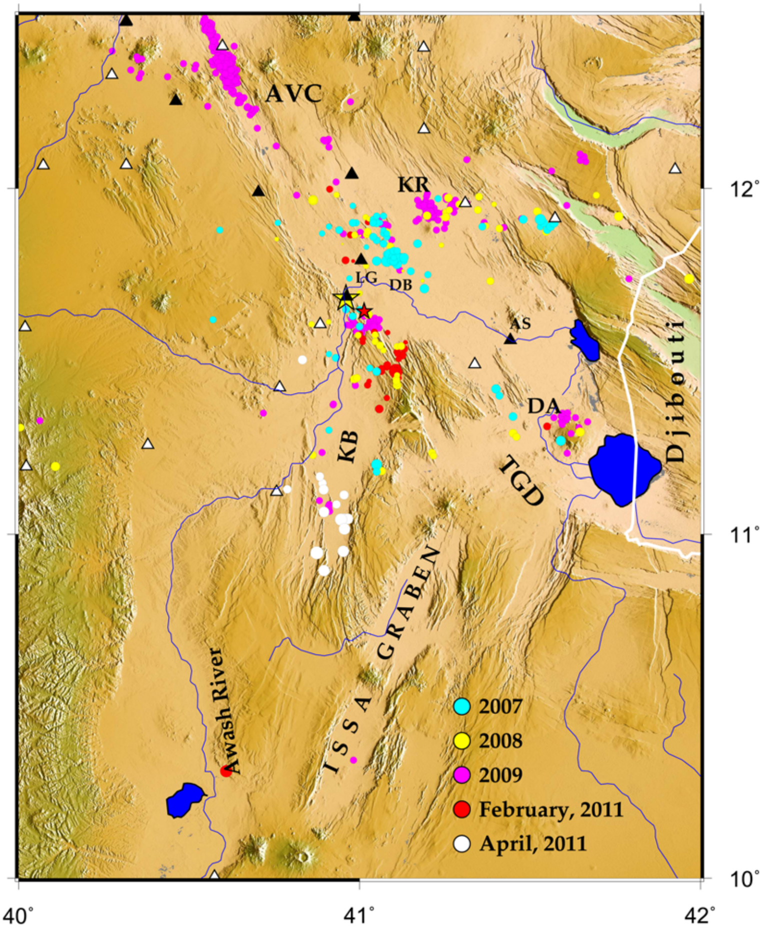

Fig. 4. Detailed topography and seismicity of the Tendaho dam region from 2007 to 2011. This is a zoomed version of the black box shown in Figure 1. The circles represent earthquakes, with the size of the circle being proportional to the earthquake magnitude. The seismicity of the corresponding years is detailed in the legend. Black triangles represent the distribution of the seismic stations for the post-2009 deployment, while the grey ones represent both the US and UK seismic station networks after the Dabbahu activity. The black line segments are fault traces while the white traces are national boundaries. AVC, Ado Ale Volcanic Complex; KR, Kurub Volcano; DA, Dam Ale Volcano; KB, Karrayu Basin. The yellow star shows the location of the intake tower while the red star shows the location of the Allalobeda Hot Springs.

Aden and Red Sea oceanic rifts (Figs 1, 4 & 5). The Tendaho dam reservoir lies in a seismically and volcanically active rift zone at the intersection between the NNE-striking Karrayu Basin of the Ethiopian rift and the NW-striking Tendaho Graben of the southern Red Sea Rift (e.g. Tesfaye *et al.* 2003; Soliva & Schulz 2008; Keir *et al.* 2013). Faulting and magmatism initiated in the Afar region of Ethiopia around 30 Ma ago with the onset of rifting between the African (Nubian) plate and the Arabian plate (Fig. 1), which is being pulled NE by the subducting Tethys oceanic lithosphere (e.g. Hofmann *et al.* 1997; Bellahsen *et al.* 2003; Wolfenden *et al.* 2005). From decades of geodetic observations, the current plate motion velocities relative to Nubia are estimated to be *c.* 15 mm a^{-1} of NE-directed motion of the Danakil Block (Vigny *et al.* 2007; McClusky *et al.* 2010) and *c.* 2–6 mm a^{-1} of ESE motion of the Somalian Plate (e.g. Bilham *et al.* 1999; Bendick *et al.* 2006). These rates may have been slower during early rifting phases, based on triple-junction migration rates (Tesfaye *et al.* 2003).

Structural and stratigraphic data indicate that the Main Ethiopian Rift (MER) formation started >10 Ma after the flood basaltic magmatism and

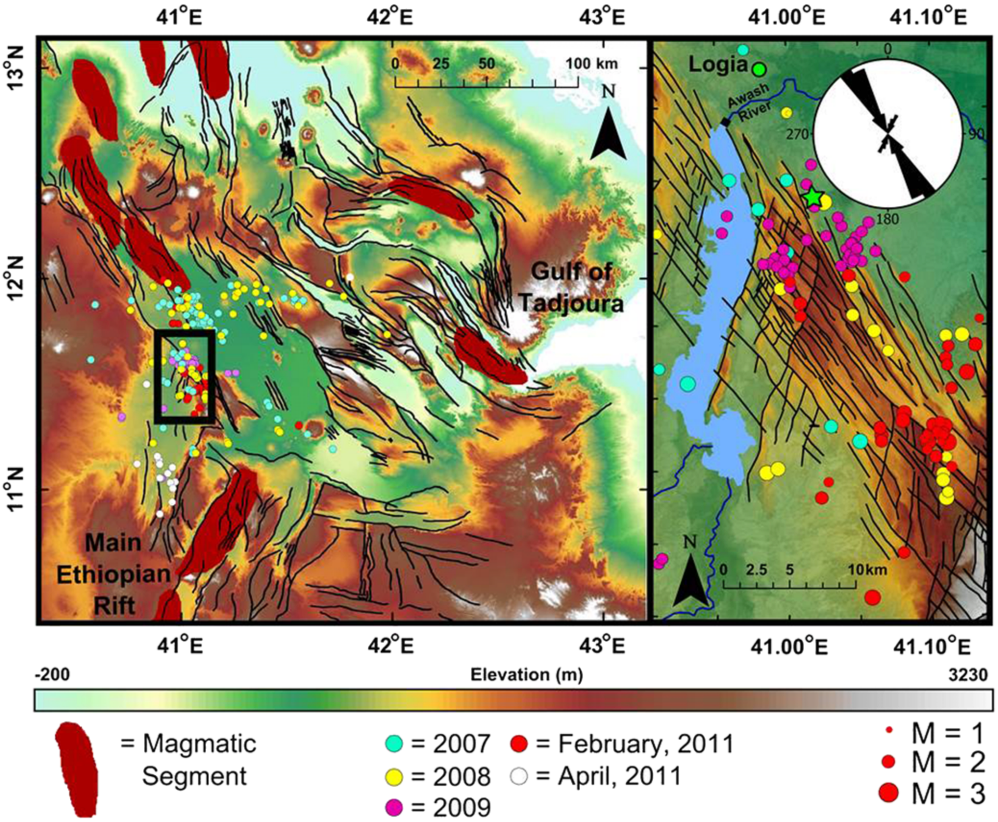

Fig. 5. Left panel (**a**): detailed structural map of the Afar Depression with major fault patterns in black and magmatic segments in red. The black square marks the area shown in the right panel. Right panel (**b**): cross-cutting active fault network near the Tendaho dam with the dam reservoir area in blue. The Dam reservoir area is dominated by NNW-trending and dense distribution of faults along the Southern Red Sea trend as shown by the rose diagram while some faults are NNE-trending along the axis of the Main Ethiopian rift (MER).

initiation of Arabia–Africa separation at *c.* 30 Ma (e.g. Hofmann *et al.* 1997; Wolfenden *et al.* 2005). The Arabia–Africa separation created the Danakil microplate, a sliver of stretched continental crust that forms a horst between the highly extended Afar Depression, and the southern Red Sea rift zone (Fig. 1). The separation of the Danakil microplate and Nubia motion accounts for strike-slip and oblique-strike-slip deformation observed between the Danakil–Nubian boundary (Chu & Gordon 1998; Eagles *et al.* 2002). Although fault-plane solutions from moment tensor inversion indicate active deformation parallel to plate opening vectors in the past (e.g. Jacques *et al.* 1996; Ayele *et al.* 2007*a*, 2009; Belachew *et al.* 2013), at present the region is experiencing purely extensional tectonics (Ayele *et al.* 2007*a*). Extension in the northern section of the MER developed within the last 11 Ma (Wolfenden *et al.* 2004). Active deformation within the highly extended Afar and MER zones is localized to a series of magmatic segments: *c.* 50–70 km-long zones of intense magma intrusion, volcanism and closely spaced, relatively small faults (Figs 1, 4 & 5; Barberi & Varet 1977; Hayward & Ebinger 1996). This style of deformation initiated within the broader Oligo-Pliocene rift zone at around 2 Ma (e.g. Kidane *et al.* 2003). The highly oblique *c.* E–W extension direction of the MER relative to the NE–SW extension directions of the Red Sea and obliquely-opening Gulf of Aden rifts is decoupled by the NW-striking TGD fault scarp, which passes beneath the region (Manighetti *et al.* 1997; Figs 1, 4 & 5). As a result, the Tendaho dam is in close proximity to an intensely faulted zone related to the complex plate boundary interactions at the triple junction. The Tendaho dam reservoir itself lies within a half-graben structure controlled by a large NNE-trending fault that bounds the reservoir to the east. In this paper we conduct detailed mapping of faults surrounding the Tendaho dam and its reservoir in order to better understand the complexity and seismic activity of the nearby fault network (Fig. 5b).

Seismicity

The Afar region is the most seismically and volcanically active part of the EARS. The most notable recent earthquake activities that occurred not far from the location of the Tendaho dam are the 1969 and 1989 earthquake sequences at Serdo and Dobi graben, respectively. The March and April 1969 earthquake sequence (maximum surface wave magnitude M_S 6.3), which occurred in central Afar, destroyed the town of Serdo with significant casualties of 40 dead and 160 wounded from a total population of 420 (Gouin 1979). All the masonry structures including the highway authority compound, the school and the police headquarters buildings were completely destroyed. The reinforced concrete water tower was the only structure that survived the shaking. The epicentre for the main shock of the Serdo sequence was only 40 km away from the current Tendaho dam site.

A significant number of large (M_S 5.5–6.5) and moderate (M_S 4.5–5.5) earthquakes and hundreds of smaller events occurred over a 40 h duration between 20 and 22 August 1989 with epicentres mainly confined to the Dobi and Guma Graben in central Afar (Sigmundsson 1992; Asfaw & Ayele 2004). The events caused deaths, injuries and major rock slides that blocked a 30 km segment of the main highway to the Red Sea port of Assab and destroyed six bridges (Asfaw & Ayele 2004). This sequence of earthquakes was the largest contributor to seismic moment release in Afar since 1960 (Ebinger *et al.* 2013). The resultant disruption of access to the main seaport made the 1989 Dobi sequence economically the most devastating to Ethiopia of all earthquake activities that occurred in the last 100 years (Asfaw & Ayele 2004). The epicentre of the main shock of the 1989 Dobi sequence was just 100 km away from the Tendaho dam.

The first network of four seismic stations was installed and operated by the University of Durham in south-central Afar during 1973 and 1974 (Searle & Gouin 1971; Rigden 1981). In connection with a proposed dam across the Awash River at Tendaho in south-central Afar, the Ethiopian AVA subcontracted a feasibility study on seismicity to Durham University as part of the site investigation. Each station consisted of a three-component set of seismometers. Located epicentres correlate well with Holocene magmatic segments, and epicentral distribution patterns reflect intense regional NW–SE-trending activity along the Tendaho Graben, just NE of present-day Semera town (Rigden 1981). The 1974 Ethiopian revolution caused the contract to be terminated prematurely.

Another local seismicity study investigated about 60 earthquakes recorded by a network of six stations deployed around the Semera area from October 1993 to June 1994 for a geothermal investigation by Aquater (Gresta *et al.* 1997). Most of the epicentres in the 1993–94 monitoring were located in the NW–SE-trending Tendaho Graben along the southern part of the Manda-Hararo rift while some activity was reported around Kurub volcano. In 1999, one broadband station was installed in the Aquater compound in Semera (TEND) as part of the Ethiopia Broadband Seismic Experiment (Nyblade & Langston 2002). There is no interesting data from this single station for local seismicity due to amplification of heavy road noise by the thick sedimentary basin fill.

The Tendaho Graben was again monitored immediately after the first of 14 major dyke intrusions between 2005 and 2010 that occurred within the Dabbahu-Manda-Hararo (DMH) rift segments (Wright *et al.* 2006; Ayele *et al.* 2009; Ebinger *et al.* 2010). The duration of dyke activity coincided with the construction and filling of the Tendaho dam, which provided an unintended opportunity to study seismicity around the Tendaho dam. Geological evidence shows that the dominant surface faults and fractures present along the Tendaho Graben are oriented NW–SE or NNW–SSE, with predominantly normal faulting mechanisms (Abbate *et al.* 1995). Earthquake data demonstrated that the Tendaho area is one of the most seismically active sectors of the Red Sea propagator in central Afar, which demands proper evaluation of any development activity in the area and real-time monitoring of seismic and geodetic data (Acocella *et al.* 2008; Belachew *et al.* 2011).

Data and methods

Structural mapping

The fault network around the Tendaho dam was mapped in detail using high resolution Landsat satellite imagery and Shuttle Radar Topography Mission (SRTM) digital elevation models. The remote sensing data were imported into ArcGIS (a geospatial data visualization and analysis tool) where the surface manifestations of minor and major faults were digitized manually to create a fault trace map. The orientation of the faults was determined using a length-weighted rose diagram, which was obtained by calculating the total trace length of faults within orientation bins of 10°. The results were combined with a map of seismicity data in the area to establish which faults have recently been active (Fig. 5b).

Station network and seismic dataset

The Afar Depression is one of the most ideal places on Earth to study active rifting and volcanism on land. However, installation and maintenance of a dense seismic network to detect and accurately locate changes in microseismicity is logistically challenging and financially expensive in Afar owing to the lack of road, electric power and communication infrastructure. As a result, we commonly do not observe detailed information associated with interesting magmato-tectonic events. During the September 2005 dyke intrusion in the DMH, only the major events were captured by sparsely distributed permanent stations deployed in the region (Ayele *et al.* 2009) and the major dynamics of the mega-dyke intrusion were recovered by time-averaged patterns evident in InSAR (interferometric synthetic aperture radar) data (Wright *et al.* 2006; Ayele *et al.* 2007*b*).

In October 2005, Addis Ababa University and Royal Holloway University of London mobilized seismic stations and resources with urgency funding to closely monitor subsequent dyke intrusions and the background seismicity in the area (Ebinger *et al.* 2008). Nine seismic stations operated in Afar until October 2006 coincident with dam construction and filling. A station in Semera was installed closest to the dam (Figs 1 & 4), which created an opportunity to look at the reservoir neighbourhood seismicity. The primary focus of the 2005–06 array was the DMH magmatic intrusion and only events of $>c$ $\mathrm{M_L}$ 2.5 were recorded outside the network (Ebinger *et al.* 2008). During March 2007–October 2009, the University of Rochester deployed 15 stations in Afar, including at the Tendaho dam (Ebinger *et al.* 2008; Belachew *et al.* 2011). This network was surrounded, during the October 2007–October 2009 period, by 29 stations from the Afar Rift Consortium (University of Leeds and University of Bristol). We used data during 2007–09 as a primary dataset to indicate a continuous record of microseismicity. Interpretation of the seismicity in Ebinger *et al.* (2008) and Belachew *et al.* (2011), focused only to the dyke intrusion events and earthquake activity around the Tendaho dam site, was not interpreted to this effect. During October 2009 through 2011, data from 12 stations comprising the Afar0911 network deployed by University of Southampton and University of Bristol have been used to specifically constrain the locations and magnitudes of major sequences near the dam (Fig. 4). These networks recorded the regional seismicity patterns and showed persistent earthquake swarms beneath Kurub volcano, the Serdo region and the southern Manda-Hararo rift zone (Belachew *et al.* 2011) (Fig. 4).

As a contribution to the task force assigned by the Water Work Design and Supervision Enterprise of Ethiopia to investigate the Tendaho dam leakage in 2010, which was observed on the right abutment, the DAME station was reoccupied and high quality data were collected from 15 December 2010 to 14 February 2011 (Fig. 3). This station has been used as a guide to examine temporal and spatial changes in the local seismicity around the dam, including a swarm of earthquakes in February 2011. Although no pre-, syn- and post-impoundment seismicity was monitored for the dam construction project, the seismicity time-series from the Afar research projects can be used to inform and advise earthquake and volcanic hazard mitigation programs throughout the Afar region and to mitigate against the impact of future hazards on the downstream population. Three major towns, Logia, Dubti and Asaita (Fig. 4), have populations of about 32 000, 27 000 and 25 000, respectively, from a 2008 census of the Central Statistical Agency of Ethiopia. These data can be roughly projected to about 100 000 inhabitants in 2013 living nearby the Awash River bank.

Seismicity data analysis

All P- and S-wave arrivals were picked manually. All events were located using the absolute location program Hypoinverse2000 (Klein 2002). A 3-layer one-dimensional P-wave velocity model of Jacques *et al.* (1996) derived from earlier seismic refraction studies in Afar (Berckhemer *et al.* 1975; Ruegg 1975; Makris & Ginzburg 1987) and V_P/V_S ratio of 1.8 determined from regression of travel times were used for the earthquake locations (Belachew *et al.* 2011). Magnitude for all the earthquakes was estimated using the local magnitude scale and distance correction terms for the MER (Keir *et al.* 2006). Maximum zero-to-peak body-wave amplitudes were measured on simulated Wood-Anderson horizontal displacement seismograms. Between 2007 and 2009, a total of *c.* 5320 earthquakes were recorded on four or more stations from within the Afar Depression and adjacent regions. The dataset is complete to *c.* $\mathrm{M_L}$ 1.9, and the b-value is 0.79 ± 0.01 (Belachew *et al.* 2011). Almost half of the earthquakes occurred during the dyke intrusion episodes along the DMH rift segment (Fig. 1). Hypocentre accuracy for the earthquakes is about ±1 km in horizontal directions and ±3 km in depth (Belachew *et al.* 2011). Similar uncertainties apply to locations derived from the 2009–11 array.

The background seismicity in the Afar region was projected on the S-wave seismic tomography anomalies at 75 km depth to examine possible correlations with upper mantle low-velocity zones associated with melt generation regions (Hammond *et al.* 2013).

Results and discussion

Fault network characteristics

Detailed mapping of the surface manifestations of both major and minor faults surrounding the Tendaho dam and its reservoir illustrates a complex normal fault network (Fig. 5b). The fault network comprises two coeval fault sets, a NNE-trending fault set and a NW-trending fault set, that form numerous cross-cutting and abutting relationships with each other (Fig. 5b). The network is dominated by numerous NW-trending faults as indicated by the length-weighted rose diagram in Figure 5b. The NNE-trending faults are more widely spaced, in comparison to the NW-trending faults, and mainly down throw to the west. The fault trends of this complex fault network are caused by the superposition of the two stress systems associated with the N110°E extending boundary between the Africa and Somalia plates (Karrayu Basin of the MER) and the N45°E extending Africa–Arabia boundary marked by the Tendaho Graben of the southern Red Sea rift propagator. The orientations of the two fault sets favour fault interaction and the possible transfer of displacement between faults of each set (e.g. Maerten *et al.* 2001; Nixon *et al.* 2014), which may have implications for potential ground ruptures.

Recent seismic activity

The combined seismicity datasets from the region surrounding the Tendaho dam has allowed us to assess the recent activity in the area between 2007 and 2011. Results indicate that the Tendaho Graben and TGD faults, across which the Tendaho dam was built, were seismically active during this time. In this section we describe in detail the temporal and spatial pattern of this seismic activity.

Activity prior to dam impoundment (2007 and 2008). Numerous earthquakes occurred in the Tendaho Graben, 10 km east and NE of Semera, in 2007. The elongated cluster was 20 km long and strikes NW–SE which is parallel to faults of the Tendaho Graben. The cluster may have been related to stress transfer from the August and November dyke intrusions in the DMH rift segment in that same year, or be representative of background level seismicity (Fig. 1, 4 & 5b; Belachew *et al.* 2011). In addition, there was some distributed activity around the Tendaho dam in 2007, but it was minor in comparison to the subsequent years. This area is reported to have been seismically active in previous studies (Rigden 1981; Gresta *et al.* 1997). From the available constraints, the Tendaho rift axis is the most seismically active zone in the immediate vicinity of Semera town.

The overall activity in 2008 seems to be sporadic with most earthquakes occurring in a cluster 10 km NE of Semera, as well as on fault systems which define the eastern side of the Tendaho Graben (Figs 4 & 5b). Earthquakes also occurred near the dam and along both the NW- and NNE-trending fault zones mapped by Abbate *et al.* (1995) and this study. Thus, these limited time period studies show some earthquake activity around the dam both in 2007 and 2008 before the impoundment in 2009. This makes it difficult to determine whether the increased seismicity post-dating dam impoundment is solely due to dam loading or natural.

Activity during dam impoundment (2009). In February and June 2009, the Ado Ale Volcanic Complex (AVC) of the DMH segment hosted two dyke intrusions (Belachew *et al.* 2011). The one in February was characterized by intense seismicity with no eruption, but the latter one in June featured less seismicity and was accompanied by a fissure eruption (e.g. Ferguson *et al.* 2010). In the same year, localized earthquake activity was observed elsewhere in Afar. The distribution of earthquakes defines a 10 km-long NW-striking cluster on the eastern side of the Tendaho Graben. Earthquake activity also occurred near the Kurub and Dama Ale volcanoes *c.* 100 km SE and 40 km NE of the dam, respectively, both areas of persistent seismicity (Fig. 4). Some earthquakes were also located near the dam and, in particular, close to the Allalobeda geyser (Fig. 4). The observed seismicity in 2009 correlates well with the magmatic centres in the area (Figs 4 & 5), which may indicate that there is a causal relationship between the magmatic plumbing system in the region, and/or groundwater table fluctuations accompanying the increased magmatic activity. Groundwater fluctuations might also have accompanied dam impoundment, which resulted in the disappearance of Allalobeda geyser in June 2012 after phreatic eruption and was associated with increased seismicity (Lavelle 2012)

Activity post-dam impoundment (2011). February 2011 sequence. Leakage of the dam was reported in 2010 and the Institute of Geophysics Space Science and Astronomy was involved in the task force team organized by the Water Works Design Enterprise (WWDE) of the Ministry of Water Resources and Energy. The DAME station, which is located close to the right abutment of the dam, was reoccupied and high quality data were collected from December 2010 to February 2011 (Fig. 3). In addition, a few earthquakes occurred on 19

December 2010. A minimum of four stations were used in the location of over 50 earthquakes, with RMS values of less than 0.5 s and in the magnitude range of M_L 1.0–3.6. The earthquake locations are clustered mainly along a NNE-trending fault system sub-parallel to the eastern margin of the Karrayu Basin (Figs 4 & 5a, b). This is a clear indication, from well-constrained earthquake locations, that the Karrayu Basin margins are active and can potentially trigger a damaging earthquake beneath or around the Tendaho dam. During the February 2011 earthquake sequence, additional events occurred along the NW-striking faults of the southern Red Sea on the eastern side of the Tendaho reservoir.

April 2011 sequence. Continued seismic monitoring led to the detection of another major sequence of earthquakes during 1–9 April 2011 at the southern end of the Karrayu Basin, roughly 50 km south of the Tendaho dam. During 1–9 April 2011, we located 28 earthquakes with local magnitude in the range of M_L 2.1–3.8. The earthquakes define two North–South-striking clusters 20 km long and positioned on both eastern and western boundary faults of the Karrayu Basin (Fig. 4). The sequence of earthquakes commenced with an event of magnitude 3.8, the largest in the sequence. The seismicity was most intense on 1 and 2 April. During 3–5 April, the magnitude of earthquakes decreased, then on the 6 and 7 April there was an increase in seismic activity. The activity then remained relatively low until termination of the earthquake sequence on 9 April 2011.

Implications for potential hazard

Without a longer time-series of observation prior to dam construction, and given the swarm-like activity typical of this volcanically active rift zone, it is difficult to conclude that seismicity increased significantly after dam impoundment in 2009. However, irrespective of the cause of seismicity, the results indicate that the Tendaho dam and the surrounding area were seismically active between 2007 and 2011. Detailed analyses of the geometry and kinematics of fault networks from remote sensing and seismicity data indicate that the region is actively deforming as a response to the superposition of the southern Red Sea Rift and MER stress systems (Figs 4 & 5b). Seismicity clusters can be located on both NNE-trending and NW-trending faults (Figs 4 & 5b), indicating that both fault sets are active. Ultimately, this ties the seismicity to actual structures, identifying these fault sets as potential sources of seismogenic hazard. Furthermore, considering the complex crosscutting relationships between the two fault sets and the close spacing (<2000 m) of faults within each fault set, it is possible that stress changes associated with earthquake slip along one fault may trigger slip on one or more nearby faults (e.g. Lin & Stein 2004). For example, this is a pattern of deformation that has been observed in other regions such as the 1987 March, M_L 6.3 Edgecumbe earthquake, which ruptured several faults on the Rangitaiki Plains, New Zealand (Nairn & Beanland 1989). Overall, the presence of such an active fault network in close proximity to the Tendaho dam area illustrates a large number of potentially hazardous seismogenic structures and sites for possible future ground ruptures.

It is also evident that the Tendaho dam is in fact placed within the actively deforming rift zone near the Afar triple junction. The dam lies within an area of active volcanism, and only 70 km from the site of an eruption in 2005, and *c.* 30 km from a zone of dyke intrusion and eruptions in 2007, 2009 and 2010 (Ayele *et al.* 2009; Belachew *et al.* 2011; Figs 4 & 5a, b). The relatively shallow depths of earthquakes that occurred beneath and around the newly-formed reservoir lake are not unusual for this region: the average seismogenic depth in the Afar region is <10 km (Ayele *et al.* 2007*a*; Belachew *et al.* 2011). Overall, the impending earthquake and volcanic activity in the area poses a threat for development activity. Therefore, improved hazard mitigation in the future will require continuous monitoring led by Ethiopian scientists and resourced from sustainable national and international funds.

Triple-junction tectonics

The *c.* 7 years of seismic monitoring also provide new insights into rifting processes in the tectonically complex Afar triple junction zone. The identification of diachronous activity on multiple fault sets that are related to different stress systems highlights the complexity of triple junction tectonics and indicates direct interaction between the three rifting plate boundaries. Comparison of seismicity patterns and evidence for melt and lithospheric thinning beneath the *c.* 300 km-wide Afar Depression show distinct correlations. The S-wave tomographic image at 75 km depth (Hammond *et al.* 2013) shows low shear-wave velocity anomalies that clearly mimic the zones of seismicity marking the active triple junction zone (Fig. 6). The low velocity zone corresponding to the southern Red Sea rift appears to connect with the Gulf of Aden rift zone beneath a series of right-stepping en echelon rift basins above the East–West-trending low velocity zone. The unusually high crustal V_P/V_S ratios (1.9–2.2) determined from receiver function studies (Dugda & Nyblade 2006; Stuart *et al.* 2006; Hammond *et al.* 2011) and the amplitude of the

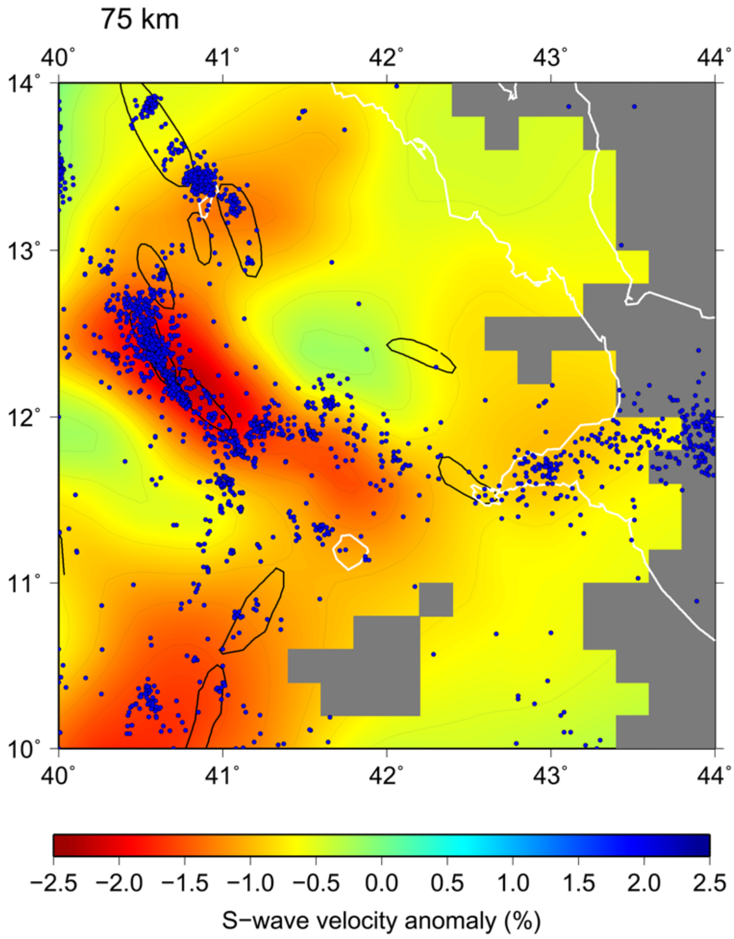

Fig. 6. Background seismicity in the Afar region superimposed on the S-wave seismic tomography anomalies at 75 km depth (Hammond *et al.* 2013). Black dots are location of earthquakes not scaled to magnitude.

shear-wave velocity anomalies indicate the presence of melt within the mantle. These patterns in the Afar Depression suggest that the lithosphere above the melt production zones is the most actively deforming region. The volcanic and earthquake activity in the Afar region is exciting for scientific research on continental rupture processes and rift development.

Conclusions and recommendations

Temporary seismic arrays in the highly extended and magmatically intruded Afar triple junction zone from 2007 to 2011 surrounding the Tendaho region of Ethiopia shed light on potential hazards associated with the construction of the Tendaho dam. The reservoir is located in a tectonically and geothermally active region of Afar. Owing to the intense volcano-tectonic rifting episode occurring <100 km to the north of the dam and the short time period of pre-dam impoundment monitoring, it is challenging to distinguish whether the increase in earthquake activity and changes in hydrothermal systems are dam induced or the result of stress transfer southward from rapid rift opening in the DMH segment to the north. Regardless of the causative mechanisms, we observe: (1) high levels of seismicity coinciding with conjugate fault systems; (2) major changes in the Allalobeda hydrothermal system after dam impoundment; (3) the time–space pattern of seismicity and hydrothermal activity suggests the NW-striking and North–South-striking conjugate fault sets of the Tendaho-Goba'ad fault zone (Fig. 4) are partially open for hydraulic flow. If the increased levels of seismicity are indeed induced by dam loading, the very short time period between impoundment and induced seismicity indicates that a very weak crust underlies the dam site (e.g. Simpson 1976). Gravity–isostasy relations also indicate that the thinned and intruded plate beneath Afar is very weak, with effective elastic thickness *c.* 6 km (e.g. Ebinger & Hayward 1996; Pérez-Gussinyé *et al.* 2009).

Our results document that fault, magmatic and hydrothermal systems beneath and near the Tendaho dam site are active. Prior to construction, engineers estimated a Peak Ground Acceleration value of 0.35 g for rock-site conditions based on site-specific seismic hazard assessment using the updated version of Ayele's (1995) earthquake catalogue. This estimate may be appropriate to the intake tower of the dam, as the reinforced concrete structures are still intact, but may not apply to the earth-filled dam, as it lies on a highly extended magmatic rift zone. In the case of the Tendaho dam, preliminary work did not recognize that the faults were seismically active, nor was consideration taken of the extensive hydrothermal sources along parts of the fault system and the numerous Holocene volcanic systems. To what extent the increase in microseismicity contributes to the observed leakage remains unclear, given that the concrete supports and earthen dam remain intact. As the instrumentally observed seismicity beneath and around the dam is associated with fractures and faults at depth, fault displacement and/or dilatation of faults and fissures may eventually trigger dam collapse. One method to reduce the potential for collapse may be to lower the water level of the dam to minimize the threat to both the tens of thousands of downstream residents in Dubti and other nearby towns and to the new agricultural development sites downriver. Our results clearly document significant potential threat to downstream populations and infrastructure, irrespective of the cause of the increased seismicity levels. If a multifaceted development activity is to be planned and executed in the area in an environmentally friendly manner, close follow-up of the background activity with state-of-the-art geophysical and geological activities is highly recommended. Future developments would benefit from site evaluations that include mapping of active fault and magmatic systems, and that include pre-construction seismic monitoring.

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