



**ANALYSIS OF THE INTER-DYKING DEFORMATION PATTERN AT THE
ONGOING DABBAHU-MANDA HARARO (AFAR) RIFT SEGMENT USING GPS AND
InSAR TECHNIQUES**

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List of abbreviations

C/A-CODE	Coarse Acquisition code
CGPS	Continuous GPS
CIS	Convention International reference System
CTS	Convention Terrestrial reference System
DEM	Digital Elevation Model
DMS	Dabbahu Magmatic Segment
DOP	Dilution of Precision
EAR	East Africa Rift
ENVISAT	Environmental Satellite
GDOP	Geometric Dilution of Precision
GPS	Global Positioning System
GNSS	Global navigation and satellite system
HDOP	Horizontal Dilution of Precision
InSAR	Synthetic aperture radar interferometry
JPO	Joint Program Office
MER	Main Ethiopian Rift
Ma	Million ago
GLOBK	Global kalman filter
RDOP	Relative Dilution of precision
PRN	pseudo Random Noise
ROI_PAC	Repeat Orbit Interferometry Package
SA	Selective Availability
SV	Space vehicle
TAI	The international Atomic Time (Temps Atomique international)
TDOP	Time Dilution of Precision
TEC	Total Electron Content
UT	Universal Time
UTC	Universal Time coordinate
VDOP	Vertical Dilution of Precision
WGS84	World Geodetic System 1984

Abstract

The Afar Depression, in the northeastern part of Ethiopia, offers unique opportunities to study the transition from continental rifting to ocean floor spreading. This process, which is the outcome of tectono-magmatic events, has been under investigation using different geophysical and geological techniques. The current study mainly focused on GPS and InSAR methods to analyze the inter-dyking deformation pattern along the Dabbahu-Mnada Hararo (Afar) rift segment. The InSAR data was used to identify the time of dyke events and the GPS data to study the inter-diking deformation pattern. A sequence of 12 dyke events occurred from June 2006 to June 2009 and based on the GPS data two major pattern of deformation have been identified. These are being categorized into before and after June 2009 dyke events. Most of the GPS stations before June 2009 showed larger displacement rate whereas after June 2009 intrusion, the displacement in most of the stations was relatively smaller. Even though the deformation process is still active, sites such as DAFT, DA45, DAYR and DATR indicated that the displacement rate is relatively stabilizing in the post seismic relaxation period. Moreover, sites such as, DA25 and DA35, had large offsets in their time series right at the time of dyking events, which is an indication of major deformation due to the rifting process. Except the distant sites DA60 and DASM all the other stations were mostly affected by the dyke intrusion, such that there was an offset in the data during the dike intrusion. Stations DA25, DA35, DA45, DA60, DAFT and DAYR that are located in the west side of the rift, where the 2005 diking event took place, showed displacement as large as ~84mm/yr, ~53mm/yr, ~46mm/yr, ~17mm/yr, ~23mm/yr, ~17mm/yr and ~6.36mm/yr towards the west direction respectively. Sites DASM, GABH and DABB have a displacement towards the North East direction. The site GABH, which is situated in Gabh'o volcano, shows rapid inflation from January to June (2006) and continued with a slow uplifting till February 2007. Inflation began in June 2006 in the composite volcano DABB site while subsidence that amount of about 16mm/yr is observed in Semera station called DASM.

Key words: Afar, Deformation, Inter-Dyking, InSAR, GPS, Rifting

1. Introduction

1.1 Overview of Plate Tectonics

The theory of plate tectonics links together the idea of sea floor spreading with old hypothesis of Continental Drift. This theory of plate Tectonics states that the Earth's outer crust is divided into a number of ridge, shifting block of varying size called plates. As these plates move apart (see figure 1.1) ,slide past one another , or converge towards each other, new crust come into being , lava outpour ,continents drift , mountain are formed, earthquake occur , rocks become metamorphosed, segment of crust become faulted ,folded and destroyed. At present, it is dominant theory used by Earth scientists to explain the internally generated process and feature of the earth .According to this theory

- Large area of the Earth's outer portion (lithosphere) act as rigid caps(plate) that undergo no significant internal deformation
- Earth plate is in relative motion with respect to other plate on the surface of the Earth, and these plates undergo significant deformation only at their boundaries with each other.

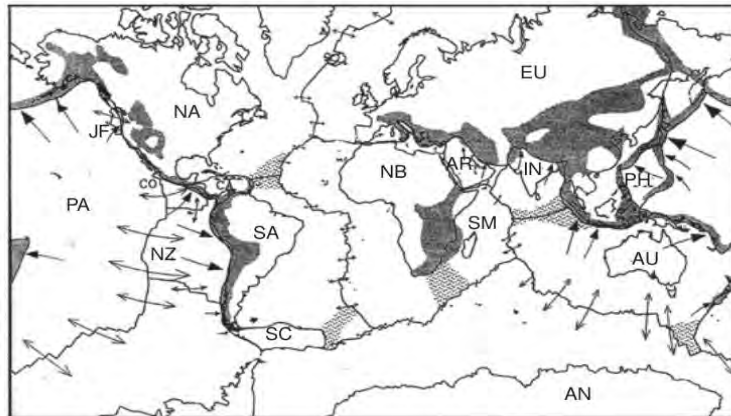


Figure1. 1 Map showing the relative motion between the major plates, and regions of diffuse deformation within plates (shaded areas). Solid arrowheads indicate plate convergence, with the arrow on the underthrusting plate; open arrowheads indicate plate divergence at mid ocean ridges. The length of the arrows represents the amount of plate accretion or subduction that would occur if the plates were to maintain their present relative velocities for 25 Ma. Note that, because of the Mercator projection, arrows at high latitudes are disproportionately long compared to those at low latitudes. AN, Antarctica; AR, Arabia; AU, Australia; CA, Caribbean; CO, Cocos; EU, Eurasia; IN, India; JF, Juan de Fuca; NA, North America; NB, Nubia; NZ, Nazca; PA, Pacific; PH, Philippine; SA, South America; SC, Scotia Sea; SM, Somalia (modified from Gordon, 1995).

The confirmation of sea floor spreading led to recognition of crustal motion. In particular , the position of earthquake belt , oceanic ridges and volcanic center showed the crust to be divided into moving plates each relatively rigid within itself but bounded by zone of profound crustal movements.

In this chapter the mechanisms thought to be responsible for seafloor spreading and continental rifting will be discussed. In addition to this, an overview of the Geology and Tectonic setting of Afar depression and the Dabbahu Manda Hararo rift episode, which is found along the central part of Afar depression (the area of interest for this study) will be discussed.

1.2. Sea floor spreading and continental rifting

1.2.1. Sea floor Spreading

Sea-floor spreading is the process in which the ocean floor is extended when two plates move apart. As the plates move apart, the rocks break and form a crack between the plates. Magma rises through the cracks and seeps out onto the ocean floor like a long, thin, undersea volcano. As magma meets the water, it cools and solidifies, adding to the edges of the sideways-moving plates. As magma piles up along the crack, a long chain of mountains forms gradually on the ocean floor. This chain is called an oceanic ridge. The boundaries where the plates move apart are 'constructive' because new crust is being formed and added to the ocean floor. The ocean floor gradually extends and thus the size of these plates increases. As these edges of the of the plates get bigger, others edges become smaller as they melt back into the Earth in the process called subduction. It was suggested that new oceanic lithosphere is created by the upwelling and partial melting of material from the asthenosphere at the ocean ridges. As the ocean gradually grows wider with the progressive creation of lithosphere, the continents marginal to the ocean are moved apart. According to (Wegener, 1929), the drift between North America and Europe, for example, would have been accomplished by the gradual growth of the Atlantic Ocean over the past 180 Ma. Since the Earth is not increasing in surface area by any significant amount, the increase in size of those oceans growing by sea floor spreading would be balanced by the destruction of lithosphere at the same rate in another, shrinking, ocean by subduction at deep sea trenches situated around its margins.

1.2.2. Continental rifting

Continental rifts are regions of extensional deformation where the entire thickness of the lithosphere has deformed under the influence of deviatoric tension. The term “rift” thus applies only to major lithospheric features and does not encompass the smaller-scale extensional structures that can form in association with virtually any type of deformation. Rifts represent the initial stage of continental break-up where extension may lead to lithospheric rupture and the formation of a new ocean basin. Here, extension and thinning of the lithosphere takes place by normal faults and dike injection. Early studies defined rifts as major elongate depressions bounded by normal faults with no implications for the mode of development or for the mechanism of formation. Rifts are now generally accepted as extensional features though they may be associated with earlier, contemporaneous or later compression. Morphologically, they are well defined as elongate depressions bounded by normal faults. However, their common association with volcanism, high heat flow, anomalous crust and upper mantle structure and seismicity provides evidence that rifts are not confined to the upper crustal level, but they are linked to dynamic processes in the lithosphere and asthenosphere. A rift system is a tectonically interconnected series of rifts. This definition implicitly includes the transient thermal as well as the permanent structural/compositional modification of the lithosphere during extension. Many models have been proposed to explain the mechanical processes of continental extension. The simplest models assume the rapid stretching of the lithosphere and upwelling of asthenospheric material (e.g. McKenzie, 1978).

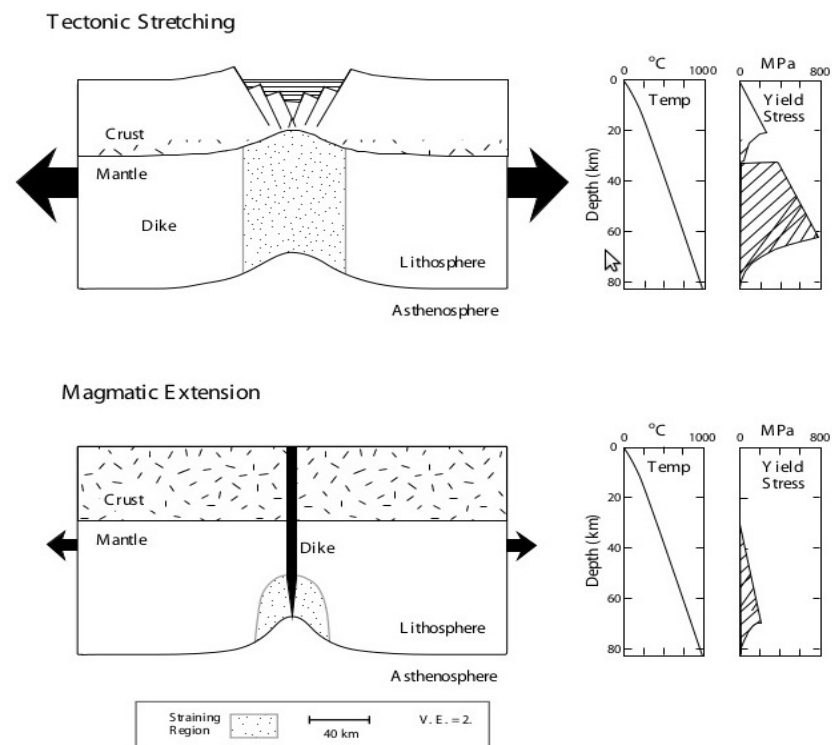


Figure1. 2 Schematic of the difference between extension of thick lithosphere with and without magmatic intrusion. Note the large difference in the yield stress, the stress difference needed to get extensional separation of two lithospheric blocks after Buck (2004)

Where the lithosphere is thick, cool, and strong, rifts tend to form narrow zones of localized strain less than 100 km wide. The Baikal Rift, the East African Rift system, and the Rhine Graben are examples of this type of rift. Where the lithosphere is thin, hot, and weak, rifts tend to form wide zones where strain is delocalized and distributed across zones several hundreds of kilometers wide. Examples of this type of rift include the Basin and Range Province and the Aegean Sea. Both varieties of rift may be associated with volcanic activity. Some rift segments, such as those in Kenya, Ethiopia, and Afar, are characterized by voluminous magmatism and the eruption of continental flood basalts. Others, such as the Western branch of the East African Rift system and the Baikal Rift, are magma starved and characterized by very small volumes of volcanic rock.

1.3. The Afar Depression

The Afar Depression is an area of lowland plains dotted with shield volcanoes (Figure 1.3). It is cut by faults which separate areas of higher ground (or fault blocks) from the rest of the plain. It is bound to the west by the Ethiopian Plateau and escarpment, to the northeast by the Danakil block, to the southeast by the Ali-Sabieh block and to the south by the Somalian Plateau and escarpment. To the north the southern Red Sea rift is extending down through the Gulf of Zula into the northern Afar Depression, to the east the Gulf of Aden rift is spreading through the Gulf of Tajura into the eastern Afar Depression and to the southwest extension continues through the Main Ethiopian Rift to the East African Rift System (Beyene & Abdelsalam, 2005).

The Afar depression, comprising the Afar triple junction, covers an area of ~200,000 km² and is formed as a result of rifting between Nubian, Somalian and Arabian plate and it is one of the major rift zone recognized on land. Rifting between the Arabian, Somalian and Nubian plates during the past ~30my produced ~300km wide and ~600km long afar depression formed within the palaegene flood basalt province (Hoffman et al , 1997). Crustal deformation induced by the motion of tectonics plate produced a wide variety of landform at the surface of the earth and their size depends on the duration of the process involved in their formation and the geology make up of the area.

The geology of the Afar Triple Junction incorporates multiple rock types. Most of this area is composed of basalt, a volcanic rock formed by rapid cooling of magma at the Earth surface. There are also sedimentary and metamorphic rocks, but not as much as the igneous rocks. The rifting in the northern

Manda Hararo rift was triggered by magma upwelling in the Dabbahu area, at the northern extremity of the magmatic segment (R. Grandin et al., 2009).

Although vigorous dike injection occurred during the September 2005 event, the tectonic stress deficit since this rifting episode was not fully released, leading to further intrusions in 2006-2009 (R. Grandin, 2009).

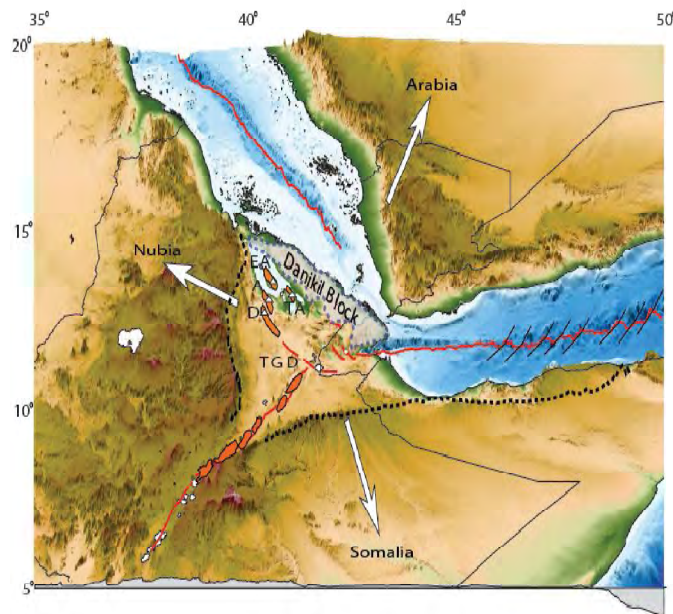


Figure1. 3 The Main Ethiopian Rift (MER) and Afar Depression. Red lines show the location of the RedSea (RS), Gulf of Aden (GA) and East African Rift (EAR) systems. Orange areas show the location of magmatic segments through the MER and into Afar and their corresponding volcanoes (white triangles - Dabbahu (D), Alayta (A), Tat' Ale (TA) and Erta' Ale (EA)) (Hayward & Ebinger, 1996). TGD is the Tendaho-Gobaad discontinuity. The area highlighted in blue shows the location of the Danakil block and the large white arrows denote the approximate plate motions of Nubia, Somalia and Arabia.

1.3.1. Dabbahu- Manda Hararo Rifting Episode

The Dabbahu magmatic segment (DMS) is ~60 km in length and ~15 km wide (Figure 1.4). The orientation of the segment changes near Ado' Ale, a dissected, silicic central volcanic complex (Lahitte *et al.* 2003). Crustal growth at divergent plate boundaries develops as a consequence of dyke intrusion, which also appeared to be important within rifts transitional from continental to oceanic, where dykes accommodate an equal or possibly larger proportion of strain than recent normal faults (Keir *et al.* 2006a). The Dabbahu- Manda Hararo rifting episode (Afar, Ethiopia) initiated in a rift segment showing an

early stage of seafloor spreading, which, together with the Asal rift, had previously been recognized as one of the most advanced in the process of oceanization that has been affecting the hot spot influenced Afar triple point for nearly 30 Ma[e.g., Barberi et al., 1972; Varet, 1975; Varet and Gasse, 1978; Hayward and Ebinger, 1996; Manighetti et al., 2001; Lahitte et al., 2003; Audin et al., 2004].

From June 2006 to June 2009, a series of twelve smaller dikes were emplaced in the southern part of the segment that had ruptured in 2005 [Hamling et al., 2009]. The dike intrusion of 2005-2009 occurred at different dates and location along the Dabbahu-Manda Haro rift segment and it shows variety of geometrical and kinematic features. The Dyke events were happened in June, July, September and December of 2006 and in January, August and November of 2007. The rift episode continued in 2008 and 2009 with the intrusion of three dyke events in 2008 and two dykes in 2009 as well as the recent intrusion in May 2010. To study this rift episode around 13 continuously operating GPS sites which are installed in and in the vicinity of the rift (Figure 1.4) were used with 2006-2010 dyke sequence coverage. 21 international IGS stations (Figure 1.5) were included in the GPS analysis for stabilization purposes. This makes the whole network to be with 34 stations.

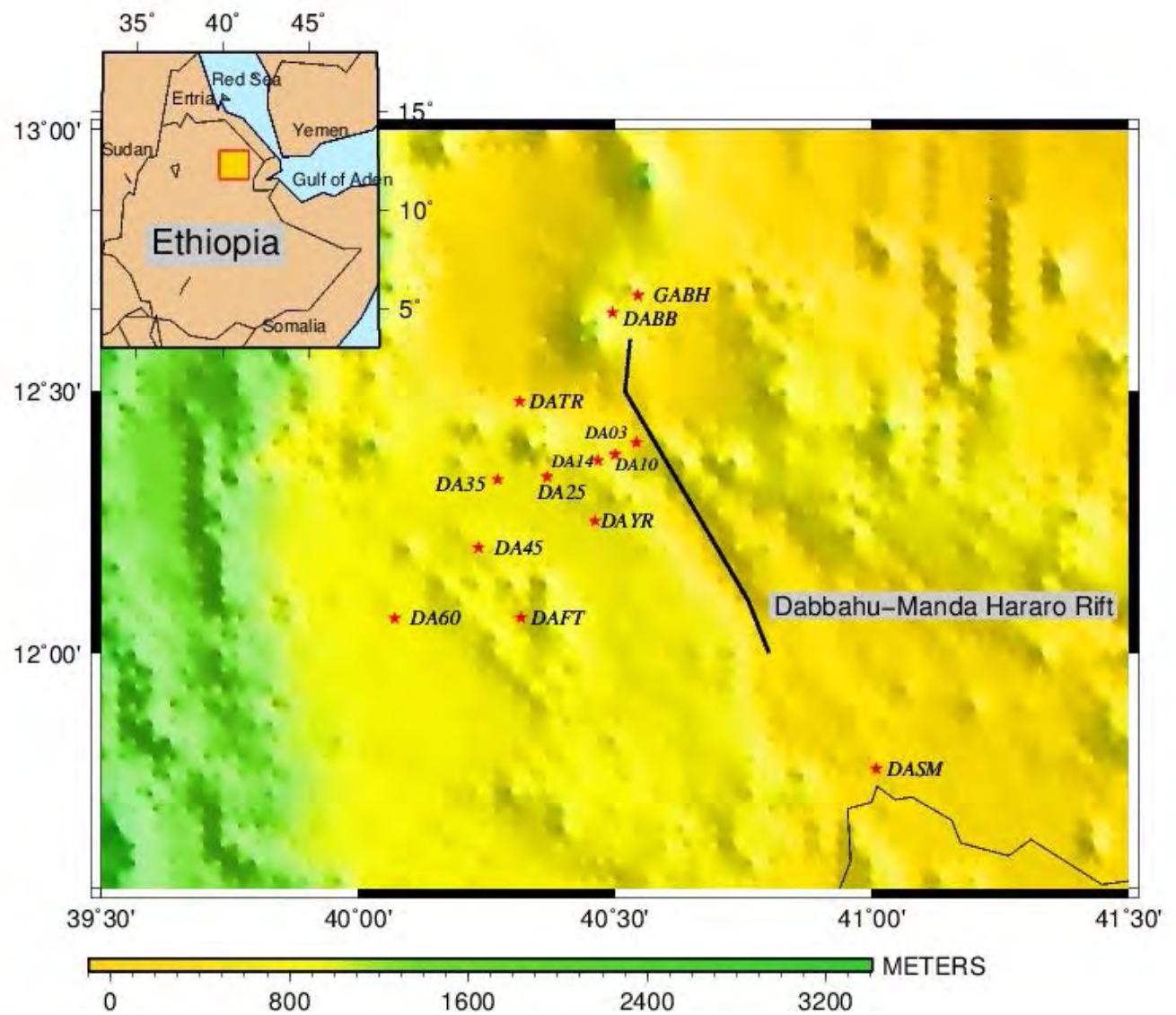


Figure 1. 4 location of the study area with continues GPS site and Dabbahu-Manda Hararo rift

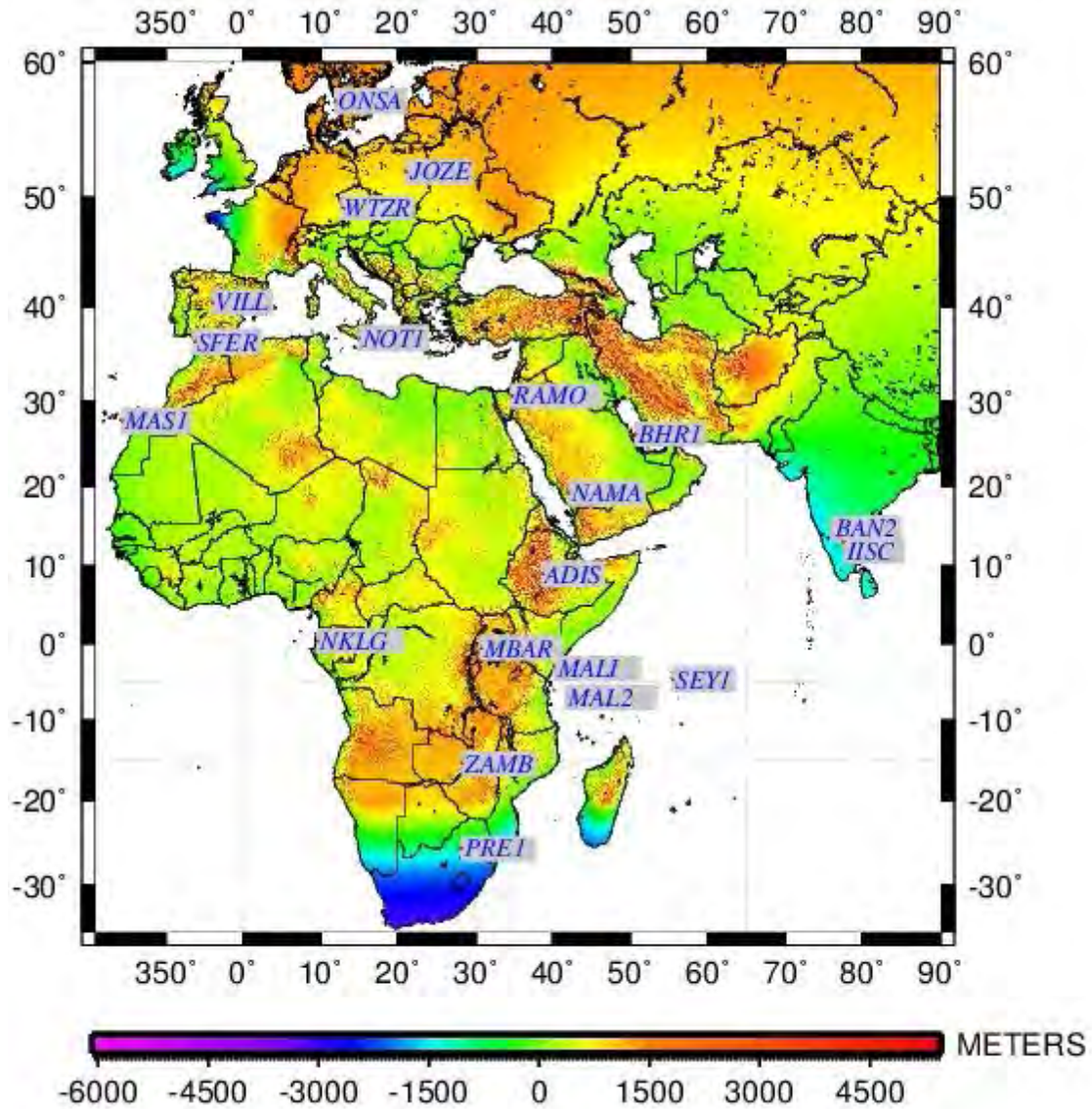


Figure 1. 5 IGS station used for this analysis

1.4. Objectives of the study

1.4.1. General objectives

The overall goal of this thesis is to analyze the inter-diking deformation pattern using GPS time series, from continuous operating GPS station in Afar, Ethiopia, and InSAR data. Moreover it is the aim of the work to study the displacement as a result of dyke injection around the rift zone of Manda Hararo-Dabbahu rift segment.

1.4.2. Specific Objectives

Specifically, this study focuses on

- i. Investigating the deformation pattern and charactersic between dike events
- ii. Determining the amplitude of displacement related with the occurrence of dyke event
- iii. Estimating the average rate of movement or velocity after removal of offsets due to the diking events
- iv. Detection of stress acumilation related with the recent dyke event in May 2010.
- v. Assessing what happened after June 2009 dyke intrusion

1.5. Thesis Organization

Chapter two discusses about the Geology and tectonic setting of Afar depression. Chapter three discusses the overview of GPS and InSAR techniques. Chapter 4 briefly describes the Data analysis methods and discusses the results of the study. Chapter 5 summaries and discusses the main findings of the study and chapter 6 concludes the results and gives recommendations for future work. The appendices contain more figures that support the results and discussion part.

2. Geology and Tectonic Setting of Afar depression

2.1. Geology of Afar depression

As it is given in Varet & Gasse (1978), the geological units of the Afar depression and marginal areas can be divided into four broad groups: 1) Neoproterozoic basement, Mesozoic sedimentary rocks Eocene-Miocene basalts; 2) Miocene Igneous rocks; 3) Pliocene volcanic rocks and 4) Quaternary volcanic and sedimentary rocks (Fig. 2.1).

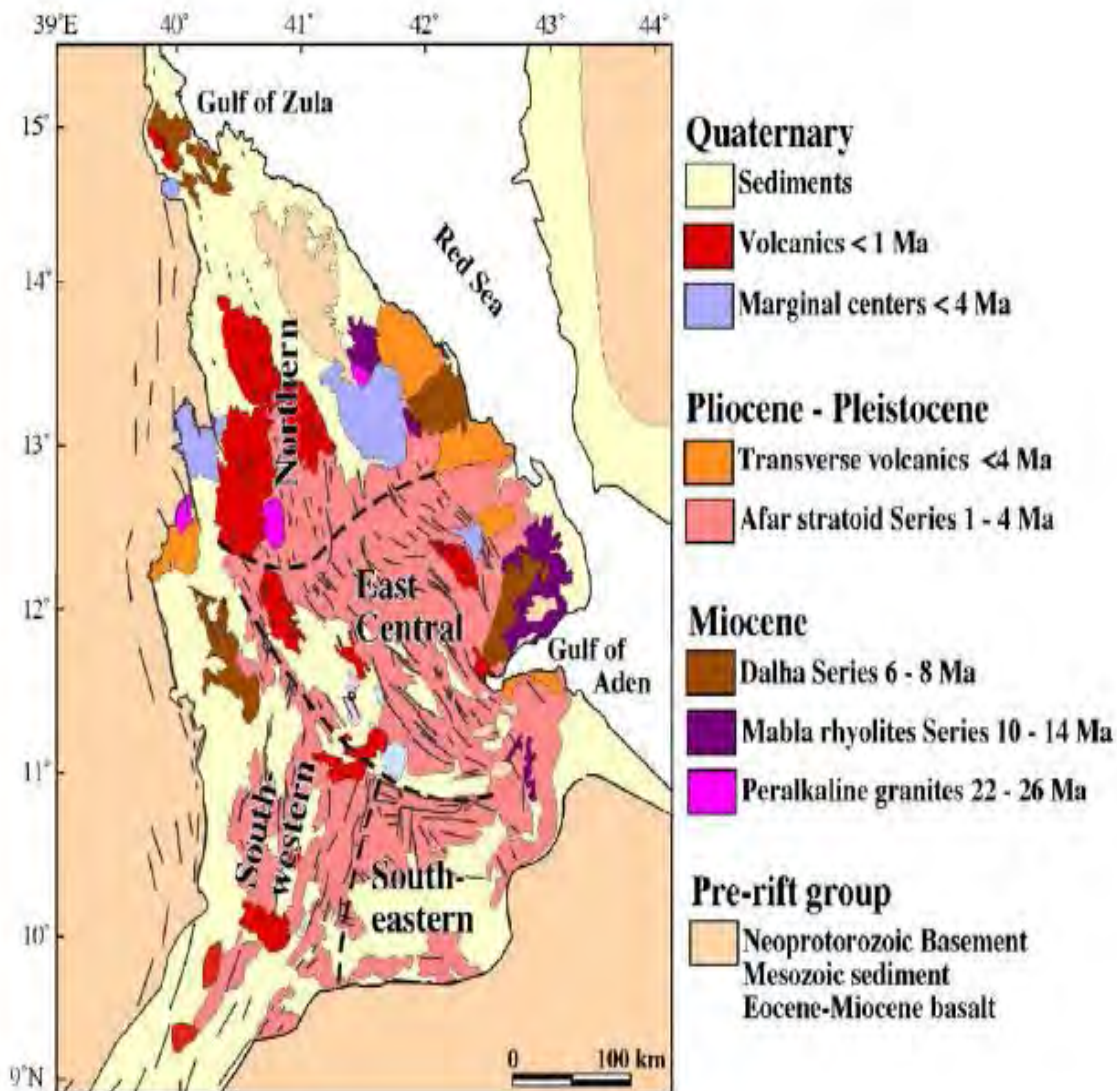


Figure 2. 1 Geological map of the Afar Depression after (Acton & Stein, 1991; Varet, 1978).

Although not found within the Afar depression the Neoproterozoic basement and sedimentary rocks, part of the Arabian-Nubian Shield, cover large areas around its edge (Stern, 1985; Vail, 1985). Many authors have concluded however, that the development of the Main Ethiopian, Red Sea, and Gulf of Aden rifts have been significantly influenced by pre-existing Neoproterozoic structures as in the Red Sea (Almond, 1986; Bosworth & McClay, 2001; Crane & Bonatti, 1987; Montenat et al., 1998; Sultan et al., 1992). The flood basalts of the Trap series were the first major volcanic series since Neoproterozoic times (Beyene & Abdelsalam, 2005). Berhe et al. (1987) suggest that the series was emplaced in three distinct stages at ~50-40, 40-30, and 30 Ma, some authors suggest that the main phase of volcanism took place between 45 and 30 Ma (Ebinger et al., 1993) while others propose that the sequence was erupted over a short period of time at ~30 Ma (Hofmann et al., 1997). Hofmann et al. (1997) and Kazmin & Byakov (2000) estimated the thickness of the sequence to be ~2 km. The neoproterozoic basement rocks are overlain by Mesozoic sedimentary rocks that get progressively younger towards the south and southwest on the Ethiopian and Somalian plateau, respectively.

During the Miocene a series of alkaline to per-alkaline rocks was intruded along the western and eastern margins and in parts of northern Afar (Beyene & Abdelsalam, 2005) and are reported to be derived from a mantle source associated with early continental breakup (Barberi et al., 1972, 1974). Two additional sequences were erupted within the Afar Depression: the Mabla series consisting of rhyolites, ignimbrites and some minor basaltic flows (Varet, 1978; Vellutini, 1990) and the Dahla series consisting of basaltic flows up to ~800 m thick interbedded with rare sedimentary rocks and ignimbrites (Varet, 1978).

The next significant period of volcanism in Afar occurred during the Pliocene and Pleistocene. The Pliocene-Pleistocene volcanic rocks most important volcanic unit in Afar is the Stratoid series that covers approximately the 2/3 of the Afar floor. This unit preserves igneous features and tectonic activities in Afar. The Afar Stratoid series is affected by numerous faults and fissures over all in Afar, except its eastern margin. Faulting and block tilting have been continuous during the emplacement of the stratoid series, as indicated in several fault scarps by the increase of the dip towards the basis. The thickness of the stratoid series reaches up to 1500m with individual flows varying from one to six meters (Varet and Gasse, 1978; Tefera et al., 1996). The Afar stratoid series was originally dated to be between 0.4 and 4.4Ma in age (Varet & Gasse, 1978). Using both updated K-Ar and ^{40}Ar - ^{39}Ar , Courtillot et al. (1984) reduced this range to 1.3-2.2Ma.

Quaternary volcanism in Afar is characterised by basaltic flows, scoria cones and silicic rocks (Tefera et al., 1996)). In most places basaltic fissure eruptions were followed by central eruptions that produced

differentiates of basalt comprising alkaline and per-alkaline silicic rocks (Varet and Gasse, F. 1978; Tefera *et al.*, 1996). However, the rift-parallel axial ranges in the northern and east central Afar are dominated by basalts which are ~1Ma old. Rhyolites occur here and there in some of the axial units. They are well developed at Boina (also known as Dabbahu) (Barberi *et al.*, 1975), but small patches also occur at Dama'ale and Manda Hararo (Gablaytu). Quaternary sedimentary rocks in the Afar depression are dominated by lacustrine deposits. Significant lacustrine sedimentary rocks were deposited in the central Afar along the Manda Hararo-Gobbad rift zones between ~12 and 1Ma (Rognon, 1975). The very recent tectonic and magmatic activity has happened in Dabbahu Magmatic Segment of North Afar. In September 2005 a seismo-volcanic event of unprecedented scale and intensity took place along this magmatic segment. Between September 4 and October 4, 163 earthquakes with Mb between 3.9 and 5.6 occurred. This event produced volcanic products of thin layers of fine to coarse pumice clasts, dense glass and lithics of rhyolitic lava.

2.2. Tectonic setting of Afar depression

The evolution of the Afar Depression has been characterized as passive and/or active rifting or neither, based on the sequence and timing of the rifting process related to the Main Ethiopian Rift, the Red Sea and the Gulf of Aden, the uplift of the Afar Dome and the flood basalt volcanisms. The basic difference between the passive and active rifting models is whether the asthenosphere (induced by mantle convection or mantle plume) is passively raising as the lithosphere moves away due to a pull of a subducting slab or whether a raising asthenosphere forces the lithosphere (through thermal erosion due to mantle convection or mantle plume) to open along the rift zones (Sengor and Burke, 1978; Sengor, 2001). The progression of events in passive rifting would be rifting–uplift–volcanism. Alternatively, for active rifting the sequence becomes uplift–volcanism–rifting (Sengor and Burke, 1978; Bohannon *et al.*, 1989). There is a consensus that the vast volcanism in the Afro-Arabian region is related to upwelling mantle plume. The question remains, however, whether or not the lithosphere is stretching and thinning primarily passively responding to tensile far-field stress (Makris and Ginzburg, 1987; Mohr, 1989) or it is a manifestation of an active local stress due to an upwelling mantle plume (Gass, 1970; Morgan, 1970; Schilling, 1973; Schilling *et al.*, 1992). Contrary to both models, Menzies *et al.* (1992) argued that the sequence of events in the Afar Depression could best be described by volcanism –rifting–uplift, which hints neither passive nor active rifting models.

The major factors that influenced the evolution of the Afar Depression include:

- (1) The Rise of the Afar Dome;
- (2) Sequence of magmatism, uplift, rifting and lithospheric rupture;
- (3) The development of the Main Ethiopian Rift, the Red Sea and the Gulf of Aden, and interaction with other plate boundaries; and
- (4) The internal rearrangement of the tectonic elements of the Afar Depression.

The Afar Dome started rising at ~40 Ma (Gass, 1975) and probably reached an elevation of ~1 km by early Oligocene time and its peak reached 3.5 km (Sengor, 2001). The rate of rise of the Afar Dome was 110 m/Ma. It is most likely that the initial uplift associated with the Afar Dome had occurred as a result of dynamic uplift propelled by plume upwelling involving heat and mass transfer rather than thermal erosion of the underlying mantle lithosphere (Sengor, 2001). While parts of the Afar Depression were uplifted, others might have subsided. White and McKenzie (1989) proposed that stretching of the lithosphere by a factor of 5 under normal temperature produces subsidence of more than 2 km to maintain isostatic equilibrium. On the other hand, the same amount of stretching in an environment of 150 °C above normal temperature causes uplift.

The lithosphere around the Gulf of Aden and the Southern Red Sea regions might have suffered significant stretching under normal temperature (as indicated by the low heat flow data (Zeyen et al., 1997) mainly due to far-field tensile stress associated with the subduction of the Arabian Plate under Eurasian Plate along the Zagros Orogenic Front. An upwelling mantle plume reached the base of the lithosphere ~50–40 Ma resulting in an anomalous mantle below the Afar Depression with a density of $\rho = 3.15 \text{ g cm}^3$ and seismic velocity of $V_p < 7.3 \text{ km s}^{-1}$ (Gass, 1975; Makris and Ginzburg, 1987). The Afar Depression is formed of an unusually thin (14–26 km) lithosphere that is transitional between continental and oceanic (Makris and Ginzburg, 1987).

The first voluminous volcanism ~45 Ma in the Ethiopian Plateau might be related to the arrival of the upwelling mantle plume at the base of the lithosphere (Ebinger et al., 1993) although the main phase of the Trap Series might have erupted ~30 Ma and lasted ~1 Ma (Hofmann et al., 1997; Hempton, 1987). However, Ebinger and Sleep (1998) and Sengor (2001) regarded any volcanism prior to ~30 Ma as being related to rifting in the Rudolf area in southern Ethiopia rather than being related to the Afar Dome. Nevertheless, volcanism seems to be older than widespread faulting in the Afar Depression and the Ethiopian Plateau in both cases. Zeyen et al. (1997) indicated that due to continental lithosphere rupturing along narrow zones, volcanism occurred prior to widespread faulting in the Afar Depression. The early

stages of deformation in the Afar Depression might have occurred as diffused faulting developed in response to far-field stress due to the Arabian Plate subducting under the Zagros Orogenic Front (Joffe and Garfunkel, 1987).

A strain pattern dominated by NW-trending rifts was first established in the Cretaceous and accommodated much of the strain along the Red Sea and the Gulf of Aden axis by the end of the Oligocene (Almond, 1986). With this favorable condition for rifting, the upwelling mantle plume added further extensional tensile stress by upward bending of the lithosphere in the Afar Depression. This might have triggered the development of the Afar triple junction with strong extension in the direction of the Far-field stress (e.g. 9). Zeyen et al. (1997) and Sengor (2001) argued that neither the Far-field stress nor the rising mantle plume is independently adequate to rupture the continental lithosphere and it would require a combined tensile stress to initiate the development of the Afro- Arabian Rift system. Rifts commonly form by normal faulting as the result of horizontal deviatoric tension whereas uplift takes place above a low-density region in the upper mantle due to an increase of temperature (Bott, 1980).

In active rifting doming and rifting are often genetically related, in which doming takes place first and rifting or rupturing of the lithosphere follows and leads to the upwelling of mantle material (Sengor and Burke, 1978; Bott, 1980). Kampunzu and Mohr (1991) concluded that there is a clear spatio-temporal association of volcanism and rifting the East African rift although the role of uplift is not clear. In addition, Sengor (2001) suggested that no amount of doming is sufficient to rupture the continental lithosphere and create a major rift such as the East African rift. However, doming could lead to rifting by helping build gravitational potential as argued by Bott (1980) and Sengor (2001). The lithosphere was stretched and thinned through extensive faulting and rifting during uplifting and thickened during magmatism (Kazmin and Byakov, 2000).

When rifting was sufficiently localized the Afro-Arabian lithosphere ruptured at ~10 Ma along the Gulf of Aden and at ~4 Ma in the Red Sea. The slow rate of opening of the Main Ethiopian Rift might be the result of a limited influence of rift opening by upwelling mantle plume due to area increase by doming. The Afar Depression was formed after the collapse of the Afar Dome at least 24 Ma (Kurstén, 1975). Separation of the Arabian, Nubian and Somalian Plates and the rotation of the Danakil Block guided the stress accommodation to the weak zones or the proto- rifts (Gass, 1975). Propagation of the Red Sea and the Gulf of Aden towards the center of the Afar Depression and the opening of the Main Ethiopian Rift were developed due to stress concentration because of lithospheric inhomogeneity and preferential Far-field and local forces distribution (Gass, 1975). Separation of the Nubian, Arabian and Somalian Plates,

the northward translation and counter-clockwise rotation of the Danakil Block, and the accompanying southward propagation of the Red Sea trend and the westward and subsequent northwestward propagation of the Gulf of Aden are major causes for the internal deformation in the Afar Depression.

3. GPS and InSAR Overview

3.1. GPS theory

The Global positioning system designed by the US Department of Defense (DoD) for military and civilian navigation and positioning, has become the geodetic method of choice for studying a wide range of geophysical phenomena (Herring et al, 2006a). GPS measurement are now in use to determine the motion of the earth tectonic plate, to study deformation around active fault and volcanoes with providing three dimension relative positions and few millimeter to approximate one centimeter precision. The Global positioning system is the responsibility of the Joint Program Office (JPO) located at the US Air Force systems command centre in Los Angeles. In 1973 JPO was directed by DoD to develop NAVSTAR) Global Positioning System (GPS). The NAVSTAR GPS is an all-weather, space-based navigation system that has been developed by the DoD to satisfy the accuracy requirements of the US defence forces in determining position, velocity, and time in a common reference system, anywhere on or near the earth on a continuous basis. The NAVSTAR configuration currently consists of 24 satellite (plus 3 active spares) at an altitude of 20200 km above the earth's surface. These satellites are placed in 6 orbital plane with their ascending nodes of their orbital planes are equally spaced by 60 degrees and inclined 55 degrees. The satellites transmit at frequencies $L1 = 1575.42$ MHz and $L2 = 1227.6$ MHz modulated with two types of codes viz p-code and C/A code and with navigation message. Mainly two types of observable are interest to the user. In pseudo ranging the distance between the satellite and the GPS receiver plus a small corrective term for receive clock error is observed for positioning whereas in carrier phase techniques, the difference between the phase of the carrier signal transmitted by the satellite and the phase of the receiver oscillator at the epoch is observed to derive the precise position information. The GPS satellites act as reference point from which receiver on the ground detect their position. The fundamental navigation principle is based on the measurement of pseudorange between the user and four satellite. Each satellite measure pseudoranges and broadcast its position to determine its spatial position, so that users can determine their position on or above the earth surface by trilateration.

3.2.1. Geodetic Reference System

It is a complete conceptual definition of how coordinate system is formed. It defines the origin and the orientation of the fundamental planes or axes of the system. It also includes the fundamental mathematical and physical models. Both vectors must be expressed in a uniform coordinate system. The definition of a 3-D Cartesian system requires a convention for the orientation of the axes and the location of the origin.

The practical realization of a reference system through observations consists of a set of identifiable fiducial points on the sky (e.g. stars, quasars) or on Earth's surface (fundamental stations). A set of coordinates axes in ordinary space. In satellite geodesy two fundamental systems are required. A space fixed, conventional inertial reference system (CIS) for the description of satellite motion (obeys Newtonian law of motion). Inertia is the property of bodies to maintain constant translational and rotational velocity, unless disturbed by forces or torques, respectively (Newton's first law of motion). An inertial reference frame is a coordinate frame in which Newton's laws of motion are valid. Inertial reference frames are neither rotating nor accelerating. A coordinate system at rest or in a state of uniform rectilinear motion without any acceleration.

3.2.2. Coordinate System Transformations

The rotation of a three-dimensional coordinate system involves three rotations (Figure 3.1). Each rotation is a two-dimensional coordinate rotation where one coordinate axis is held fixed while the other two are rotated about this fixed axis. The rotation is considered positive for counter-clockwise rotations as viewed from the positive end of the rotating (fixed) axis. Reference coordinate systems in satellite geodesy are global and geocentric by nature, because the satellite motion refers to the centre of mass of Earth. Terrestrial measurements are by nature local in character and are usually described in local reference coordinate systems. The relationship between all systems in use must be known with sufficient accuracy. The results of different observation methods in satellite geodesy refer to particular reference coordinate systems which are related to the individual methods. The establishment of precise transformation formulas between systems is one of the most important tasks in satellite geodesy.

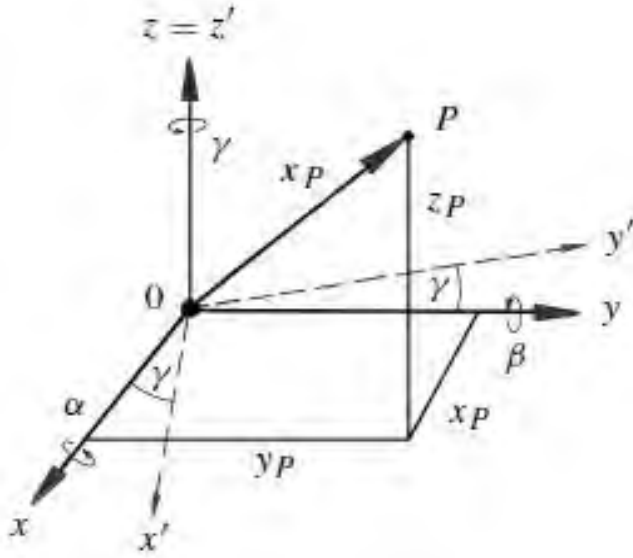


Figure 3. 1 Three-Dimensional Rotations

$$R = \begin{bmatrix} \cos\beta\cos\gamma & \cos\beta\sin\gamma & -\sin\beta \\ \sin\beta\cos\alpha\cos\gamma - \cos\alpha\sin\gamma & \sin\beta\sin\alpha\cos\gamma + \cos\alpha\cos\gamma & \cos\beta\sin\alpha \\ \sin\beta\cos\gamma\cos\alpha + \sin\gamma\sin\alpha & \sin\beta\cos\gamma\sin\alpha - \sin\alpha\cos\gamma & \cos\beta\cos\alpha \end{bmatrix} \quad (3.1)$$

Where R is a Rotation parameter and the other variables are shown in the figure 3.1.

3.2.3. Ellipsoidal Reference Coordinate Systems

For most practical applications ellipsoidal coordinate systems are preferred because they closely approximate Earth's surface, and they facilitate a separation of horizontal position and height. Usually a rotational ellipsoid is selected which is flattened at the poles and which is created by rotating the meridian ellipse about its minor axis b .

The geometric parameters. A reference ellipsoid is a selected ellipsoid (of revolution) to serve as a reference for geodetic computations in a country or a continent. Such ellipsoid is locally defined by its semi-major and semi minor axis. A special reference ellipsoid is an Earth ellipsoid for the total Earth.

$$f = \frac{a - b}{a} \qquad e^2 = \frac{a^2 - b^2}{a^2}$$

Where f is flattening, e is eccentricity, a is referring to the major axis and b is the minor axis

3.2.4. WGS84 ellipsoid

The World Geodetic System of 1984 (WGS84) is an international standard for navigation coordinates. WGS84 is a reference earth model released in 1984. It approximates mean sea level by an ellipsoid of revolution with its rotation axis coincident with the rotation axis of the earth, its center at the center of mass of the earth, and its prime meridian through Greenwich. Its semimajor axis (equatorial radius) is defined to be 6,378,137 m, and its semiminor axis (polar radius) is defined to be 6,356,752.3142 m.

3.2.5. GPS Satellite Signals

The SVs transmit two microwave carrier signals. The L1 frequency (1575.42 MHz) carries the navigation message and the SPS code signals. The L2 frequency (1227.60 MHz) is used to measure the ionospheric delay by PPS equipped receivers. Three binary codes shift the L1 and/or L2 carrier phase. The C/A Code (Coarse Acquisition) modulates the L1 carrier phase. The C/A code is a repeating 1 MHz Pseudo Random Noise (PRN) Code. This noise-like code modulates the L1 carrier signal, "spreading" the spectrum over a 1 MHz bandwidth. The C/A code repeats every 1023 bits (one millisecond). There is a different C/A code PRN for each SV. GPS satellites are often identified by their PRN number, the unique identifier for each pseudo-random-noise code. The C/A code that modulates the L1 carrier is the basis for the civil SPS. The P-Code (Precise) modulates both the L1 and L2 carrier phases. The P-Code is a very long (seven days) 10 MHz PRN code. In the Anti-Spoofing (AS) mode of operation, the P-Code is encrypted into the Y-Code.

The encrypted Y-Code requires a classified AS Module for each receiver channel and is for use only by authorized users with cryptographic keys. The P (Y)-Code is the basis for the PPS. The Navigation Message also modulates the L1-C/A code signal. The Navigation Message is a 50 Hz signal consisting of data bits that describe the GPS satellite orbits, clock corrections, and other system parameters.

3.2.6. Problems Associated with GPS Measurements

All GPS measurements, be they pseudorange or carrier phase, are affected by biases and errors which affect the accuracy of the position determination. There are several sources of bias with varying characteristics of magnitude, periodicity, satellite-receiver dependency, etc. Among these biases are ephemeris errors, satellite clock errors, receiver clock errors, ionospheric effects, tropospheric effects and satellite-receiver geometry.

GPS errors are a combination of noise, bias, and blunders. Noise errors are the combined effect of PRN code noise (around 1 meter) and noise within the receiver noise (around 1 meter). Bias errors result from Selective Availability and other factors. Selective Availability (SA) is the intentional degradation of the SPS signals by a time varying bias. It used to be controlled by the DOD to limit accuracy for non-U. S. military and government users. The potential accuracy of the C/A code of around 30 meters is reduced to 100 meters (two standard deviations). The SA bias on each satellite signal is different, and so the resulting position solution is a function of the combined SA bias from each SV used in the navigation solution. Because SA is a changing bias with low frequency terms in excess of a few hours, position solutions or individual SV pseudo-ranges cannot be effectively averaged over periods shorter than a few hours. Differential correction must be updated at a rate less than the correlation time of SA (and other bias errors).

i. Ephemeris Errors

The ephemeris information used to calculate the satellite position is based on the observations from the monitor stations of the space segment. The data is processed at the Master Control Station and the satellite navigation message information is uploaded to every satellite. The ephemeris error is therefore the discrepancy between the true position (and velocity) of the satellite and its broadcast ephemeris

ii. Satellite Clock Errors

Although GPS satellites use high quality cesium or rubidium atomic clocks for time-keeping and signal synchronization, there are unavoidable clock errors which change with time. Rubidium oscillator is correct to about 10^{-12} and that of cesium is correct to about 10^{-13} . The offset could reach 10^{-7} seconds in a day, multiplied by the velocity of light gives 26 m. As all observation made at an instant to a particular satellite, all GPS receivers are affected by equal magnitude of the same satellite clock error, the principle of differential positioning can be used to eliminate this error.

iii. Receiver Clock Errors

GPS receivers are equipped with inexpensive quartz crystal oscillators with low accuracy. The offset between receiver clock time and GPS Time is the receiver clock error, which affect all satellite receiver ranges measured at a particular epoch. Double differencing can be used to eliminate this error.

iv. Ionospheric Effects

The ionosphere extends between approximately 50 and 1500 km above the earth and it is characterized by the presence of free electrons and positively charged atoms and molecules called ions. This is as a result of the gas molecules being excited by solar radiation. The total electron content (TEC) equals the number of free electrons in the column of unit area along which the signal travels between the satellite and the receiver. TEC varies as a function of latitude of the receiver, the season, the time of the day the observation of the satellite signal is being made and the level of solar activity at the time of observation. As the electromagnetic GPS signal propagate through the medium, dispersion occurs and the free electrons delay the pseudorange and advance the carrier phase by equal magnitude. The amount is directly proportional to the TEC and inversely proportional to the carrier frequency. An effective procedure to deal with this error is to take advantage of the frequency dependence of the ionospheric effect by using a dual-frequency receiver. Measurements are made on both L1 and L2 frequency signals and combining them in a linear form, the delay is eliminated since the impact on L1 and L2 is different.

v. Multipath

Multipath effects are propagation errors arising from interference of the direct signal by reflected signals from water, metallic surfaces, and nearby buildings. The combined direct and reflected signals will give rise to incorrect pseudorange observation.

Errors which arise as a result of multipath cannot be reduced by the technique of DGPS, since they depend on the local reflection geometry near each receiver antenna. The remedies for multipath lies in site selection and effective antenna design to filter out multipath effects using advanced signal processing.

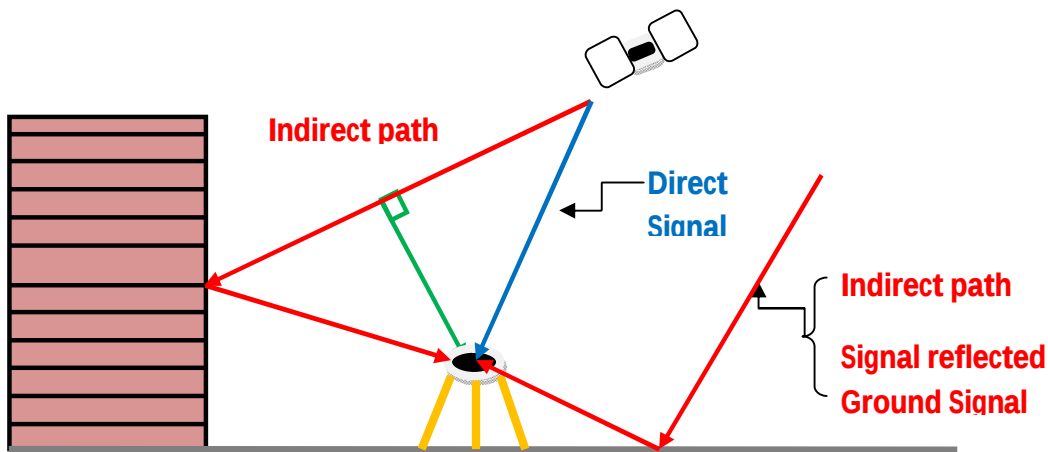


Figure 3. 2 Illustrate on how satellite signal arrives at the receiver in three different paths.

In Figure 3.2, the satellite arrives at the receiver in three different paths, one direct and two indirect ones. As a consequence, the received signals have a relative offsets and phases differences are proportional to the difference in path lengths. There is no general model of multipath effect because of the arbitrarily different geometric situations of the observing sites. The influence of the multipath, however, can be estimated using a combination of L1 and L2 code and carrier phase, which we shall see later. The principle is based on the fact that the troposphere, clock errors and relativistic effects influence code and carrier phase by the same amount, this is not true for ionosphere refraction and multipath effect which are frequency dependent. Taking ionospheric – free code ranges and carrier phases and forming corresponding differences, all aforementioned effects except for multipath are cancelled. The residuals, apart from the noise level, reflect the multipath effect.

Purely from geometry it is clear that signals received from low satellite elevations are more susceptible to multipath than signals from high elevations. Note also code ranges are more highly affected by multipath than carrier phase. The underlying theory of this method is that pseudorange measurements are noisier and more substantially affected by multipath than are the more precise carrier phase measurements.

vi. Tropospheric Effect

The weather it affects us all. Sometimes disastrously with vicious storms; sometimes pleasantly with sunshine and warm breezes. It also affects GPS. However, whereas bad weather might disrupt our lives,

causing us to curtail or postpone an activity, GPS continues to perform. it's an all-weather system. Rain, snow, fog, and clouds all have a negligible effect on GPS. However, unseen weather temperature, pressure, and humidity variations throughout the atmosphere does affect GPS observations. These parameters determine the propagation speed of radio waves, an important factor that must be accounted for when processing GPS or other radiometric observations. Because we cannot predict their exact values ahead of time, these invisible weather variables are source of error in GPS positioning and navigation.

Modeling the propagation of the electromagnetic micro- wave signals through the electrically neutral part of the atmosphere (referred as troposphere) is of common interest for the space geodetic techniques. The troposphere is the lowest part of the earth's atmosphere up to 70 km altitude. The neutral atmosphere (troposphere, tropopause and stratosphere) is a non-dispersive medium with respect to the radio waves up to frequencies of 15GHz . Thus the propagation is frequency independent unlike the ionospheric refraction, consequently affects both the code and phase measurements the same way. The disadvantage is that an elimination of the tropospheric refraction by dual/triple frequency techniques is not possible. The effect is a delay (same sign as the ionosphere has on codes) that reaches $2.0 - 2.5$ meters in the zenith direction and increases approximately the *cosecant* of the elevation angle.

The signal propagation on a layer depends on the temperature, the pressure and the water vapour. The factor that describes the variability of the troposphere is the refractive index (n).

vii. Dilution of Precision

The distribution of satellites above the observer's horizon has a direct effect on the accuracy of the position determination. The accuracy of GPS position is subject to a phenomenon called Dilution Of Precision (DOP). It is the measure of geometry of the visible satellites with respect to one another and the GPS receivers. A low DOP factor is good, a high DOP factor is bad. This is suffice to say that, when satellites are in optimal configuration for a reliable GPS position, the DOP value is low; when they are not, the DOP value is high. If all the four satellites required for 3-dimensional positioning are all crowded together in one part of the sky, then there is likely to be a less accurate position and the DOP will be high. DOP is like a warning that the actual errors in a GPS position are liable to be larger than you might expect. It must be clarified that it is not the errors themselves that are directly increased by the DOP factor, it is the uncertainty of the GPS position that is increased by the DOP factor. There are a number of DOP components; there is horizontal dilution of precision (HDOP) and vertical dilution of precision

(VDOP) when the uncertainty of a solution for positioning has been isolated into its horizontal and vertical components, respectively.

3.2.7. Positioning Techniques

In the previous section, errors associated with GPS positioning were described. Now, in this section how this error are handled and mitigated using various positioning techniques, will be described. GPS positioning techniques be it kinematic or static can be subdivided into Point Positioning, Precise Point Positioning, and Relative Positioning. These can either be real-time or post processed depending on the application.

A. Point Positioning

Point positioning refers to the estimation receiver antenna coordinates x_i and the receiver clock error Δt_i using pseudorange observables. The role of the carrier phase is limited to smoothing the pseudoranges, if used at all. There are several simplifying assumptions made in point positioning, the satellite position x^k at transmission time are assumed known and available from the broadcast ephemeris. While the receiver clock error is estimated at every epoch, neglecting the residual satellite clock error Δt^k . But the satellite clock broadcast corrections must be applied. Ionospheric and tropospheric delays are also computed from models. Hardware delays and multipath are neglected. Using the simplifying assumptions made above, it could be write as follows

$$\rho_i^k = c\Delta t_i \quad (3.2)$$

ρ_i^k is the geometric range given by $\rho_i^k = ||x^k - x_i||$ where

$$||x^k - x_i|| = \sqrt{(x^k - x_i)^2 + (y^k - y_i)^2 + (z^k - z_i)^2} \quad (3.3)$$

The four unknowns x_i , y_i , z_i and Δt_i can be computed using four pseudoranges measured simultaneously. The effect of the earth rotation during signal travel time must be incorporated in equation (2.2). The basic requirement; however is that there are four satellites visible at a given epoch. Point positioning depends on the accuracy of the navigation message and the constellation of the satellites used. In practice, not just four satellites are observed but all satellites in view in order to achieve redundancy and better geometry.

B. Precise point positioning

Precise point positioning is a method that performs precise position determination using GPS receiver. This position approach arose from the advent of widely available precise GPS orbit and clock data products with centimeter accuracy. These data can be applied to substantially reduce the errors in GPS satellite orbits and clock, two of most significant error sources in GPS positioning. Combining precise satellite positions and clocks with dual-frequency GPS receiver (to remove the first order effect of Ionosphere). PPP is able to provide position solution at centimeter to decimeter level. This method can offer several significant advantages to application compared to differential precise positioning technique. First ppp involve only a single GPS receiver and, therefore, remove the need for GPS user to establish local base stations. As a result, it eliminates the spatial operating range limit as well as the constraint of simultaneous observation on both rover and base receivers imposed by the differential RTK technique .Another significant benefit that ppp can bring to application is that it reduce labor and equipment cost and simplifies operational logistic to field work since it eliminate the dependency on base station.

C. Relative Positioning

One of the popular ways of tackling the errors in GPS positioning is by the method of Relative Positioning also known as Differential GPS (DGPS). This is done by computing differences between simultaneous observations from two receivers. The vector between the two receivers is determined which is often called baseline vector or simply baseline. Basically, three main types of differences which are frequently used are Single Difference, Double Difference and Triple Difference. But only the first two will be discussed since triple difference is not often used due to the fact that it loses its geometric strength over time and it is less stable. But triple difference is very important in estimating the integer ambiguities which become constant over time.

The objective of relative positioning, also called differential positioning employs two GPS receivers simultaneously tracking the same satellites to determine their relative coordinates. One of the receivers position is known and the other is unknown. The unknown point can be stationary or moving (Kinematic). Relative positioning can be performed with code ranges or phase ranges.

Single Differences

Two points and one satellite are involved. Denoting the points by A and B and the satellite by j . The single difference observations are constructed to cancel common effects shared by signals travelling from a satellite through different paths. The phase equations for the two points are (disregarding the other known GPS error such as Ionospheric, tropospheric etc.):

$$\begin{aligned}\Phi_A^j(t) + \frac{c}{\lambda} \delta t^j &= \frac{1}{\lambda} \rho_A^j(t) + \frac{c}{\lambda} \delta t_A + N_A^j \\ \Phi_B^j(t) + \frac{c}{\lambda} \delta t^j &= \frac{1}{\lambda} \rho_B^j(t) + \frac{c}{\lambda} \delta t_B + N_B^j\end{aligned}\quad (3.4)$$

The difference of the two equations is

$$\Phi_B^j(t) - \Phi_A^j(t) = \frac{1}{\lambda} [\rho_B^j(t) - \rho_A^j(t)] + \frac{c}{\lambda} [\delta t_B - \delta t_A] + N_B^j - N_A^j \quad (3.5)$$

where

Φ = carrier phase

ρ = geometric range

c = speed of light

λ = wavelength

δt = clock bias.

N = phase ambiguity, = phase noise

Equation (2.5) is referred to as the single-difference equation.

If we use the relative quantities

$$N_{AB}^j = N_B^j - N_A^j$$

$$\delta t_{AB} = \delta t_B - \delta t_A$$

$$\Phi_{AB}^j(t) = \Phi_B^j(t) - \Phi_A^j(t)$$

$$\rho_{AB}^j(t) = \rho_B^j(t) - \rho_A^j(t) \quad (3.6)$$

Substituting (3.6) in to (3.5) we get

$$\Phi_{AB}^j(t) = \frac{1}{\lambda} \rho_{AB}^j(t) + \frac{c}{\lambda} \delta t_{AB} + N_{AB}^j \quad (3.7)$$

The principal advantage of the single difference is the satellite clock bias is cancelled in the process. The single-difference observations, however, remain sensitive to both receiver clock errors.

Double Differences

Assuming two stations A and B and two satellites j, k , two single differences according to equation (3.5) can be formed:

$$\Phi_{AB}^j(t) = \frac{1}{\lambda} \rho_{AB}^j(t) + \frac{c}{\lambda} \delta t_{AB} + N_{AB}^j \quad (3.8)$$

$$\Phi_{AB}^K(t) = \frac{1}{\lambda} \rho_{AB}^K(t) + \frac{c}{\lambda} \delta t_{AB} + N_{AB}^K \quad (3.9)$$

The double difference is formed by subtracting two single differences in equations (3.6) and (3.7):

$$\Phi_{AB}^K(t) - \Phi_{AB}^j(t) = \frac{1}{\lambda} [\rho_{AB}^K(t) - \rho_{AB}^j(t)] + N_{AB}^K - N_{AB}^j \quad (3.10)$$

In short hand notations

$$\Phi_{AB}^{jK}(t) = \frac{1}{\lambda} \rho_{AB}^{jK}(t) + N_{AB}^{jK} \quad (3.11)$$

In details

$$\Phi_{AB}^{jK}(t) = \Phi_B^K(t) - \Phi_B^j(t) - \Phi_A^K(t) + \Phi_A^j(t)$$

$$\rho_{AB}^{jK}(t) = \rho_B^K(t) - \rho_B^j(t) - \rho_A^K(t) + \rho_A^j(t)$$

$$N_{AB}^{jK}(t) = N_B^K(t) - N_B^j(t) - N_A^K(t) + N_A^j(t) \quad (3.12)$$

The most important feature of double-difference observation is the cancellation of the large receiver clock errors. These receiver clock errors cancel completely as long as observations between satellites j and K are taken at the same time, or the receiver clock drifts between the observations are negligible. The

integer ambiguity plays an important role in double differencing. If it is possible during the least-squares estimation to fix the integer, that is, to constrain the estimates $\hat{N}_{AB}^{JK}$ to integers, then the fixed solution is the preferred one. It is only in double-difference that the integer ambiguity nature is obvious since the ambiguity term, N of the undifferenced carrier phase observations are no longer integer because they are corrupted by satellite and receiver initial phase biases. Even in the single difference, it is only the initial phase bias from the satellite that cancels out and the initial phase bias from the receiver remains.

Triple Differences

A triple difference observable is the difference between two double difference observables for successive epochs. This triple differencing does eliminate the integer ambiguity. But in our GPS data processing we do not use it as it significantly amplifies the noise.

GAMIT/GLOBK software, the software used in this study uses a double differenced observable of the ionospheric free signal. Ionospheric free signal is the combination of the L1 and L2 signals where the ionospheric effect is cancelled using dispersive nature of the ionosphere.

3.2 InSAR

The Afar depression in general and the survey area in particular is hot and dry with almost no vegetation covers. This environmental conditions are suitable to carry out measurements using remote sensing techniques such as Synthetic aperture radar interferometry (InSAR), which is a widely used to monitor deformation of the Earth surface. The images from single satellite pass are combined to derive interferometric images that can be interpreted in terms of change in the location of points on the surface of the earth. This interferogram is formed by differencing the phase from two radar images acquired at different time. The change in the range b/n the satellite and the ground can be obtained with centimeter precision.

By subtracting the phase component from two radar images separated in time, providing the backscattering characteristics of the ground remain unchanged and that the same area is being imaged, the random phase component can be removed. Any residual phase is then a result of the difference in the path length between the acquisitions and differences in the atmospheric path delay $\Delta\phi_{\text{atmos}}$. Additional

changes in the path length result from the viewing geometry, $\Delta\phi_{\text{geom}}$, topography, $\Delta\phi_{\text{topo}}$, deformation, $\Delta\phi_{\text{defo}}$ and noise $\Delta\phi_{\text{noise}}$

Components of Interferometric Phase

$$\Delta\phi = \Delta\phi_{\text{def}} + \Delta\phi_{\text{geom}} + \Delta\phi_{\text{topo}} + \Delta\phi_{\text{atm}} + \Delta\phi_{\text{noise}}$$

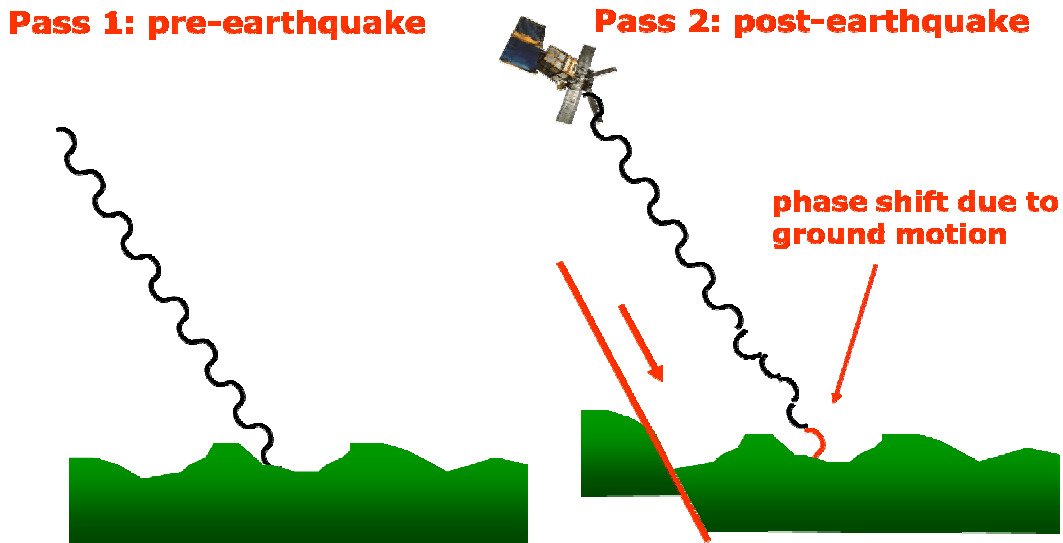


Figure 3. 3 shows phase shift due to pre and post earthquake (Wright; 2002)

There are different satellites, such as Radarsat, ERS, *Envisat*, TerraSAR-X, Cosmo, Radarsat-2, *TerraSat-X*, etc that can be used for this purpose. However, in this work we use images from ENVISAT, because of the availability of the image for this purpose. The different color band on the ENVISAT interferogram represents a 3cm change in the direction between the satellite and the ground. The interferograms allow researchers to determine where, how and by how much the ground is moving. Therefore, InSAR is a well suited technique to measure the complex deformation field associated with intruding dikes in the Dabahu-Manda Hararo rift segment.

The InSAR images was processed using JPL/caltech ROI_PAC software. The software carried out error correction such as orbital, atmospheric, surface corrections and the removal of ambiguous phase from the unwrapped interferograms. The coherence in the Afar generally is

expected to be high due to the arid environment that prevails in the area. The flow chart in figure 3.4 summarizes the InSAR data processing steps.

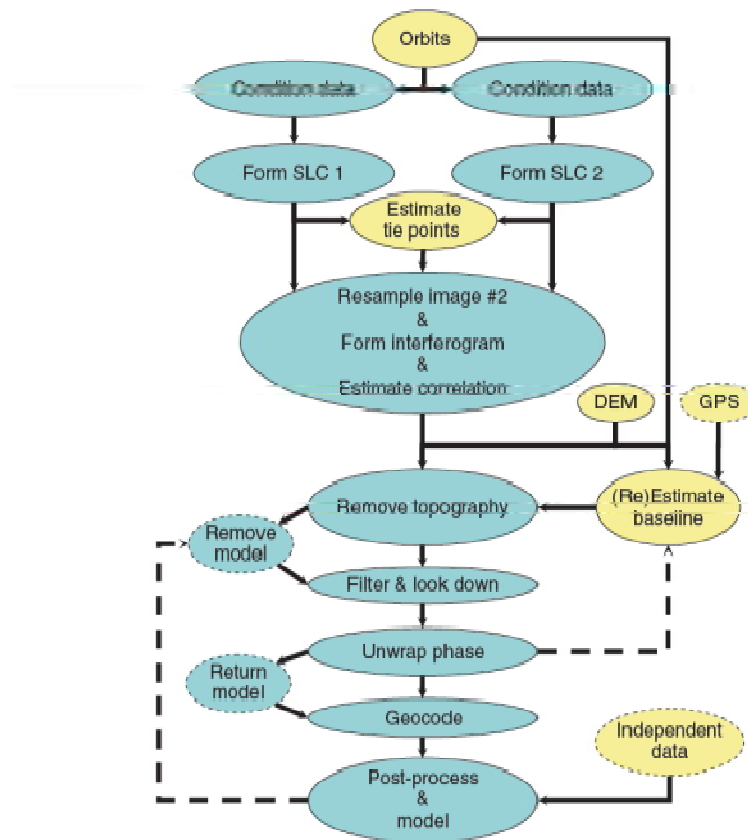


Figure 3. 4 InSAR processing flow chart Modified from Mark Simons & Eric Fielding

Orbital and Topographic corrections

To remove orbital error, InSAR processing software, such as ROI PAC, removes the effect of the baseline from the interferogram it is based on the assumption that the Earth is a smooth ellipsoid and that the satellite orbits are accurately known. Topographic corrections were made using a 3" (90 m) digital elevation model (DEM) generated by the NASA Shuttle Radar Topography Mission (Farr & Kobrick 2000)

Using the satellite's orbital information, the phase ramp due to the different viewing geometries is removed in a step known as orbital flattening. Next, the effect of the topography is removed using a Digital Elevation Model (DEM). In this stage an interferogram containing the expected phase information

due to the topography, generated using the DEM, is coregistered with the master image and subtracted from the interferogram.

Filtering, unwrapping and geocoding

To further improve the signal to noise ratio a non-linear power spectrum filter is typically applied (Goldstein & Werner, 1998). The advantage of this filter is that it adapts to the local phase slope, enhancing the frequency component that has the highest power. The filter is calculated by dividing the interferogram up into overlapping rectangular patches and the power spectrum

The next stage is the process of converting the modulo 2π interferometric phase into a continuous signal, in a process known as phase unwrapping. ROI PAC uses a branch cut algorithm based on Goldstein et al. (1988) to unwrap the interferogram. For error-free data this is a simple process. A number of algorithms, such as the branch cut used by ROI PAC, have been developed for cases where conditions are less favorable. Finally the interferogram is mapped into geographic coordinates using the information gathered while matching the simulated amplitude image from the DEM to the master geometry.

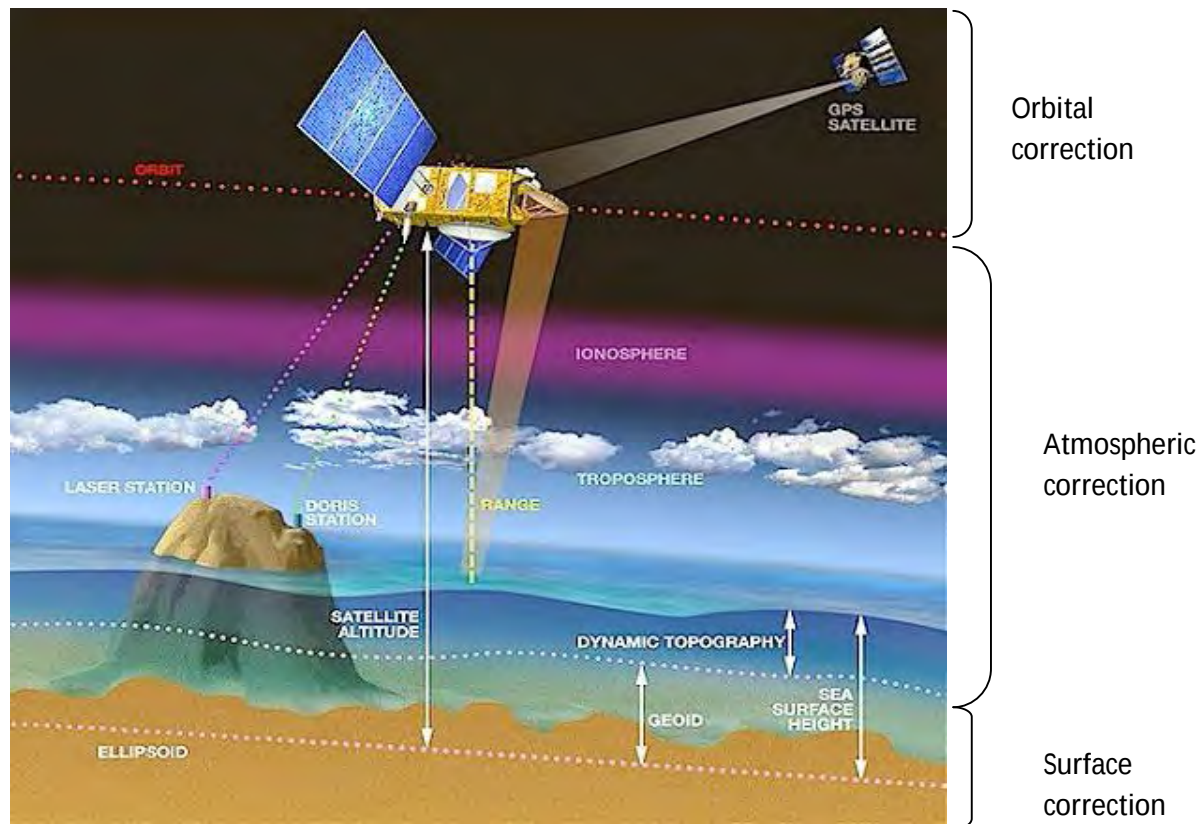


Figure 3. 5 shows conceptual model for Orbital and Atmospheric correction

Atmospheric Correction

Fortunately, coherence in the Afar region is generally high due to the arid environment, and interferograms with perpendicular baselines as large as 600 m remain coherent(Hamling ; 2010)

4. Data processing and analysis

4.1. Overview of GAMIT/GLOBK

GAMIT/GLOBK is a comprehensive GPS analysis package developed at MIT, the Harvard-Smithsonian Center for Astrophysics (CfA), and the Scripps Institution of Oceanography (SIO) for estimating station coordinates and velocities, stochastic or functional representations of post-seismic deformation, atmospheric delays, satellite orbits, and Earth orientation parameters. The software is designed to run under any UNIX (Linux) operating system. The maximum number of stations and atmospheric parameters allowed is determined by dimensions set at compile time and can be tailored to fit the requirements and capabilities of the analyst's computational environment. There are also C-shell Scripts with name beginning with *sh* which come with the package to control processing. The main aim of this chapter is to give a brief introduction to GAMIT/GLOBK but the rest will be discussed in detailed later.

4.2.1. GAMIT processing Algorithm

GAMIT incorporates difference-operator algorithms that map the carrier beat phases into singly and doubly differenced phases. These algorithms extract the maximum relative positioning information from the phase data regardless of the number of data outages, and take into account the correlations that are introduced in the differencing process. In the presence of cycle slips, initial processing of phase data is often performed using triple difference or doppler observations in order to obtain a preliminary estimates of station or orbital parameters. GAMIT software uses triple differences in editing but not parameter estimation. Rather it allows estimation of extra free bias parameters whenever automatic editor has flagged an epoch as a possible cycle slip.

GAMIT is composed of distinct programs which perform the functions of preparing the data for processing (*makexp* and *makex*), generating reference orbits for the satellites (*arc*), computing residual observations (*o-c's*) and partial derivatives from a geometrical model (*model*), detecting outliers or breaks in the data (*autcln*), and performing a least-squares analysis (*solve*). Although the modules can be run individually, they are tied together through the data flow, particularly file-naming conventions, in such a way that most processing is best done with shell scripts and a sequence of batch files set up a driver

module (fixdrv) for modeling, editing, and estimation. Though the data editing is almost always performed automatically, the solution residuals can be displayed or plotted so that problematic data can be identified (cview). It must be stated emphatically that blind reliance on the solution without any thorough analysis and the implication of the results can lead to disaster, as always.

Parameter Estimation

GAMIT incorporates a weighted least-squares algorithm to estimate the relative positions of a set of stations, orbital and Earth-rotation parameters, zenith delays, and phase ambiguities by fitting to doubly differenced phase observations. Since the functional (mathematical) model relating the observations and parameters is non-linear, GAMIT produces two solutions, the first to obtain coordinates within a few decimeters, and the second to obtain the final estimates. The GAMIT solution is not usually used directly to obtain the final estimates of station positions from a survey. Rather, GAMIT is used to produce estimates and an associated covariance matrix of station positions and (optionally) orbital and Earth-rotation parameters which are then input to GLOBK to estimate positions and velocities. In order not to bias the combination, GAMIT generates the solution used by GLOBK with only loose constraints on the parameters, defining the reference frame only at the GLOBK stage by imposing constraints on station coordinates. Since phase ambiguities must be resolved (if possible) in the phase processing, however, GAMIT generates several intermediate solutions with user-defined constraints before loosening the constraints for its final solution.

In parameter estimation based on least-squares, the conventional measure of goodness-of-fit is the χ^2 (chi-square) statistic, defined for uncorrelated data as the sum of the squares of each observation residual (post-fit observed minus computed observation, "o-c") divided by its assigned uncertainty. The value is usually normalized by dividing by the degrees of freedom (df), which is the number of observations minus the number of parameters estimated, so that the ideal value for properly weighted observations is 1.0. In a multi-parameter solution, correlations arise so the computation of χ^2/df in GAMIT involves a complex matrix operation. Later in the report we will discuss how the χ^2 statistic is used to assess the quality of a GPS analysis. It is important to state that its value depends not only on the data noise and processing models, but also on how realistic are the a priori errors assigned to the phase observations and/or the quasi-observations used by GLOBK.

4.2.2. GLOBK processing Algorithm

GLOBK is a Kalman filter whose primary purpose is to combine solutions from the processing of primary data from space-geodetic or terrestrial observations. It accepts as data, the estimates and associated covariance matrices for station coordinates, earth-rotation parameters, orbital parameters, and source positions generated from analyses of the primary observations. These primary solutions are performed with loose a priori uncertainties assigned to the global parameters, so that constraints can be applied uniformly in the combined solution.

There are three common modes, or applications, in which GLOBK is used:

1. Combination of individual sessions (e.g., days) of observations to obtain an estimate of station coordinates averaged over a multi-day experiment. For GPS analyses, orbital parameters can be treated as stochastic, allowing either short or long arc solutions.
2. Combination of experiment-averaged (from .1) estimates of station coordinates obtained from several years of observations to estimate station velocities.
3. Independent estimation of coordinates from individual sessions or experiments to generate time series assessment of measurement precision over days (session combination) or years (experiment combination).

Some things GLOBK cannot do.

1. GLOBK assumes a linear model. Therefore any large adjustments to either station positions or orbital parameters (>10 m for stations and >100 m for satellite orbits) need to be iterated through the primary processing software to produce new quasi-observations.
2. GLOBK cannot correct deficiencies in the primary (phase) analysis due to missed cycle slips, "bad" data, and atmospheric delay modeling errors. You cannot eliminate the effect of a particular satellite or station at the GLOBK stage of processing, though GLOBK can be useful in isolating a session which is not consistent with the ensemble and in some cases the effect of a station on the GLOBK solution can be reduced.
3. GLOBK cannot resolve phase ambiguities: the primary GPS solution must be strong enough on its own to accomplish this. The need to combine sessions for ambiguity resolution is the one reason one might want to perform a multi-session solution with primary observations.

GLOBK operates through distinct programs, which can be invoked with a single command or run separately. The primary functions are to combine quasi-observations either from multiple networks and or epochs (glred or globk), and to impose on this solution a reference frame appropriate to the scientific objective (glorg). It must be emphasized that globk and glred are the same program, just called in

different modes: glred to read data from one day at a time for generating time series, globk for stacking multiple epochs to obtain a mean position and /or velocity.

4.2 Data Analysis

In this section the results after data processing will be presented. The offsets of the time series will be compared, with the time of the dyke events to see any correlation. Table 4.1 lists the dyke events for the Dabbahu Manda Hararo rift segment.

Table 4. 1 Dyking events list for Dabbahu Manda Hararo rift segment

Number	1	2	3	4	5	6	7	8	9	10	11	12
Time of	17	25	10	7	14	12	12	1	9	17	11	28
dyke	Jun	Jul	Sep	Dec	Jan	Aug	Nov	April	Jul	Oct	Feb	Jun
event	2006	2006	2006	2006	2007	2007	2007	2008	2008	2008	2009	2009

4.2.1 GPS Data

I. DA25 GPS

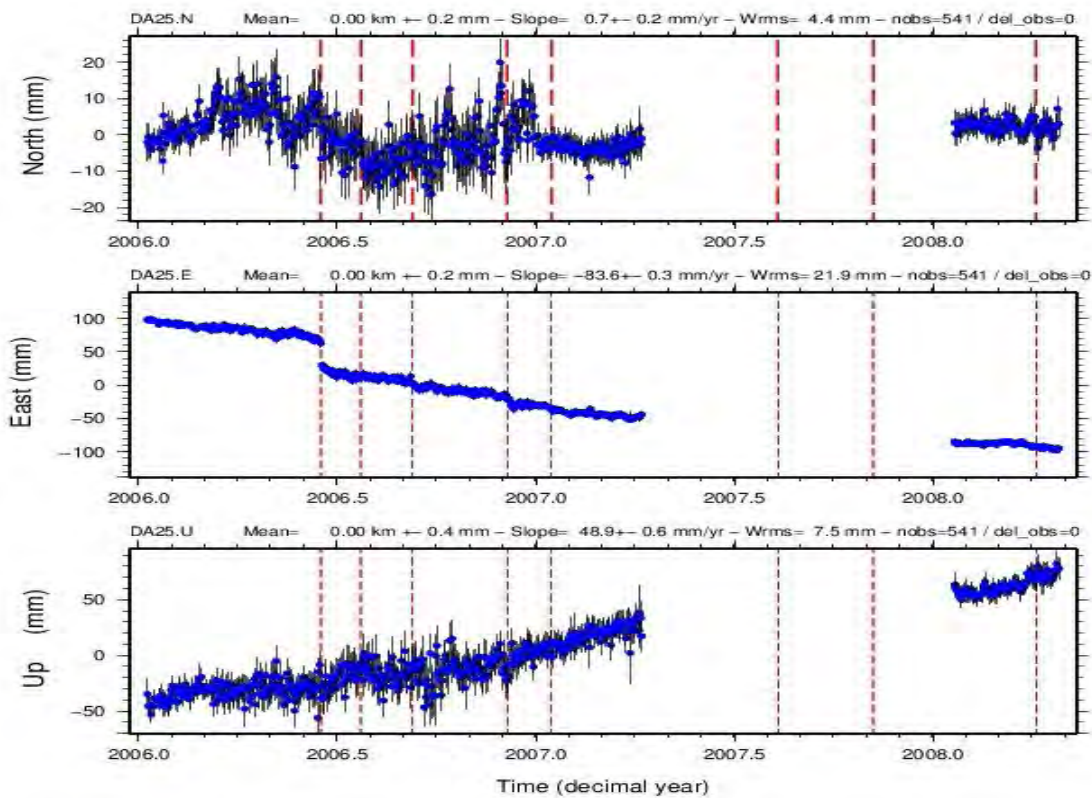
The name given to some of the stations is alphanumeric, with the first two numerals being alphabets and the rest numbers. The number represents the perpendicular aerial distance from the axis of the dyke. For example, DA25 stands for a station located 25 kilometer at the western side of the rift.

Figure 4.1 shows the daily solution of the station DA25. Before the end of April 2006, the station was moving toward northwest horizontally and upward in the vertical direction. However, the deformation mode changed dramatically at end of April, 2006 and the station started to move in the southwest direction until June 2006 dyke event. In June 2006, there was a dyke intrusion in the vicinity and to the south of the Ado'Ale volcanic complex (Keir et al. 2009). As a result of the June 17, 2006 dyke intrusion, the westward motion of the station experienced an offset of $\sim 62\text{mm}$ and it continued to

move in the southwest direction at a rate of $\sim 46.97 \pm 0.46$ mm/yr, until August, 2006. This meant that the July 25, 2006 event was not accompanied by any major directional or rate change. However, in August 2006, few days before the September 10, 2007 event another directional change from southwest to the northwest direction has been observed. This has once more been accompanied by an uplift rate change, during the September 10, 2007 event. Between this event and the December 7, 2006 event the station moved towards the NW direction which is similar to the direction before April 2006. There was no GPS data for the station DA25 until end of January 2008 and nothing can be said in conjunction with the two dyking events in August and November 2007.

Before the occurrence of the April 2008 dyking event the rate at which the station moves in all direction subsided. The site is however being removed after this period. The average movement of the station is towards the west direction with uplift in the vertical direction. As the station is relatively near to the rift axis, offsets can be clearly observed during the major dyking events. Moreover, directional changes in the north-south direction have been observed before the major dyke events.

a)



b)

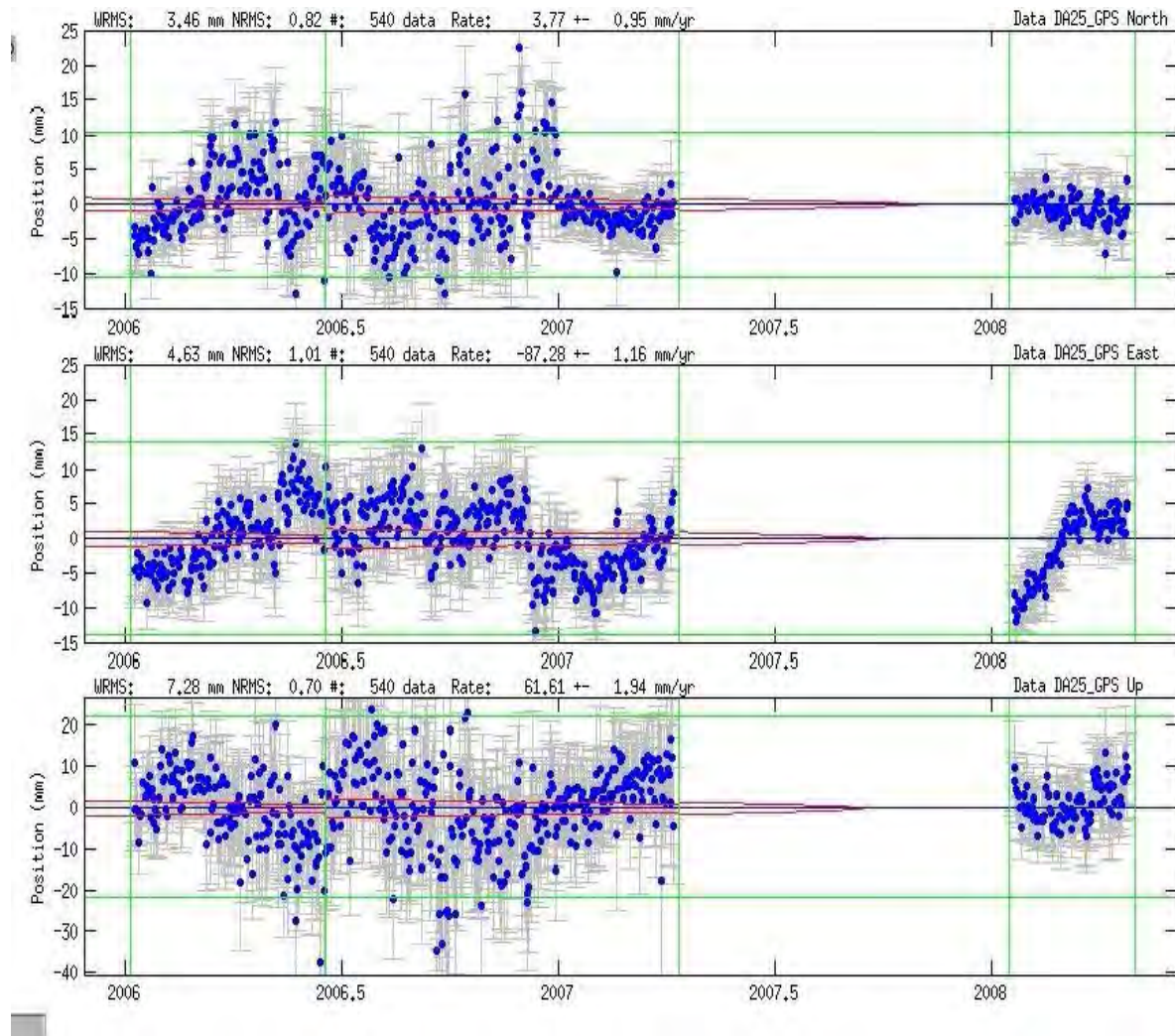


Figure 4. 1 a) Uncorrected and b) corrected offset position time series for DA25 GPS. Red dashed line indicates the time of diking events

II. DA35

The station was located in the small town called Digdiga, which is 35 kilometers west of the rift axis. As it is the next nearest sites to the rift, one can still observe an offset after the June 2006 event with a magnitude of $17.33 \pm 0.62 \text{ mm}$ and a westward displacement of 40 mm/yr see figure 4.2. Similar to DA25, there was a directional change at the end of April 2006 just before the June 2006 event. Unlike the DA25 where the uplift rate is changed after the June 2006 event, in this station the uplift rate was already

changed earlier at the end of April, to the extent that there was a short directional change. But after the occurrence of this dyke event the site moved to the SW direction though no significant change has been observed in the vertical component. However, soon after the July 2006 event and before the September 7, 2006 event the station once more changed direction to the northwest direction and it subsided for short period. Unfortunately, after the September event there was no enough data to carry out further inter-diking investigations. In general, the overall movement of the site is similar to that of DA25, which is 56.83 ± 0.54 mm/yr westward and about 19.50 ± 1.17 mm/yr upward.

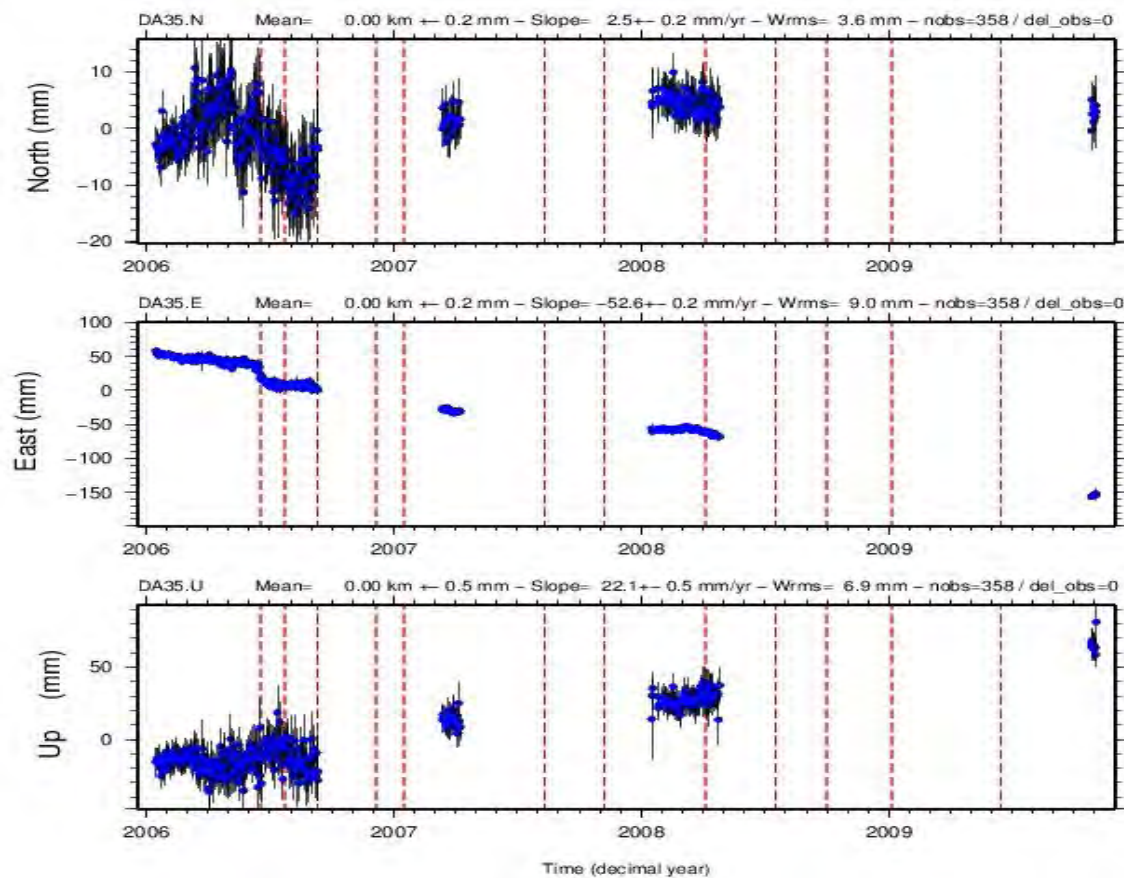


Figure 4. 2 Position time series for DA35 continuous GPS sites. Red dashed line indicates the time of diking events.

III. DA45

The station, DA45 is located 45 km west of the rift axis. The time series in figure 4.3 shows that, the station was moving toward northwest until the end of April 2006 similar to DA25 and DA35. However, after this period the site started moving towards southwest until the occurrence of the September 2006 dyke event. After this dyke event, there was a change in direction of the displacement which is oriented towards northwest. However, since there was a data gap after the September, 2006 event much can't be said when the change has occurred. During the December 2006 dyke event, the direction has been once more reversed to the southwest direction. In 2007, there was no enough data and one can't study the inter-dyking deformation pattern due to the January, August and November 2007 events. However, the April 2008 dyke intrusion caused an offset in the time series (about $\sim 2.15 \pm 66.06$ mm) towards the west direction. Between the February 2009 and June 2009 dyking events there was also an offset in the east component (about -6.01 ± 0.32 mm). One can clearly see from this site that the rate at which the station is moving changed during the June 2009 dyking event and this might be as a result of the viscoelastic relaxation of the area in response to the successive dike events. The rate before the June, 2009 event was -6.37 ± 1.08 mm/yr, 37.82 ± 1.28 mm/yr and 30.03 ± 2.26 mm/yr in North, East and Up component respectively and after the event it became 8.5 ± 0.44 mm/yr, 3.75 ± 0.52 mm/yr and 6.75 ± 0.88 mm/yr in North, East and Up component respectively. The general horizontal movement was towards the westward direction and station was uplifted vertically.

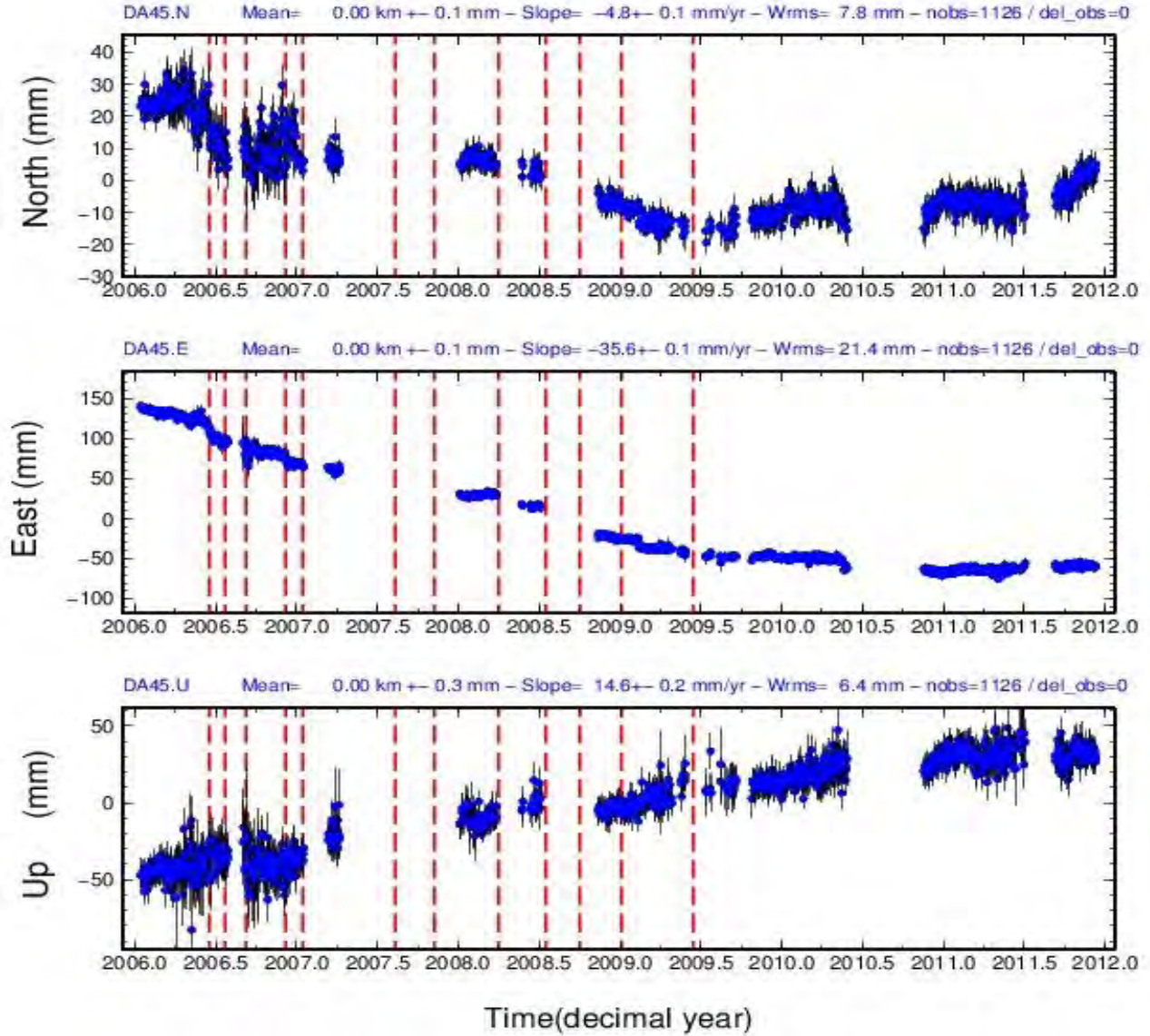


Figure 4. 3 Position time series for DA45 continuous GPS sites. Red dashed line indicates the time of dikeing events and photos for GPS station at DA45.

IV. DA60

DA60, is located at distance of 60 km west of the rift axis and is the most distant site next to DASM. Before April 2006 its displacement was towards northwest direction, but it changed to the southwest direction just before the June 2006 dyke event. Then the motion of the station changed from SW to NE direction before the July 2006 event (figure 4.4). After the September 2006 dyke intrusion the displacement was changed towards NW but the up component was stable. There was no data to be compared with the August and November 2007, July and October 2008 and February 2009 dyking events.

Especially at this station, just before the occurrence of most of the dyking events, the east component is changing direction movement. For example, after the June, 2006 event the station was moving toward west at higher velocity than what was there before. Then before the July 2006 event it changed its direction toward east. During July, 2006 event and before the September, 2006 event it changed again toward west. A change in direction also occurred before the April, 2008 event. This indicate that all major intrusions are accompanied by change of direction few days before the occurrence of the intrusion. In general, the site was moving at an average rate of $17.4 \pm 0.2 \text{ mm/yr}$ towards west.

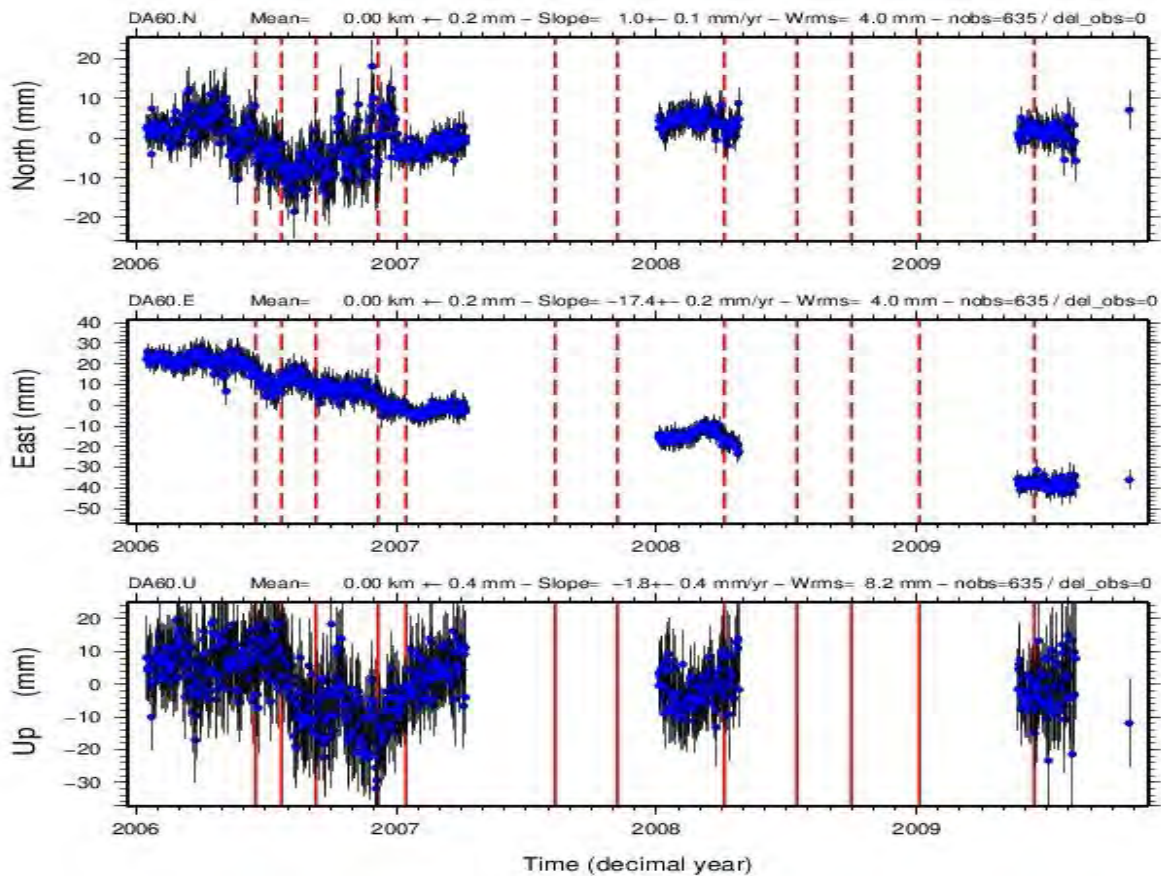
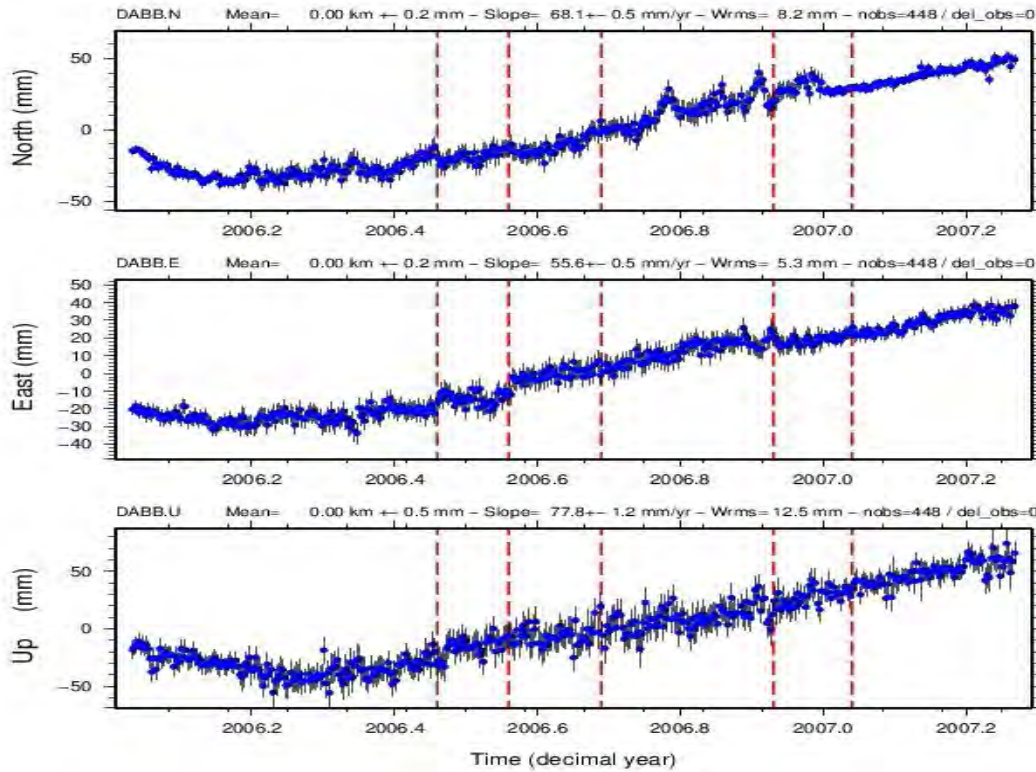


Figure 4. 4 Position time series for DA60 continuous GPS sites. Red dashed line indicates the time of diiking events.

V. DABB

Dabbahu is a composite volcano at northern end of the active Manda Hararo segment of the afar rift in northern Ethiopia. Daily averages of East, West and up components of the station motion from continuous GPS sites on Dabbahu volcano show that before April 2006 the station was moving towards south west direction and it was subsiding see Figure 4.5a. However, after April 2006 the style of movement changed dramatically from SW to NE and the station started to uplift (Figure 4.5b). The continuous GPS data from Dabbahu's northern flank shows re-inflation beginning in April (Figure 4.5b). A study in 2008 (Ebinger, 2008) showed that 25 cm of subsidence occurred between 2005 October and 2006 April. The Site on Dabbahu's northeastern flank shows slow, southward-directed subsidence between January and April 2006, consistent with the InSAR observations of subsidence on Dabbahu's south flank (Figure 4.5b). Inflation begins in April and continued through the June, July, September and December, 2006 events as well as the January 2007 event. Unfortunately the station has been removed after the February 2007 event and data is not available since then.

a)



b)

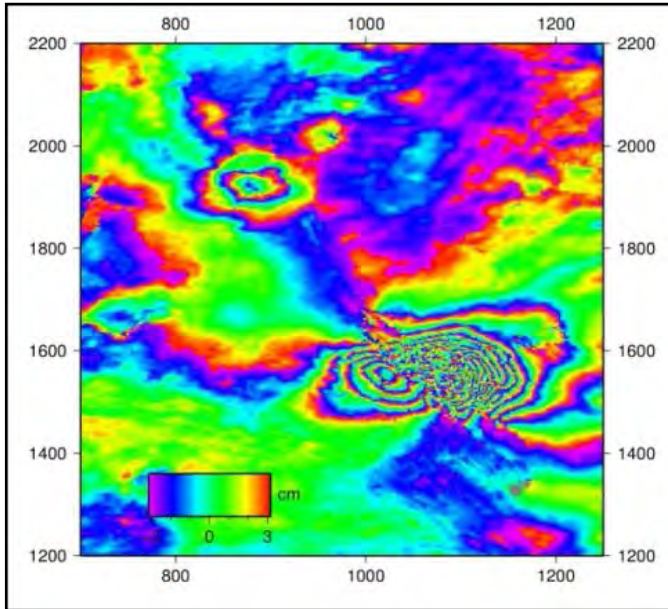


Figure 4. 5 (a)Position time series for DABB continuous GPS sites (left top). Red dashed line indicates the time of diking events. (b)Observed ascending interferograms covering July 2006 dyk intrusion which is showed in the Right top side.

VI. GABH

In general, during the life span of the station it was inflating at an average rate of 280 mm/yr (figure 4.6). However, if one see the figure properly, before the June, 2006 event the station was inflating at faster rate that amount to 520 mm/yr. This has changed after the June, 2006 event in such that the inflation rate slowed down to 70 mm/yr. The site GABH, is located on Gab'ho volcano that was one of the active area during the 2005 event. It is unfortunate that the station had to be removed and no data is available since February, 2007.

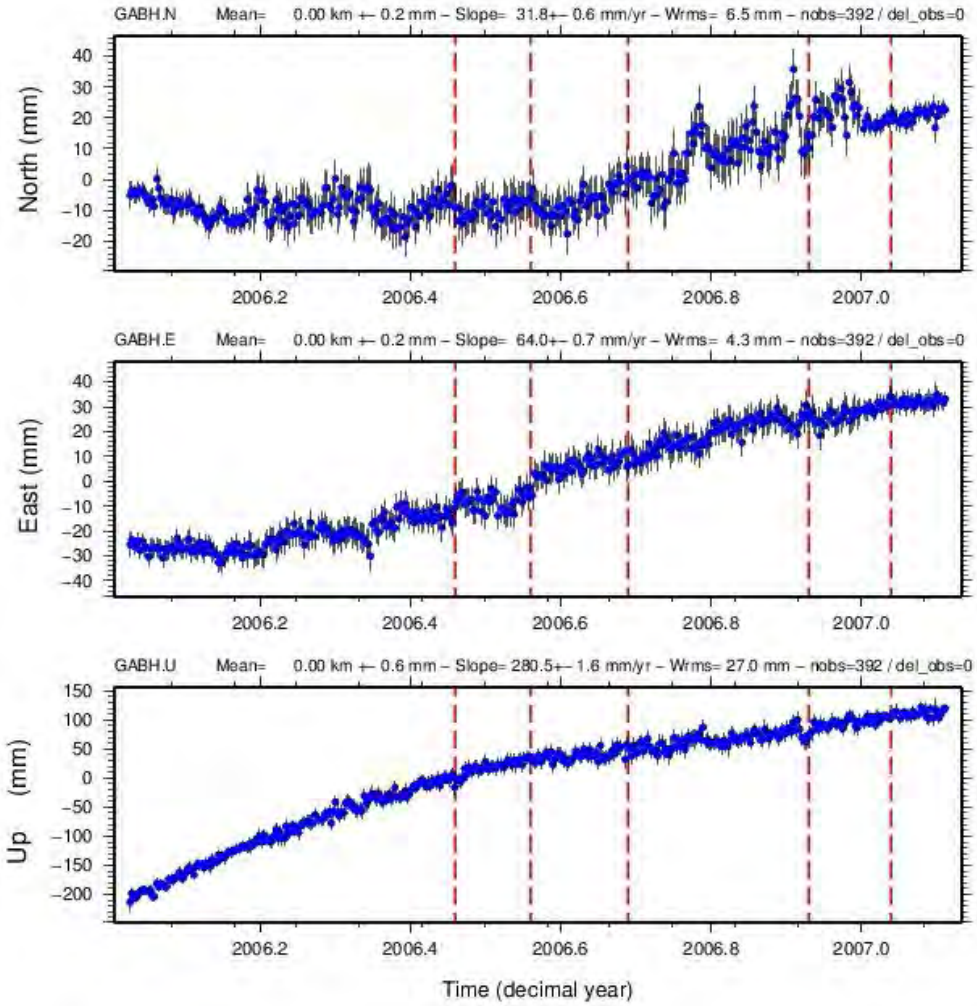


Figure 4. 6 Position time series for GABH continuous GPS sites. Red dashed line indicates the time of dike events.

VII. DASM

This site is located in Semera town roughly south of the southern tip of the dike event in 2005. The station's time series (figure 4.7) tells the story that the up component shows subsidence (the estimated deformation velocity is negative) during the whole period. The east component rate is positive implying the site is moving towards east. In general, as the north rate is also positive, we can say that station is moving 63.3mm/yr in north-east direction with a subsidence of 15.6mm/yr. As the station is far from the Dabbahu-Manda Hararo rift, the dyking injections had a little effect on it. However, since the station shows subsidence, it opened a door for the assumption that there might be a possibility of magma

movement toward north direction that feed the dabbahu Manda Hrarro magmatic rift segment, where all stations show an uplift. Generally, before October 2008 the site was moving about 36mm/yr, 32mm/yr and 0.38mm/yr in the North, East and Up component respectively whereas after October 2008 displacement rate changed in North and Up components which is about 46mm/yr and 16mm/yr respectively.

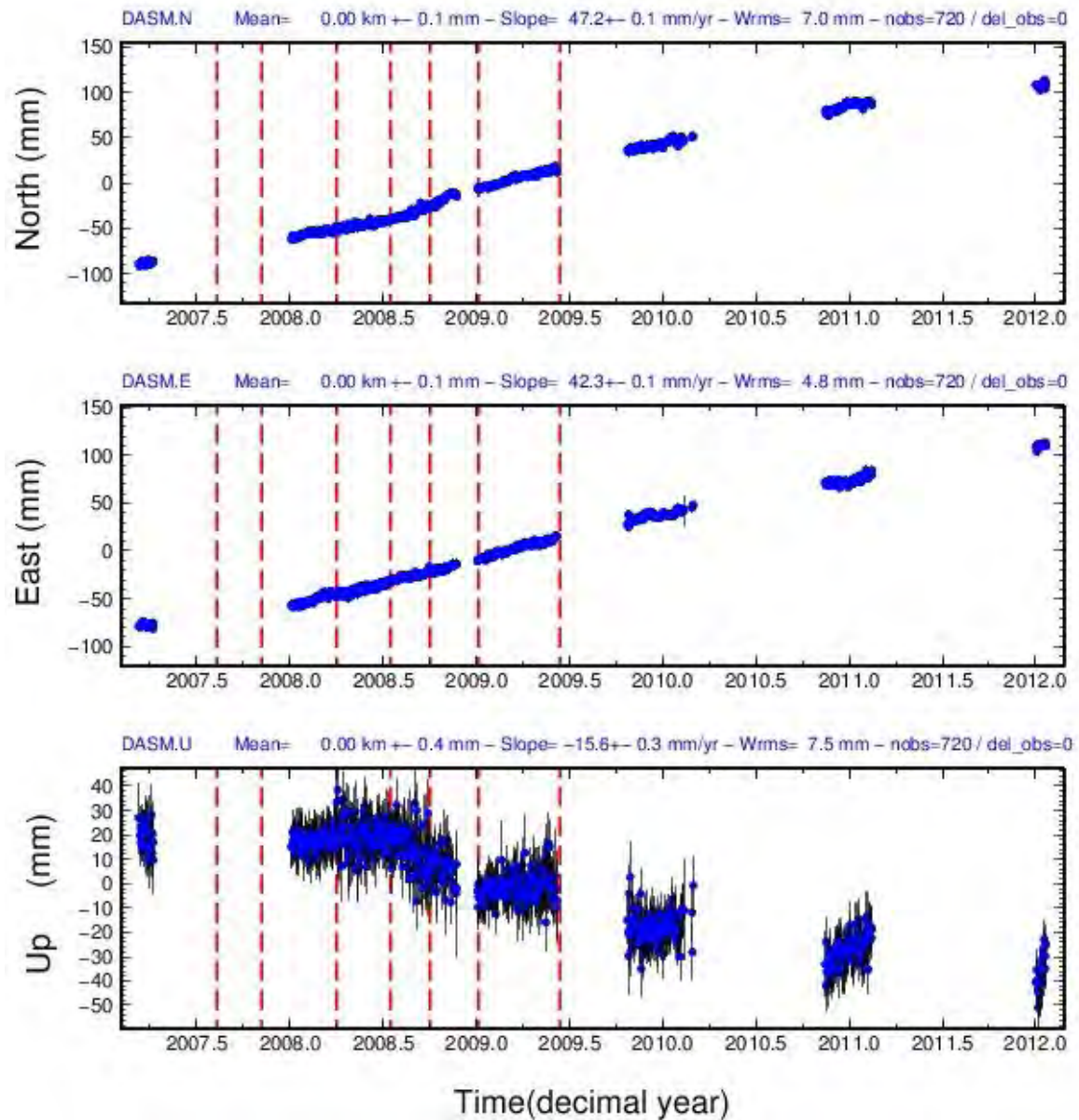


Figure 4. 7 Position time series for DASM continuous GPS sites. Red dashed line indicates the time of dike events.

VIII. DAFT

DAFT is located in a place called Finto, about 45 km west of the rift axis and about 17.5 southeast of the station DA45. Unlike the other stations this station was installed relatively late and nothing can be said about the early activities in 2006 and 2007. Moreover, since the station failed many times and there is a data gap, one cannot in general tell about the inter-dyking deformation in the area. However, from the general picture one can tell that the deformation pattern is different for the time spans before and after June 2009 dyking event. There was an average uplift of the station that amount to 16 ± 0.3 mm/yr. However the story is different for the duration before and after the January 2009 event (see Figure 4.8). Before the occurrence of the June 2009 event the station was moving at the rate of 18.54 ± 0.56 mm/yr and afterward it slowed down to 14 ± 0.38 mm/yr. Also, before the June 2009 dyke intrusion, the station was moving at the rate of -26.76 ± 0.5 mm/yr and -41.52 ± 0.54 mm/yr in the north and east directions respectively. However this has changed to -1.44 ± 0.15 mm/yr and -7.14 ± 0.23 mm/yr in the north and east directions respectively.

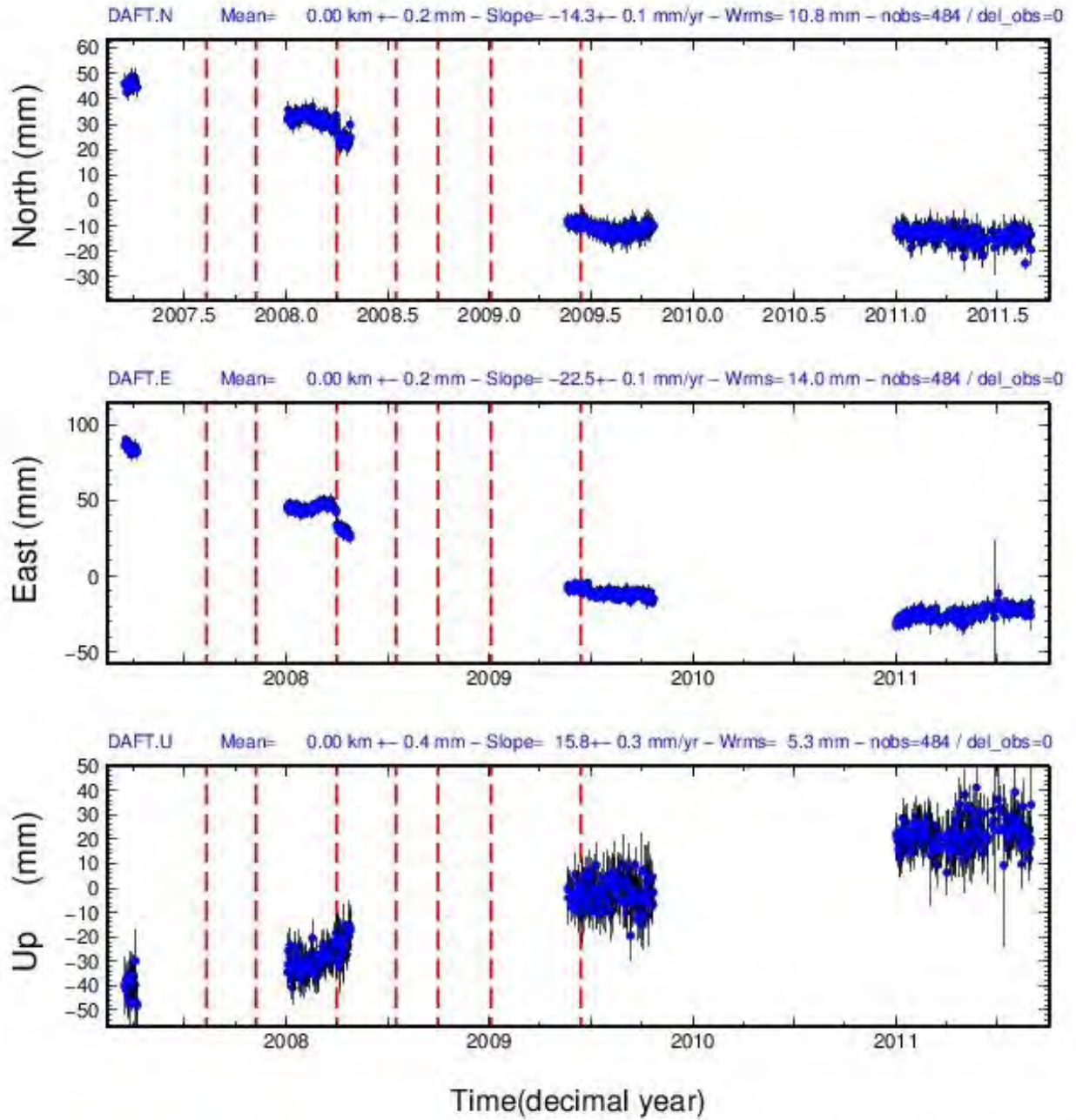


Figure 4. 8 Position time series for DAFT continuous GPS sites. Red dashed line indicates the time of diking events.

In general, figure 4.9 summarizes the overall effects of the dyking events listed in table 3.1 on the time series of the 13 continuous GPS stations in Afar (Ethiopia).

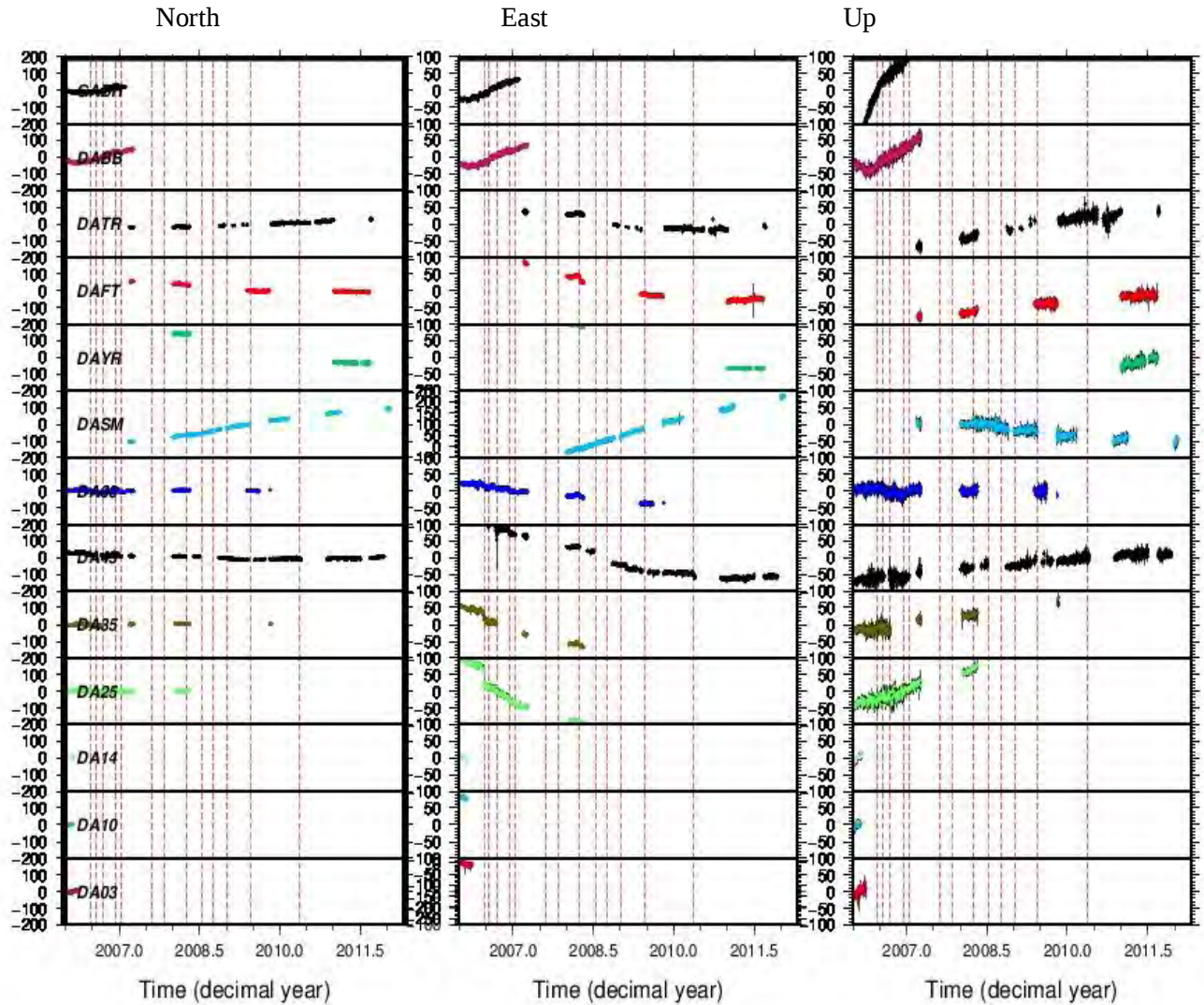


Figure 4. 9 Position time series at continuous GPS sites. Site names are listed on the left side of the east components. Red dashed line indicates the time of diking events.

As one can see from figure 4.9, almost all stations in the area are inflating since the end of 2007, except DASM which is deflating strongly and DA60 which is deflating insignificantly. To see the implication of this the vertical data from DA45 and DASM are plotted together (see Figure 4.10). The two stations are selected because they have data that spans more than 4 years. The outcome of the correlation analysis between this two data sets gave a value of -0.501 percent correlation coefficient, that signify a negative correlation. These imply that as one is inflating the other one is deflating. One of the possible

interpretation for this is that both station are governed by the same system and magma might move from one of the area to the other to cause such effect. However, this should be supported by other independent measurement.

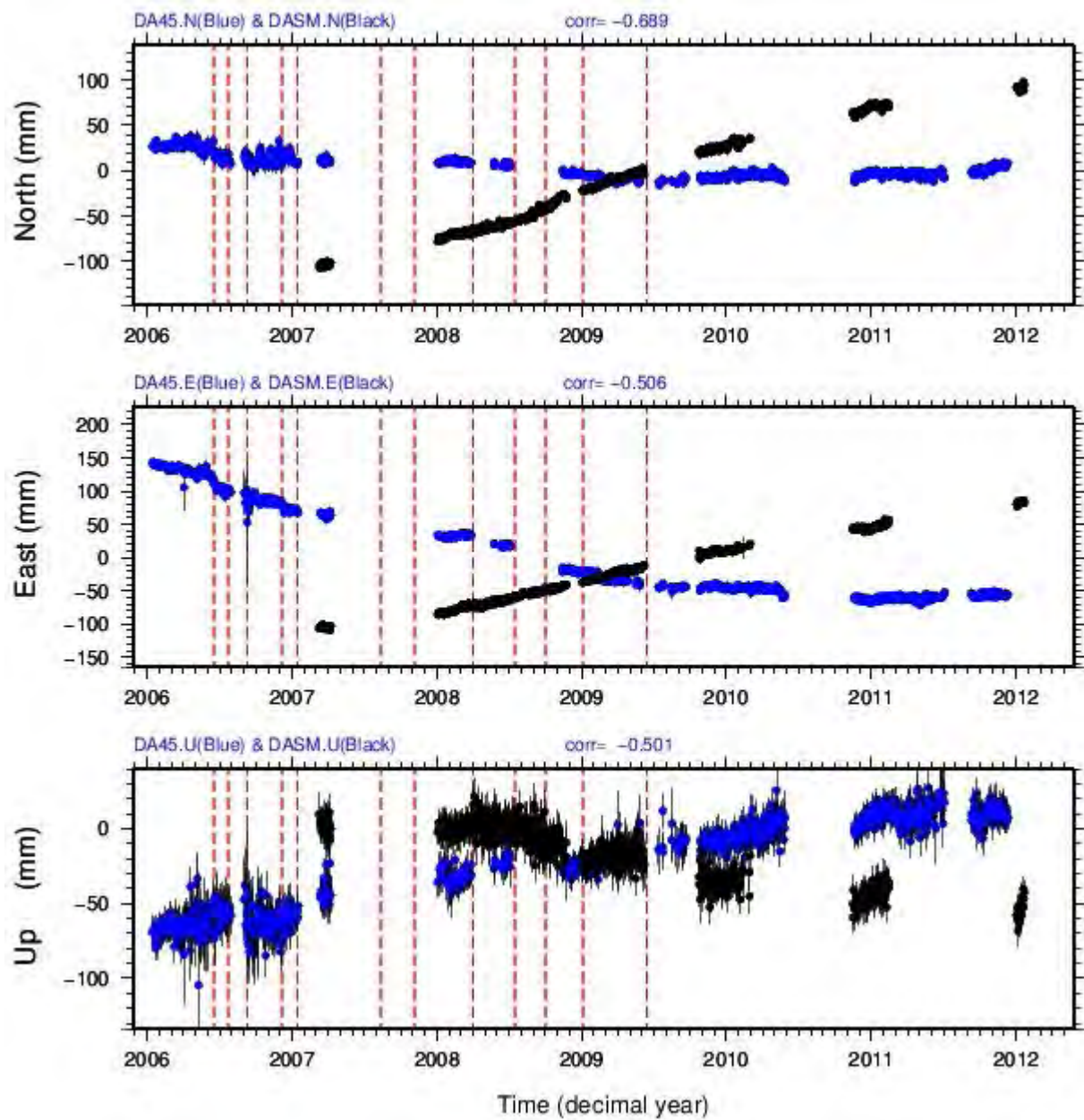


Figure 4. 10 shows the correlation between DA45 and DASM sites

4.2.2 InSAR data analysis

The InSAR data was used to identify the time of the dyking events listed on table 4.1. Figure 4.11 shows the 12 August 2007 dyking event using the InSAR technique (see appendix 7.2 for more figures on the InSAR results). The event that occurred in 12 August 2007, has been captured both the Interferogram derived from ascending and descending tracks. The figures 4.11 A and D shows ascending and descending interferogram while figures MA and MD are their respective unwrapped images.

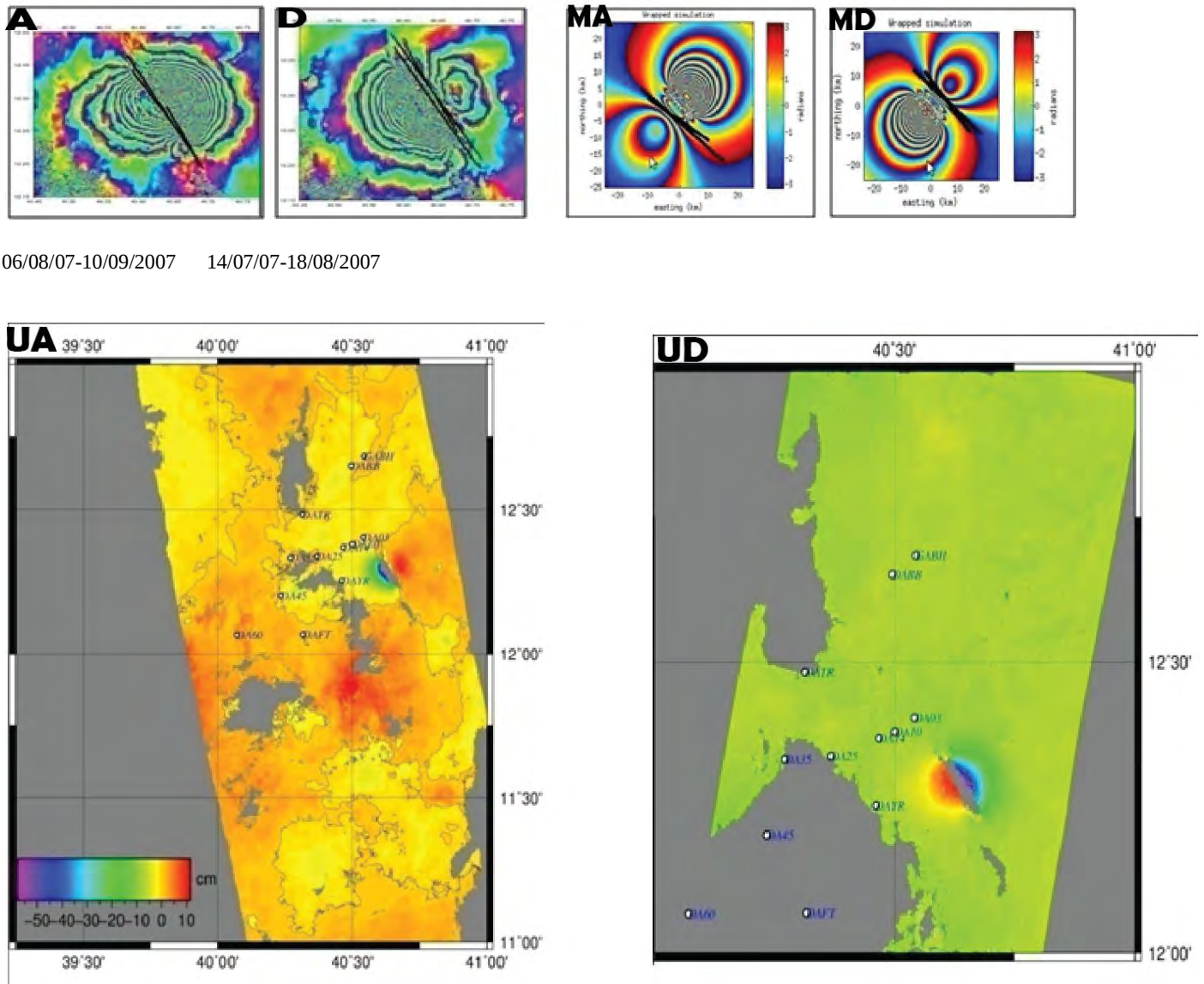


Figure 4. 11 A and D showing the fringes ascending and descending interferograms and MA and MD shows the best model for ascending and descending interferogram, UA and UD indicates Unwrapped

ascending and descending interferogram covering the 12 August 2007 dyke intrusion, blue colours indicate motion toward the satellite. The circles show the location of GPS sites around the rift segment.

Table 4. 2 Opening model output for dyke injection on 12 August 2007

Lat	Long	sat	Inc. Angle	Heading	Strike	Dip	Opening	Length	Top depth	Bottom depth
12.5	40.5	Asc	20	192	135	-90	2	9	1.3	8
		Dsc	23	348	135	-90	2	9	1.3	8

The interferogram showed the deformation associated with ongoing rifting in afar particularly Dabbahu area. The best fitting model suggests that in the ascending interferogram ,the ground was displaced by ~53.2 cm towards the satellite on west flank and moved away ~11.2 cm on the east side. The same result was found from the descending interferogram as well. These results are in a good agreement with the studies of Hamling (2009) that gave the displacement of (~54 cm and ~12 cm deformation of ascending and descending interferogram respectively). The results of all the InSAR (see appendix for moer figures) data are in a good agreement with our GPS results as it can be seen from sections 4.2.1 of this chapter and section 4.2.3.

Further analysis of the InSAR data has not been made as results are already published in Hamling (2009 and 2010) and Wright (2006).

4.2.3 Overall discussion

As it was given in the section 4.2.1 and 4.2.2, results from GPS and InSAR techniques have presented about the ongoing Dabbahu rifting episode, which gave the best opportunity to study the response of the deformation pattern induced by large dyke intrusion. This section discusses about the results on post intrusion and at times post rifting signals that represent the transient response of the lithosphere as the stress relaxed.

According to the pattern of the stations movement the time series is separated into two classes. The first class covers the time starting from 2006 to June 2009 and second class covers the time from June 2009-February 2012. In the first class most of the GPS sites show rapid displacement and jump in the position time series due to the occurrence of 12 dyke intrusions. These dyke events caused a horizontal displacement to SWW direction with 59.3mm/yr, 43mm/yr, 27mm/yr and 29.5mm/yr for DA45, DAFT, DATR and DAYR respectively in the ITRF08 frame.

The next step was then to fix the Nubian plate and see the motion of the different sites with respect to the Nubian plate. The departure of the horizontal velocities of the 13 stations, from their a priori absolute values in reference to the International Terrestrial Reference Frame 2008 (ITRF08), was minimized to define a realization of Nubian Frame. The estimated velocities were then rotated from no-net-rotation frame of ITRF08 to the Nubian fixed frame defined in this research using NUVEL-1A Euler vectors. The one sigma uncertainties for the GPS velocities were derived by scaling the formal errors by the square root of chi-square per degree of freedom of the solution. Table 4.3 shows the absolute velocities (velocities of the stations tied to ITRF08) and velocities relative to a realized plate (Nubian).

Table 4. 3 Absolute and relative site positions (2006 to June 2009) velocities in ITRF2008. The relative velocities are made with respect to Nubian plate .All velocities and velocity uncertainties are in mm/yr

Site	Horizontal Velocities						<u>Velocity uncertainties (1σ)</u>				
	Position		/ITRF2008		/Nubian fixed		Vertical			Up	Correl.
	Long.	Lat.	East	North	East	North		East	North		
DA25	40.36839	12.3373	-87.25	-12.31	-91.13	-0.07	52.75	0.33	0.26	1.17	0.010
		1									
DA35	40.27227	12.3319	-59.47	-10.55	-82.85	-16.18	23.37	0.19	0.16	0.73	-0.007
		3									
DA45	40.23488	12.2018	-55.23	-23.39	-78.61	-29.03	16.39	0.05	0.04	0.16	-0.047
		5									
DA60	40.07140	12.0661	-20.72	-12.66	-44.1	-18.31	-0.38	0.12	0.10	0.44	-0.012
		2									
DAFT	40.31738	12.0681	-43.69	-37.3	-67.07	-42.93	18.64	0.17	0.13	0.61	-0.026
		5									
DAYR	40.46126	12.2526	-30.39	-28.07	-53.77	-33.68	68.65	0.24	0.19	0.89	-0.023
		0									
DATR	40.31487	12.4814	-27.02	-5.38	-50.4	-11.01	27.82	0.12	0.09	0.42	-0.017
		4									
DASM	41.00924	11.7786	41.48	38.28	18.08	32.7	-15.6	0.09	0.07	0.37	-0.009
		0									
DABB	40.49570	12.6505	57.67	59.04	53.42	0.27	82.48	0.27	0.23	0.99	0.013
		6									
GABH	40.54471	12.6834	67.63	22.21	44.24	16.59	280.5	0.37	0.31	1.38	-0.015
		8									

Figure 4.12 shows the velocity of the stations relative to the Nubian plate. Stations DA25, DA35 and DA45, which are near to the rift, have a significantly high velocity fields comparing to the other stations. Figure 4.13 is the graphical representation of table 4.3 (for the first class). This figure shows that most of the GPS sites show rapid velocity due to the occurrence of the 12 dyke intrusions. These dyke events caused a displacement to the west direction for DA45, DAFT, DATR, DA25, DA35, DA60 and DAYR, while DABB, DASM and GABH are moving to the opposite direction in the ITRF08 frame.

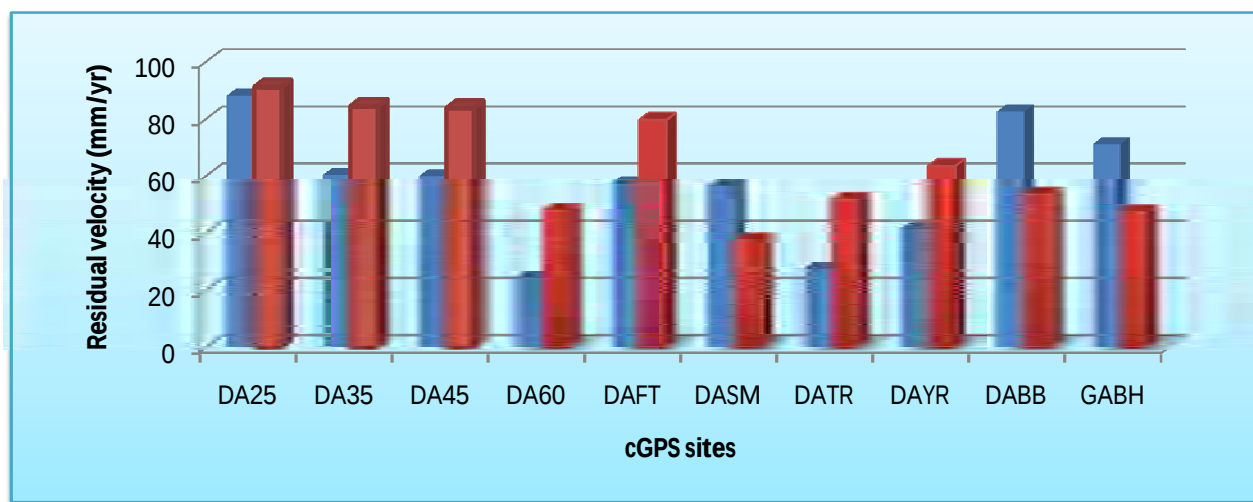


Figure 4. 12 Absolute velocity of the Afar stations (Blue Bars) and with respect the Nubia plate (Red Bar), before June 2009 period. The horizontal axis represent the station names.

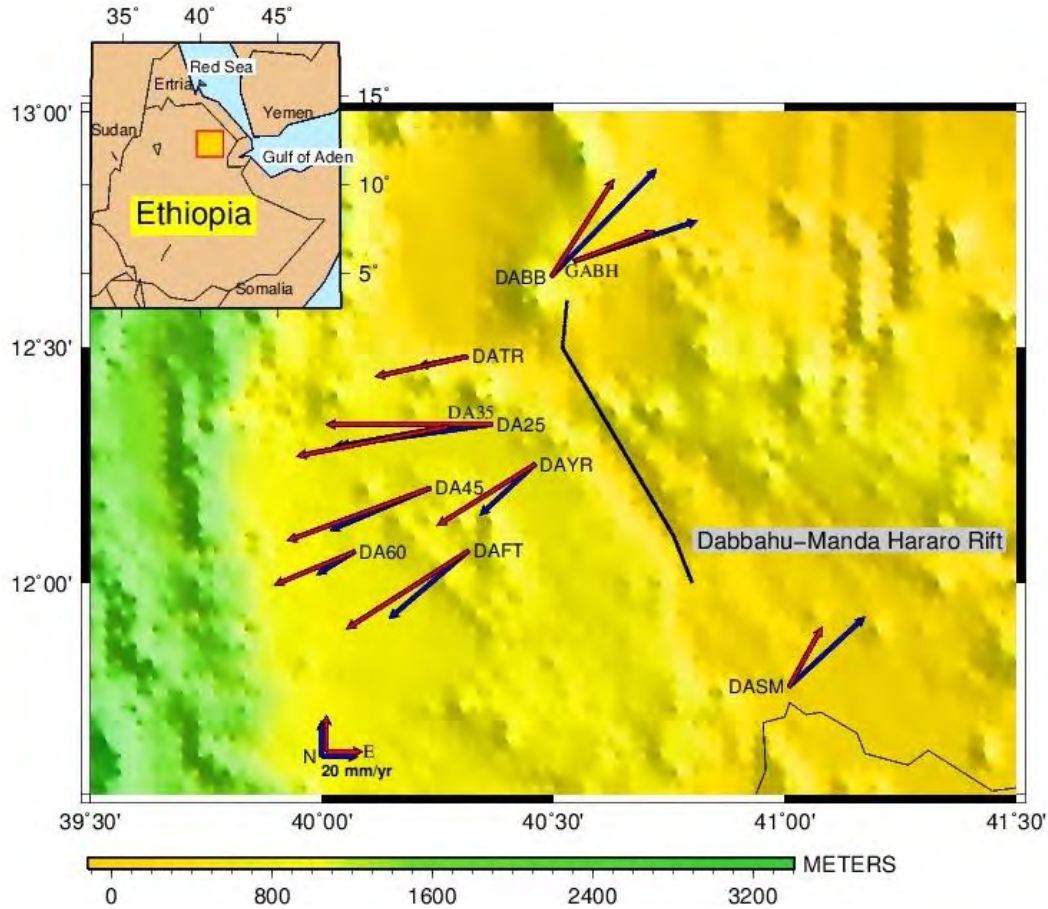


Figure 4. 13 The red arrow shows the residual velocity with respect to Nubian-fixed frame and blue arrow shows the absolute velocity with respect to the ITRF08 (before June 2009 dyke event).

If one now takes the second class (which covers the time from the second day of June 2009-2012), after the end of June 2009 dyke intrusion, the style of the absolute horizontal displacement changed dramatically towards north direction and it slightly became stable for sites DA45, DATR and DASM with 3.65mm/yr, 11.56mm/yr and 52.5mm/yr respectively. Sites DAFT and DAYR moved at rates 7.68mm/yr and 9.27mm/yr respectively towards southeast direction (table 4.4). Figures 4.14 and 4.15 are the graphical representations of the velocities for the stations DA45, DATR, DASM, DAFT and DAYR in the Nubian plate.

Table 4. 4 Absolute and relative site positions and velocities for the second class (the time from June 2009-2012). The relative velocities are measured with respect to the Nubian plate. All velocities and velocity uncertainties are in mm/yr

Site	Position		Horizontal Velocities				<u>Velocity uncertainties$1(\delta)$</u>		
			/ITRF2008		/Nubian fixed		East	North	Correl.
	Long.	Lat.	East	North	East	North			
DA45	40.23488	12.20185	-3.09	-1.94	-33.38	-14.828	0.04	0.03	-0.038
DAFT	40.31738	12.06815	-1.19	-7.59	-31.48	-20.46	0.12	0.08	-0.016
DAYR	40.46126	12.25260	-7.6	-5.31	-37.909	-18.16	0.22	0.11	-0.020
DATR	40.31487	12.48144	6.71	9.42	-23.6	-3.455	0.12	0.09	-0.010
DASM	41.00924	11.77860	42.81	30.39	12.502	17.629	0.06	0.05	-0.009

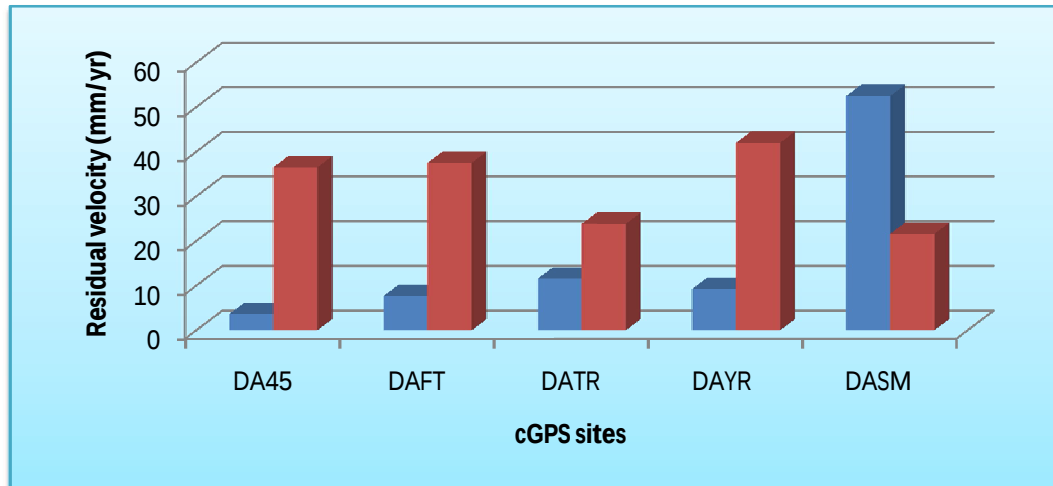


Figure 4. 14 Afar residual velocity with respect to ITRF08 with Blue color and Nubia with Red color after June 2009 period, Velocity magnitudes and (bottom) velocity components in mm/yr.

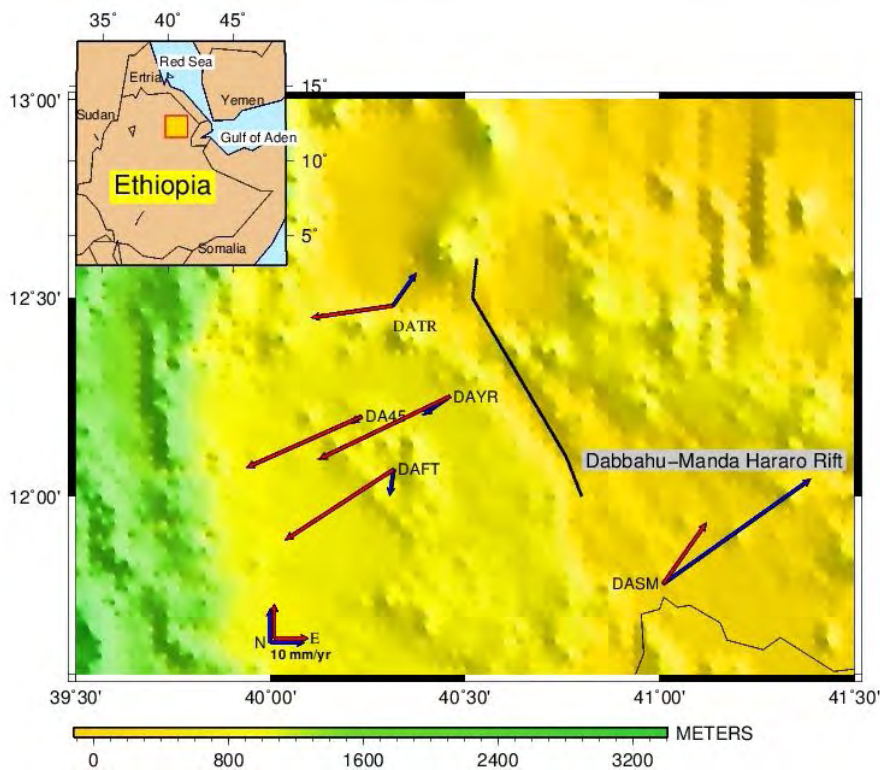


Figure 4. 15 The red arrow shows the residual velocity with respect to Nubian-fixed frame and blue arrow shows the absolute velocities with respect to the ITRF08 reference frame (June 2009 dyke event up to 2012)

Though mapping the intensity the way given in Figure 4.16 is not common, due to small number of stations, here it has been presented just to visualize the area of maximum stress. Figure 4.16 shows the intensities of the horizontal velocities for the two classes. Figure 4.16a is for the first class where the time interval is before June 2009 and figure 4.16b is for the second class where the time interval is after June 2009.

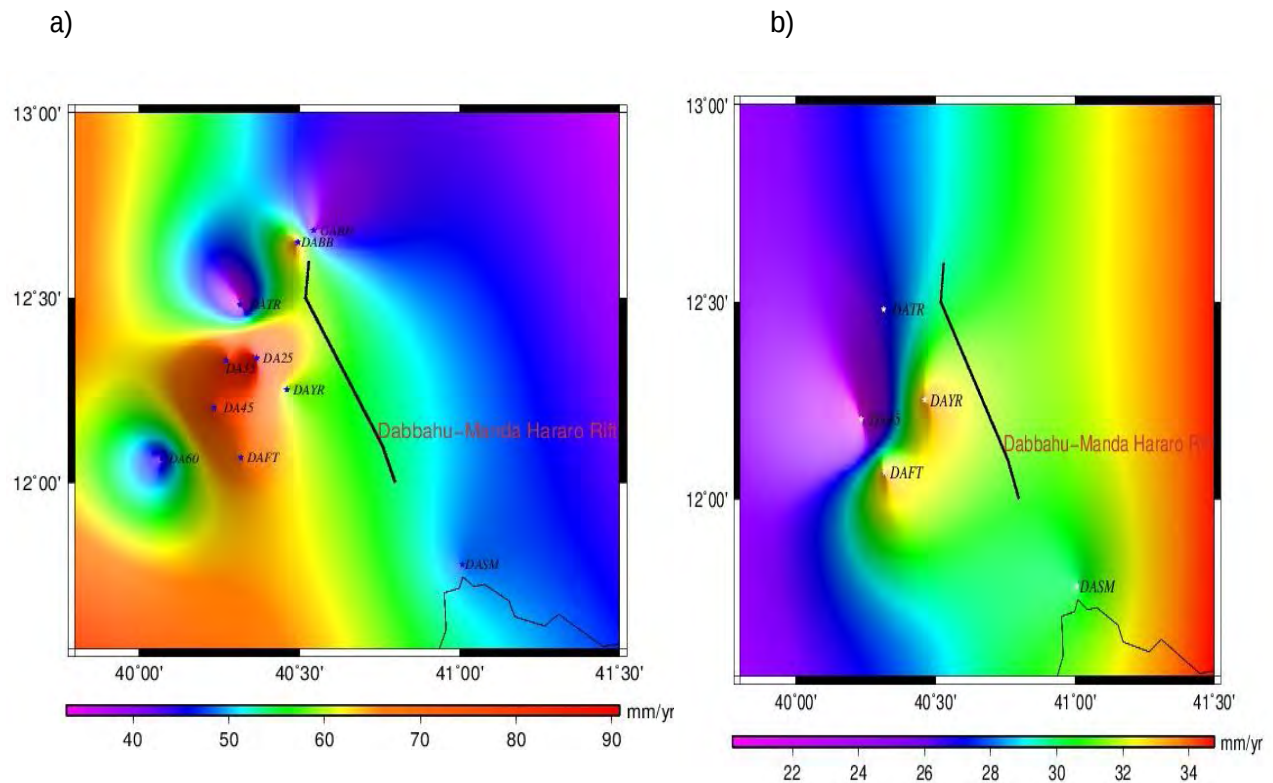


Figure 4. 16 Intensity of Horizontal velocity field, the red color shows the highest displacement rate, top left image indicates before June 2009 and the right image shows displacement rate.

Figure 4.17 shows the result of the vertical movements of the stations. Sites DASM and DA60 show subsidence while all other sites located on the northern part of the study area are being uplifted. One of the different possibilities for such occurrences would be that the shallow magma chambers in both the north (around Dabbahu-Manda-Hararo) and the south (around Semera) area are fed by a single deep sited magma chamber. When there is a stress release due to dyke intrusion and associated uplift in one of the area magma might be depleted from the chamber in the other area to cause subsidence. Generally the deformation pattern showed a higher uplift in the northern part where stations DABB and GABH are found. However, one should note that the

time span for the different stations is different and the velocities in DABB and GABB might have been influenced by local maxima for the stations have data from very short duration

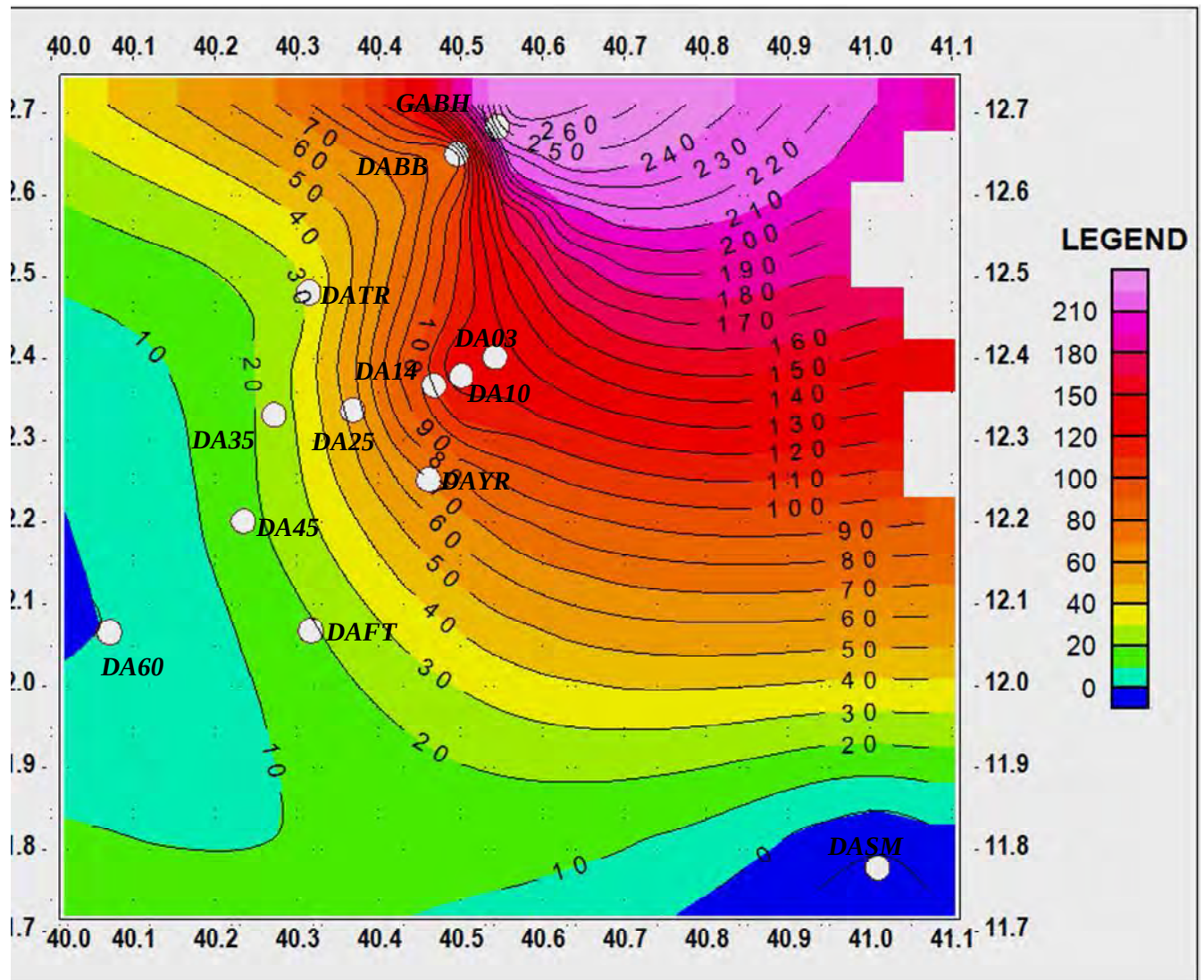


Figure 4. 17 The vertical velocity field in the ITRF08 frame.

5 Conclusions and recommendations

5.1 Conclusions

Geodetic methods are precise and very accurate ways to determine the rate of movement as well as the amount of displacement, in such areas like the Afar depression, where active deformation is taking place. In this study, GPS and InSAR data have been used to analyze the deformation patterns in the Dabbahu-Manda Hararo rift segment, mainly focused on studying the inter-dyking deformation pattern.

Thus, the GPS position time series plot indicates a subsidence occurred at Dabbahu volcano before April 2006 with a horizontal displacement towards SW direction. However, after April 2006 there was an uplift with horizontal movement to the NW. Gabho volcano shows rapid uplift from January to June 2006 and after June 2006 there was a slow rate of uplifting with a horizontal displacement to the NE direction. Since these sites were having short lifespan a lot can't be said after the event in June 2006.

When observe regionally, DASM and DA60 showed subsidence, while the sites located on the northern part of the study area showed uplift. One of the different possibilities and what has been considered as a viable analysis in this study is that the shallow magma chambers that are responsible for the surface deformations both in the north (around Dabbahu-Manda-Hararo) and in the south (around Semera) areas that are fed by a single deep sited magma chamber. When there is a stress release due to dyke intrusion and associated uplift in one of the area, there might be a depletion of magma in the chamber at the other area. However, this has to be supported by further work using data taken for longer time.

Most of the GPS position time series showed there were directional change in the movement of the stations before the occurrence of dyke intrusions. If done systematically, and data are analyzed during a real time access to the satellites, this might be used to predict the occurrence of major events. This however, should be further studied, especially in association with the events that were not accompanied with directional changes.

Most of the GPS stations before June 2009 showed larger displacement rate where as after the June 2009 dyke intrusion the GPS position time series shows that sites such as DAFT, DA45, DAYR and DATR are approximately stable. This might be an indication that the area has entered in post seismic relaxation time and the whole event is subsiding.

Since the September 2005 event that resulted in the rupture of the Dabbahu rift segment, in the Northeastern part of Ethiopia, a total of 12 dyke intrusion occurred. As previous studies (Wright et al., 2006, Grandin et al., 2009) suggested a 60-km-long dyke intrusion with a maximum opening of 8 m and intruded volume of 2-2.5 km³. Subsidence at Dabbahu and Gabho volcanoes suggested that the intrusion was fed from the north of the segment and propagated south, however, re-analysis of seismicity associated with the intrusions (Ayele et al., 2009) has shown three distinct feeding zones.

Previous work in Iceland also showed that multiple intrusions emplaced over a short space of time with an individual repeat time of ~6 months (e.g. Einarsson & Brandsdóttir, 1980; Tryggvason, 1984). The rifting episodes along the Krafla and Dabbahu segments resulted in multiple intrusions over a number of years. The fact that multiple dyking events were observed during both episodes suggests that there was sufficient magma pressure to overcome the horizontal compressive stress to initiate rifting but insufficient material to fully relieve the stresses built up by the long term plate separation.

5.2 Recommendations

From results of this study, the sites which are near to the rift show a good signal of deformation due to dyking events. In any such future events, it is better to install stations very near to the site 6-10 stations within 4-45km on the eastern part of the area, where the event took place. Systematically far away from the site, to study the driving process behind the event. In addition, around 6 stations on both west and eastern parts should be installed at about 60-100km, from the rift axis.

In a remote area, such as Afar, InSAR plays a pivotal role in obtaining deformation data. Therefore, it is recommended that research facilities are supported to purchase InSAR data such as that from Sentinel-1 which is launched in 2012 and will provide worldwide coverage every 12 days. This satellite measures frequently than its predecessor ENVISAT which was launched in 2001 and stop functioning in 2010.

Despite the availability of 13 continuous GPS stations for this study, their time series was not continuous and this hinders to see the effect of the dyking events when there is a gap on the GPS data during the occurrence of the events. So, it is recommended to have stations that well guarded and with all possible facilities to prevent damage to the instruments. Possibilities should also be made available to download data frequently so that data download time will be shorten.

6 References

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7 Appendix

7.1 More figures on GPS position time series

a)

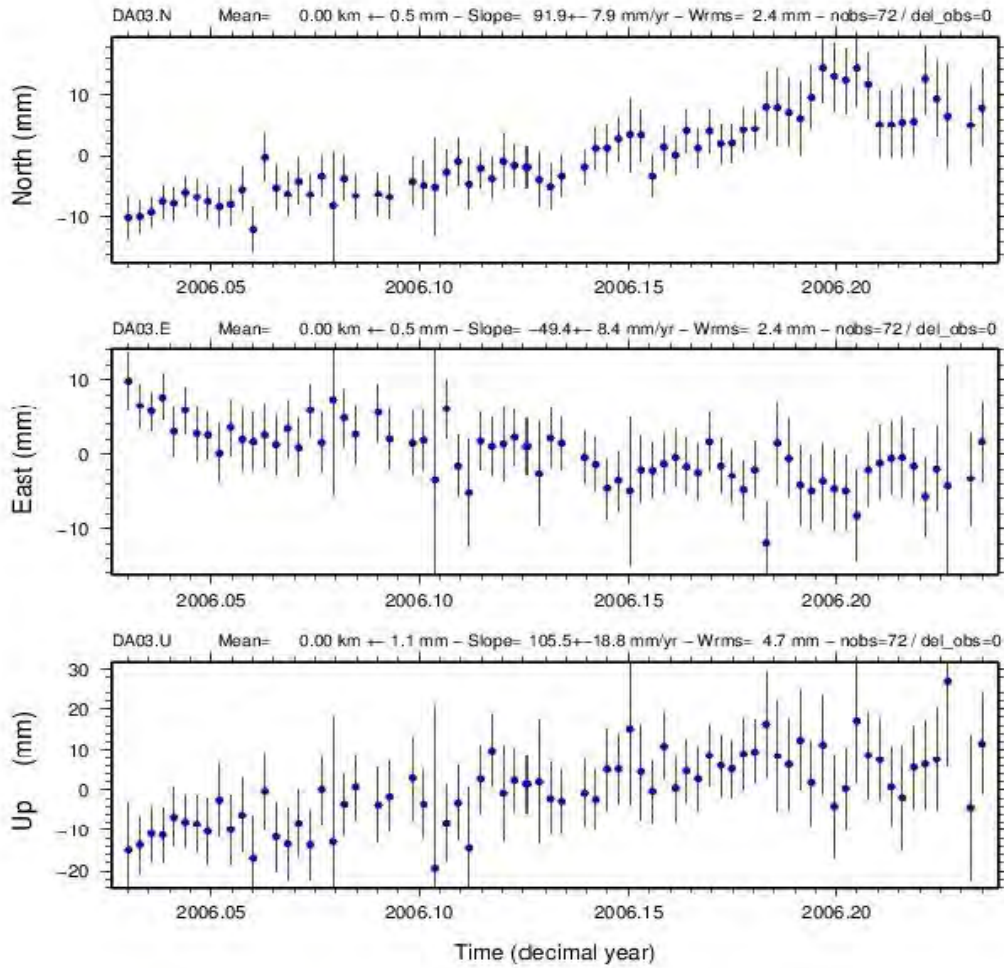


Figure to show Position time series for DA03 continuous GPS sites.

b)

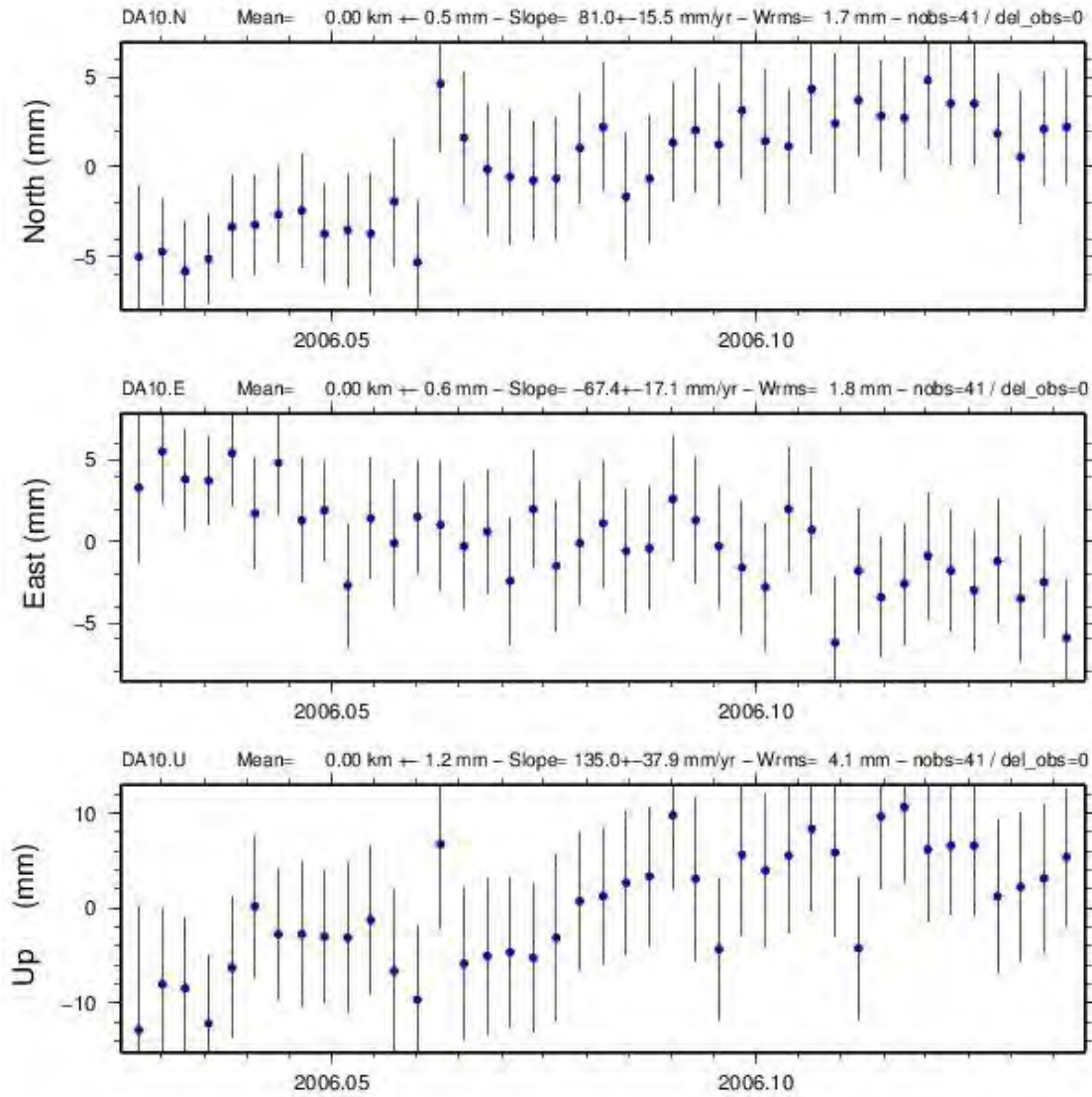


Figure to show Position time series for DA10 continuous GPS sites. Red dashed line indicates the time of dike events.

c)

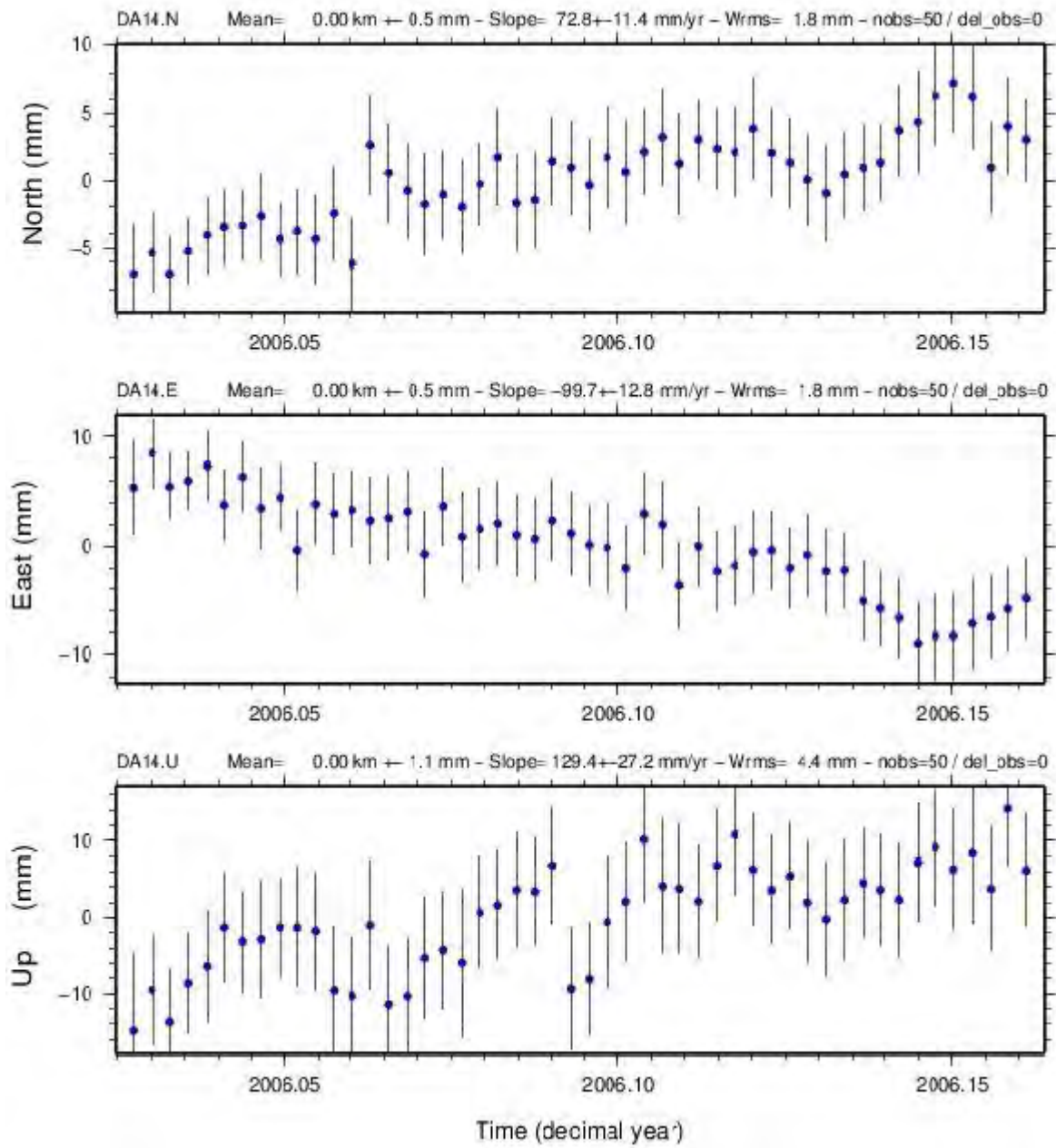


Figure to show Position time series for DA14 continuous GPS site.

d)

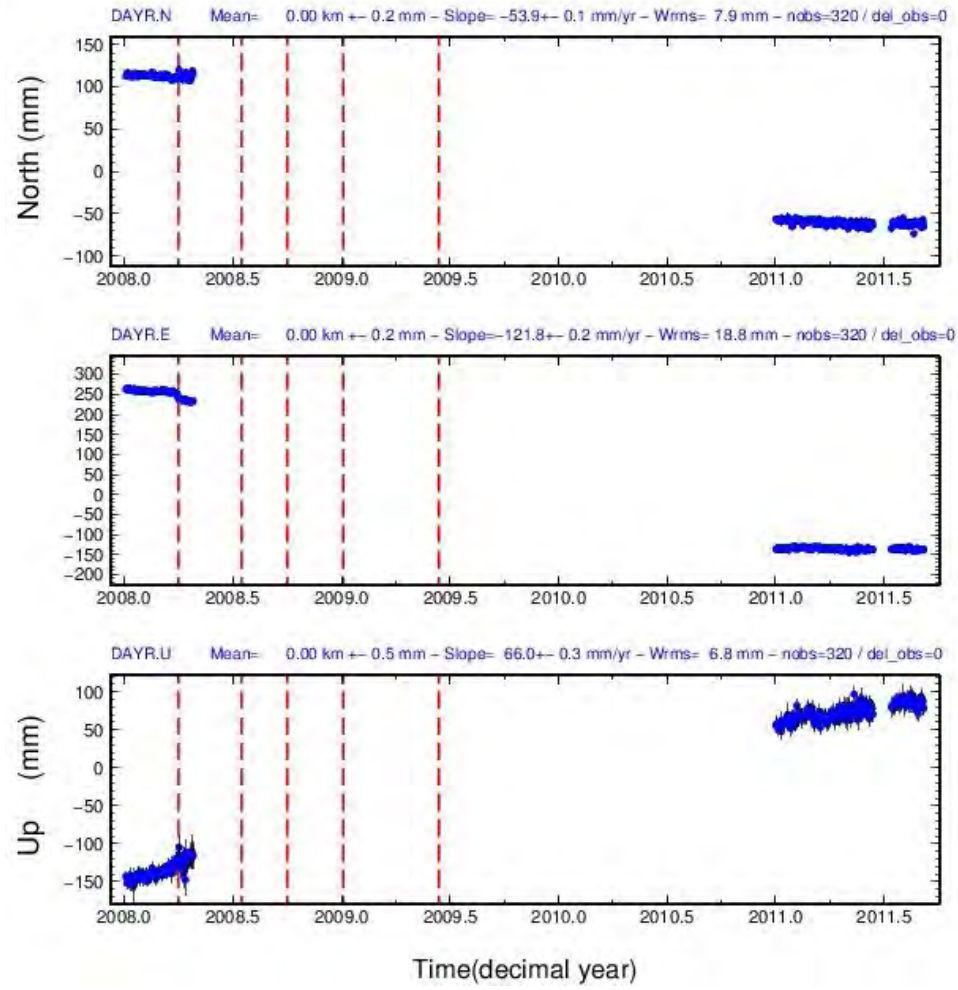


Figure to show Position time series for DAYR continuous GPS site.

e)

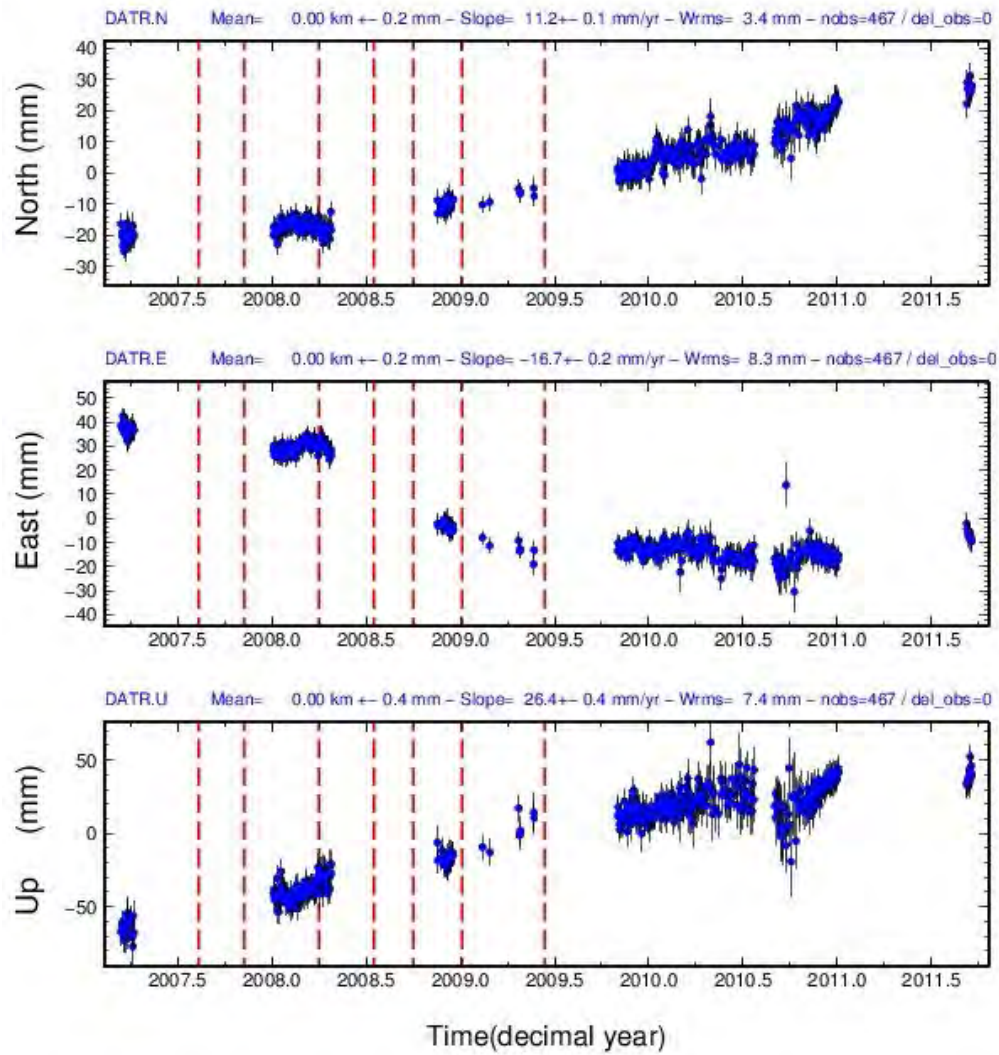
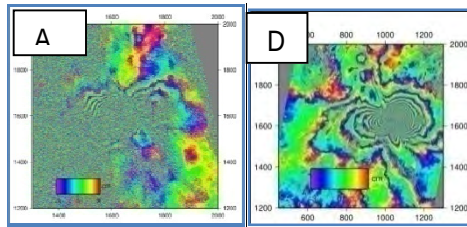


Figure to show Position time series for DATR continuous GPS site. Red dashed line indicates the time of diking events.

7.2 More figures on InSAR data

i)

a)



12/06/06-17/07/06 20/05/06-24/06/06

b)

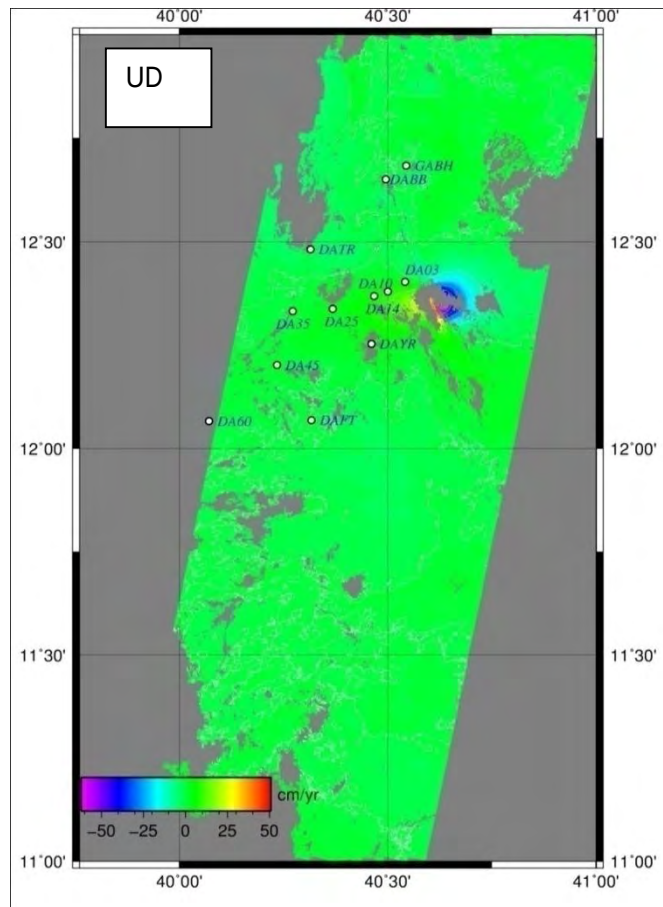
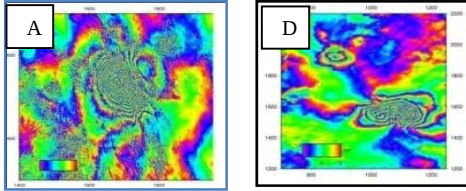


Figure to show the 17 June 2006 dyking event. A and D showing the fringes ascending and descending interferogram respectively and UD indicates Unwrapped descending interferogram covering the June 2006 dyke intrusion, blue colours indicate motion toward the satellite. The circles show the location of GPS sites around the rift segment.

ii)

a)



060624-060729 060717-060821

b)

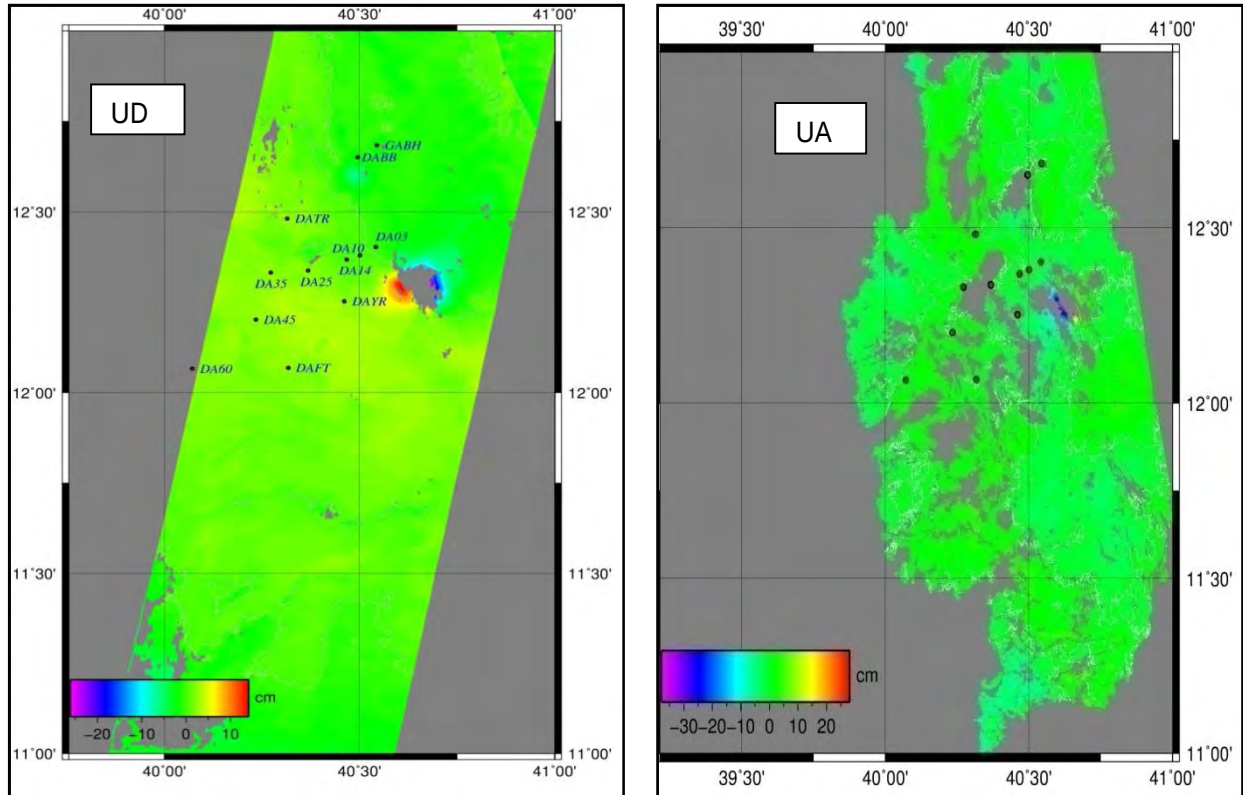
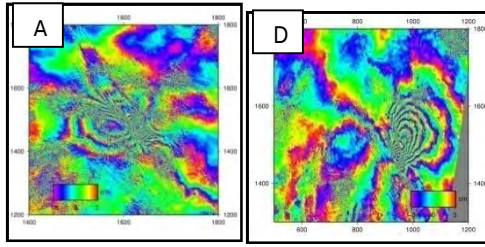


Figure to show the 24 July 2006 Dyking event A and D showing the fringes ascending and descending interferogram respectively ,UA and UD indicates Unwrapped ascending and descending interferogram covering the July 2006 dyke intrusion, blue colours indicate motion toward the satellite. Blue circles show the location of GPS sites around the rift segment.

iii)

a)



060821-060925 060902-061007

b)

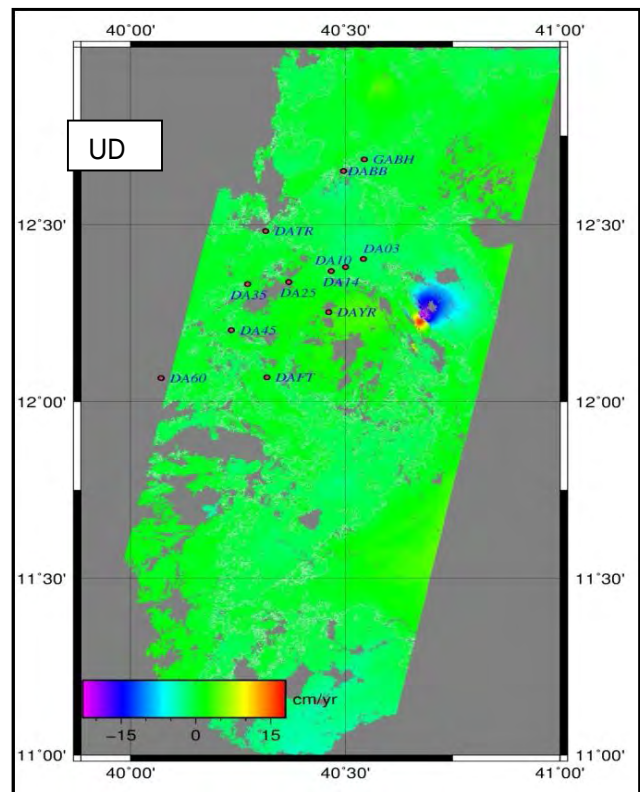
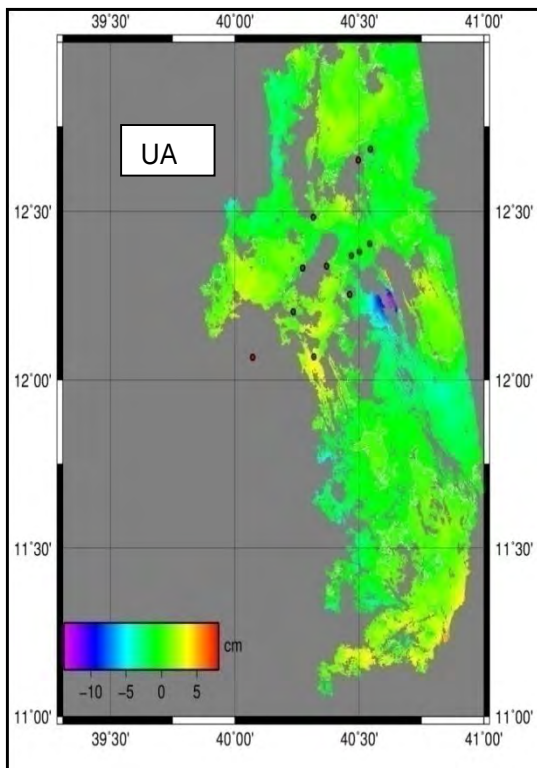
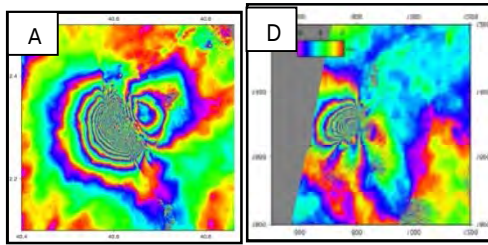


Figure to show the 10 September 2006 dyking event A and D showing the fringes ascending and descending interferogram respectively ,UA and UD indicates Unwrapped ascending and descending interferogram covering the July 2006 dyke intrusion, blue colours indicate motion toward the satellite. Red circles show the location of GPS sites around the rift segment.

iv)

a)



061204-070108 061220-070124

b)

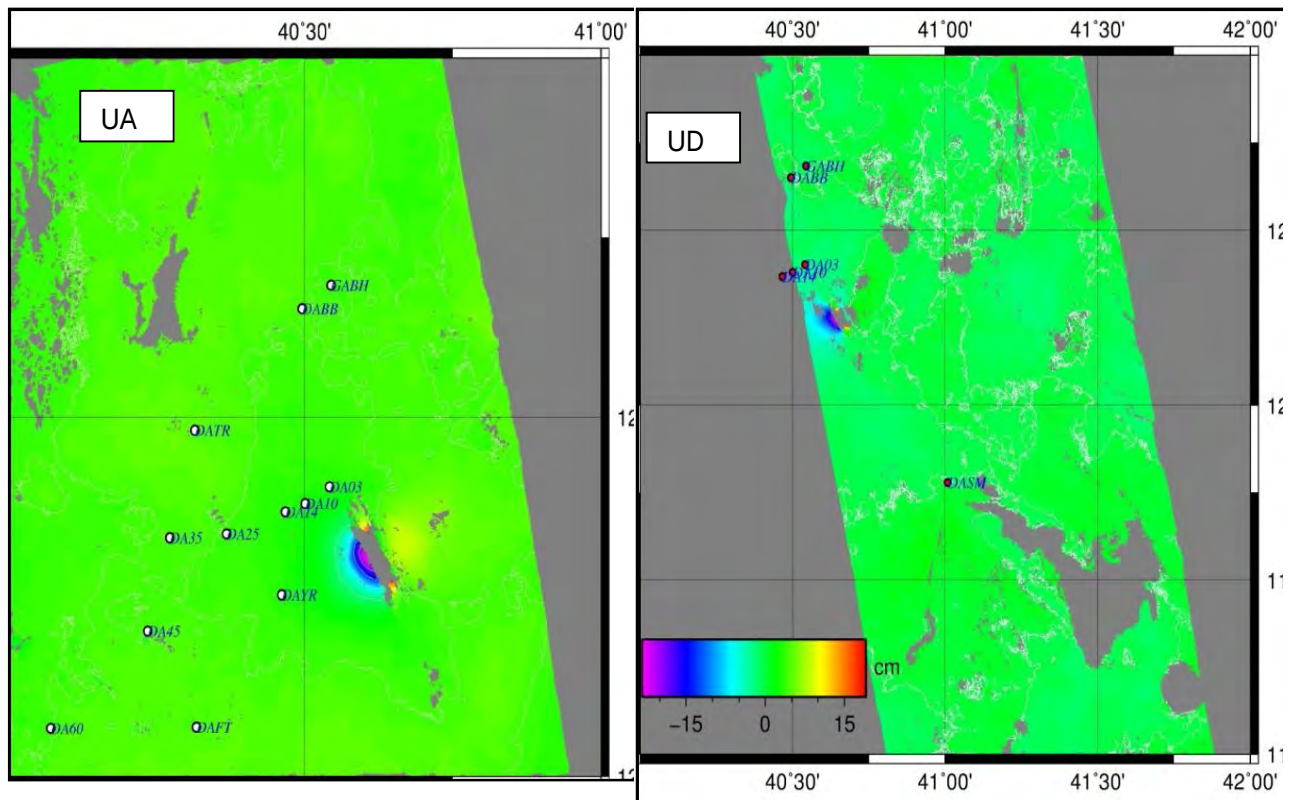
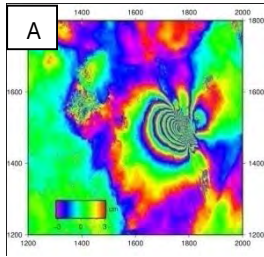


Figure to show the 7 December 2006 Dyking event A and D showing the fringes ascending and descending interferogram respectively ,UA and UD indicates Unwrapped ascending and descending interferogram covering the 7 December 2006 dyke intrusion, blue colours indicate motion toward the satellite. The circles show the location of GPS sites around the rift segment.

v)

a)



070108-070212

b)

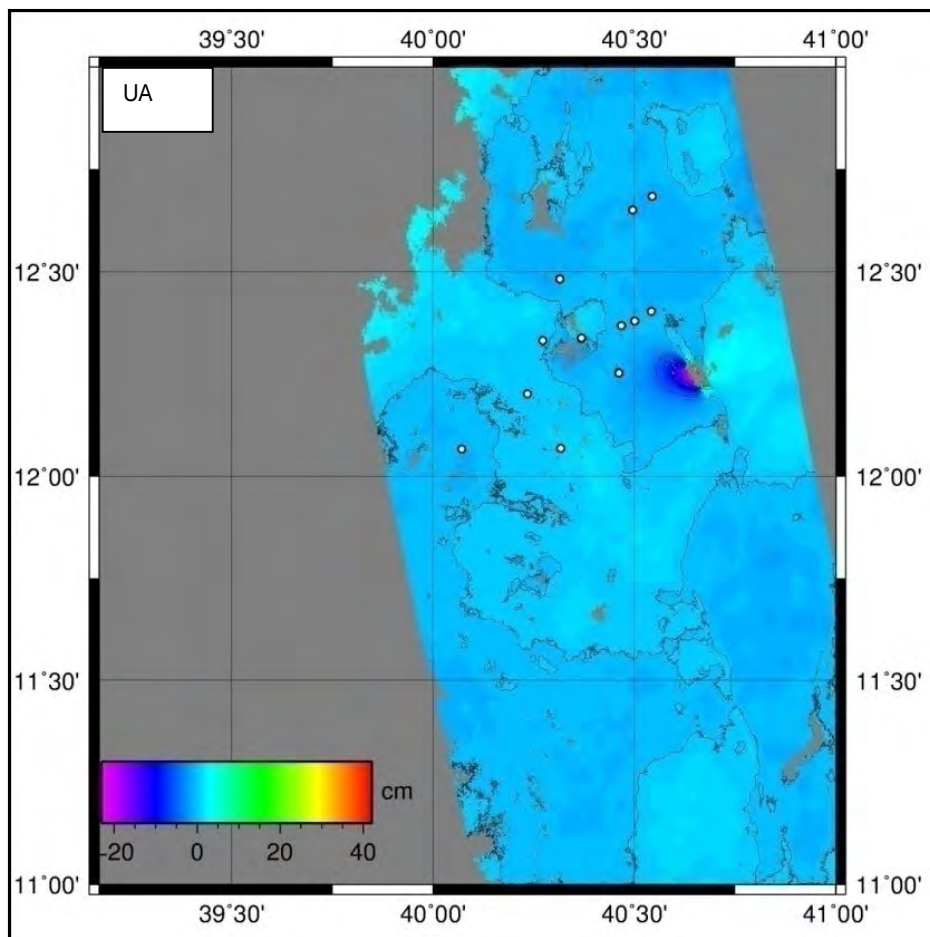
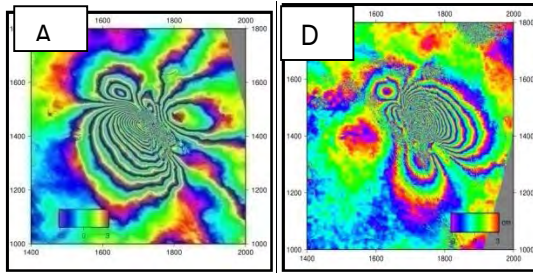


Figure to show the 14 January 2007 Dyking event A showing the fringes ascending interferogram whereas UA indicates Unwrapped ascending interferogram covering the 14 January 2007 dyke intrusion, blue colours indicate motion toward the satellite. White circles show the location of GPS sites around the rift segment

vi)

a)



071015-071119 071102-071207

b)

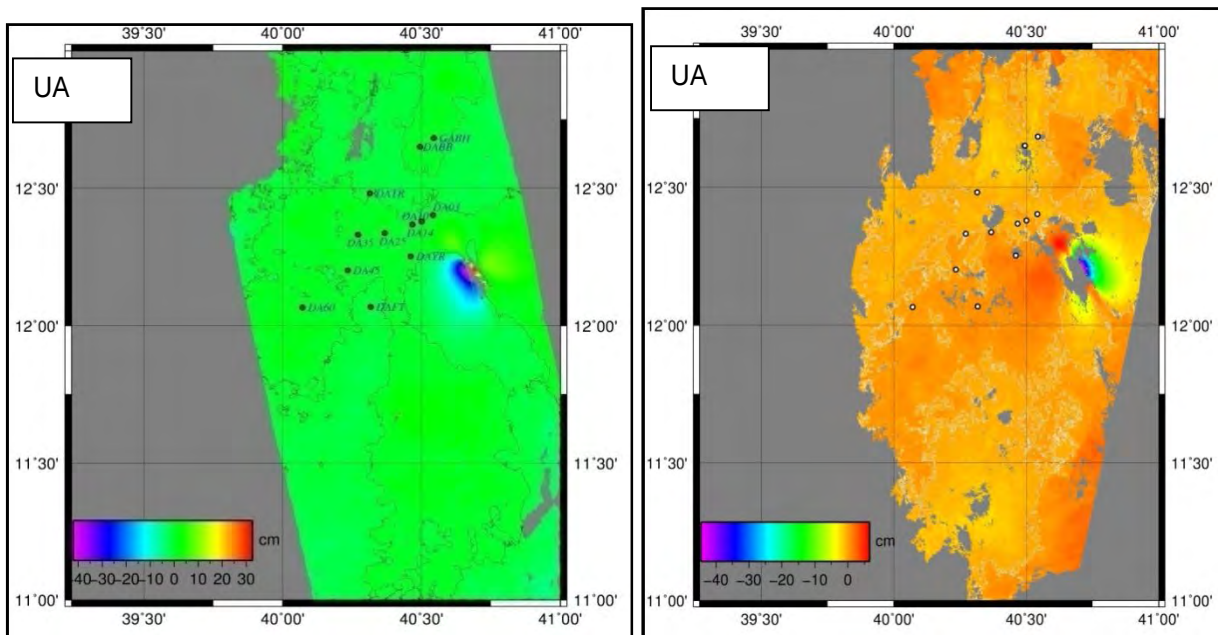
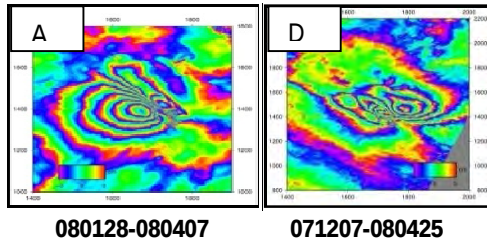


Figure to show the 11 November 2007 Dyking event A and D showing the fringes ascending and descending interferograms, UA and UD indicates Unwrapped ascending and descending interferogram covering 11 November 2007 dyke intrusion, blue colours indicate motion toward the satellite. The circles show the location of GPS sites around the rift segment.

vii)

a)



b)

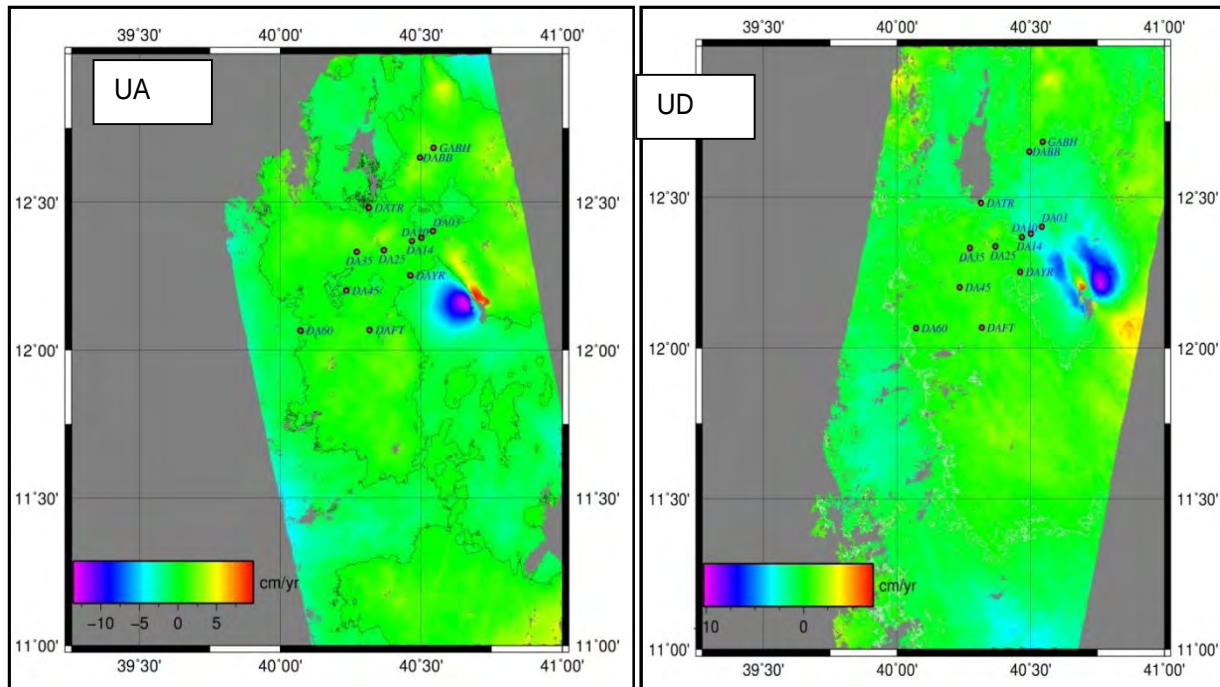
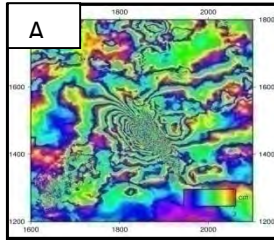


Figure to show the April 2008 dyking event A and D showing the fringes ascending and descending interferograms ,UA and UD indicates Unwrapped ascending and descending interferogram covering April 2008 dyke intrusion, blue colours indicate motion toward the satellite. The circles show the location of GPS sites around the rift segment.

viii)

a)



080616-080721

b)

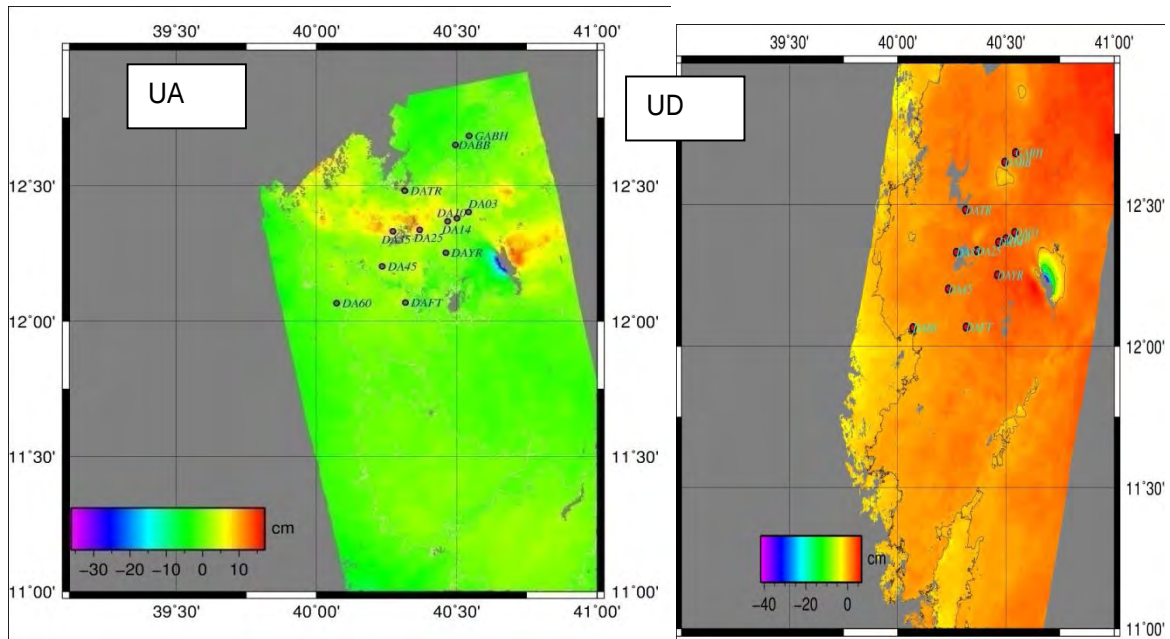
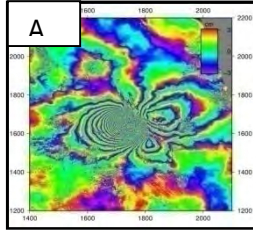


Figure to show the July 2008 dyking event: A showing the fringes ascending interferograms, UA and UD indicates Unwrapped ascending and descending interferogram covering July 2008 dyke intrusion, blue colours indicate motion toward the satellite. The circles show the location of GPS sites around the rift segment.

ix)

a)



080929-081103

b)

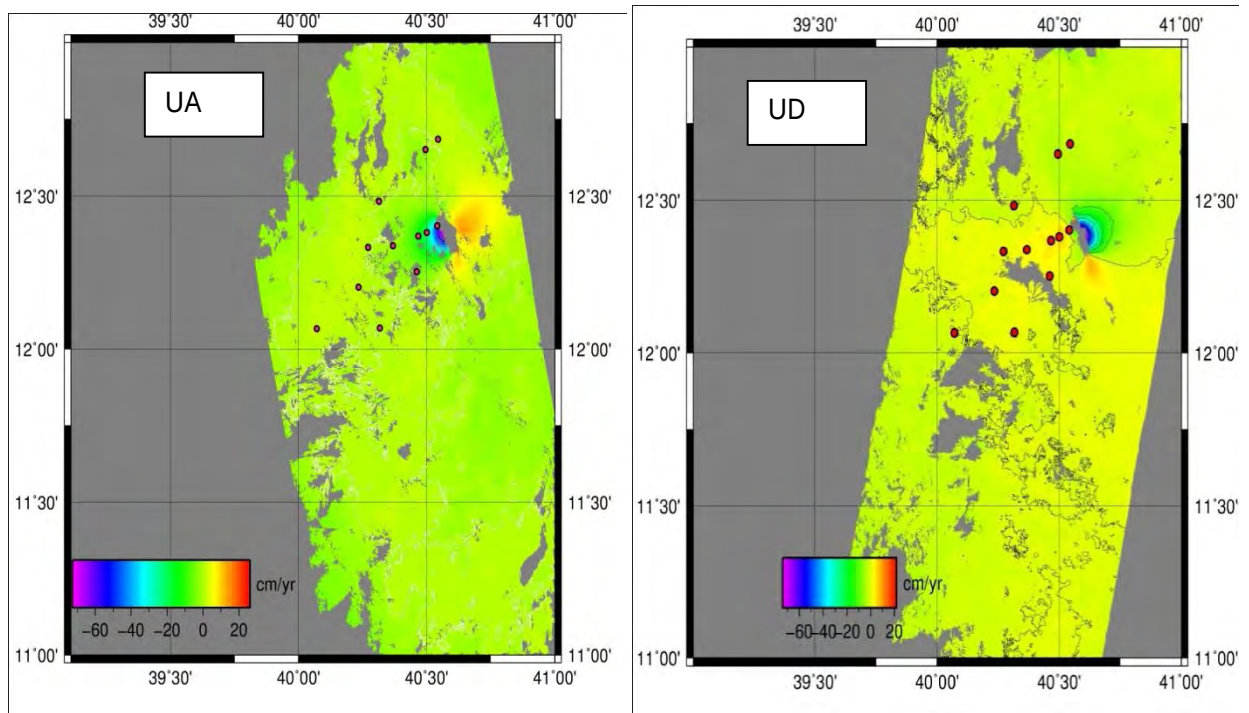
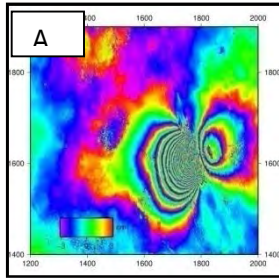


Figure to show the October 2008 dyking event :A showing the fringes ascending interferograms, UA and UD indicates Unwrapped ascending and descending interferogram covering October 2008 dyke intrusion, blue colors indicate motion toward the satellite. The circles show the location of GPS sites around the rift segmente

x)

a)



090112-090216

b)

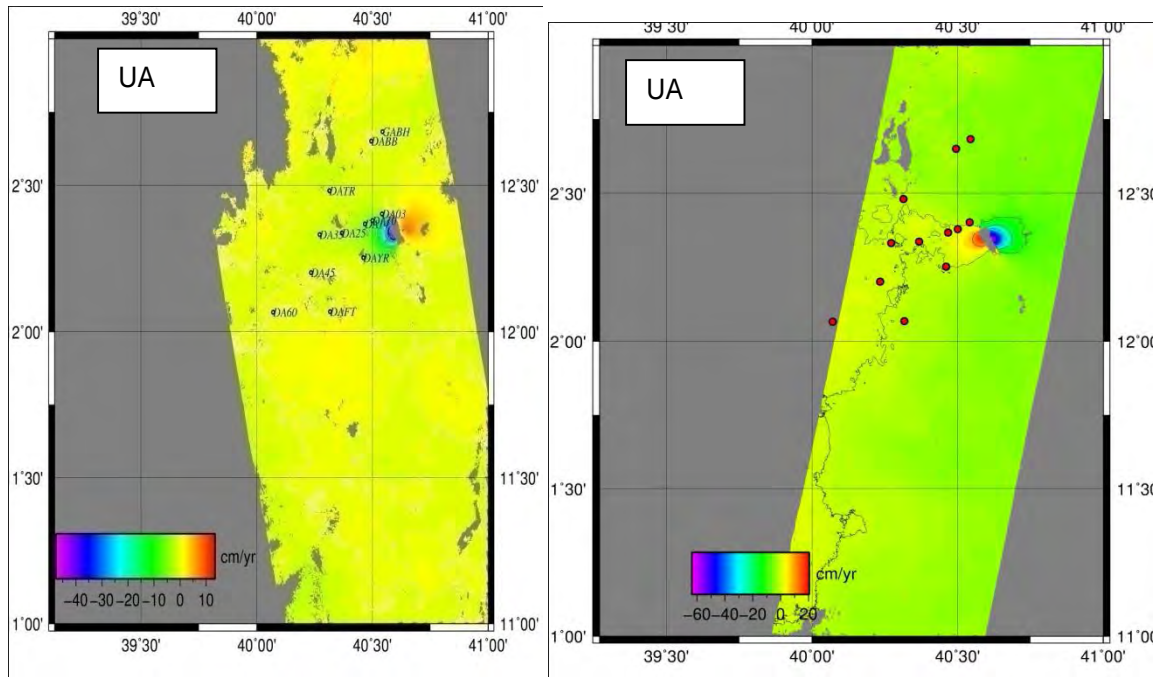
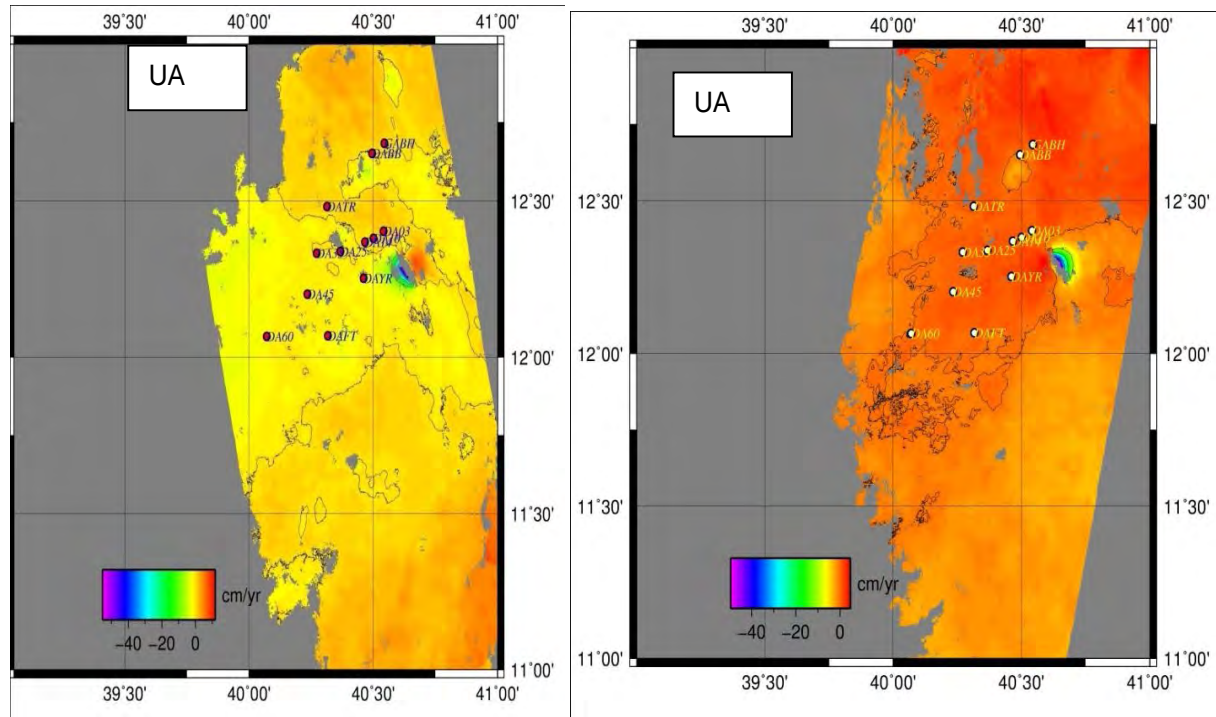


Figure to show the February 2009 Dyking event :A showing the fringes ascending interferograms, UA and UD indicates Unwrapped ascending and descending interferogram covering February 2009 dyke intrusion, blue colors indicate motion toward the satellite. The circles show the location of GPS sites around the rift segment

xi)



090601-090706 090515-090724

Figure to show the June 2009 dyking event :UA and UD indicates Unwrapped ascending and descending interferogram covering June 2009 dyke intrusion, blue colors indicate motion toward the satellite. The circles show the location of GPS sites around the rift segment.

Declaration

“This thesis is my original work and has been presented for degree of in any other university, and that all source of material used for the thesis have been duly acknowledged

SUMMITTED BY:

Esubalew Adem Yibrie

Signature

Date

CONFIRMATION

Dr. –Ing Elias Lewi

Advisor

Signature

Date