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Geodesy and Geomatics MSc Program

Monitoring Ground Surface Deformation of Fentale Volcano using Sentinel-1 InSAR Data: A Case Study of the Northern Main Ethiopian Rift

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A Thesis Submitted to School of Graduate Studies of Addis Ababa University in Partial fulfillment of the Requirements for the Degree of Master of Science in Geodesy and Geomatics program (**specialization in Geodesy**)

July, 03, 2024

Addis Ababa, Ethiopia

DECLARATION

This is to certify that this thesis entitled "**Monitoring Ground Surface Deformation of Fentale Volcano using Sentinel-1 InSAR Data: A Case Study of the Northern Main Ethiopian Rift"** is my original work completed under the supervision of **Dr. Andenet Ashagrie,** and that it has not been submitted for a degree at any other university, and all sources of materials used for this thesis work have been properly acknowledged.

Abdi Abdulahi Mohammed ______________ ________________

Name of Student Signature Date

I hereby certify that I have read and evaluated this MSc thesis

Dr. Andenet Ashagrie ________________ _______________

Name of Advisor Signature Date

APPROVAL SHEET

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The undersigned have examined the thesis entitled as “**Monitoring Ground Surface Deformation of Fentale Volcano using Sentinel-1 InSAR Data: A Case Study of the Northern Main Ethiopian Rift”** presented by Abdi Abdulahi Mohammed, a candidate for the **Degree of Master of science in Geodesy and Geomatics** with **specialization in Geodesy** and hereby certify that it is worthy of acceptance.

Approved By the Board of Examiners:

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Abstract

Ground surface deformation caused by volcanic activity serves as a critical indicator of subsurface magmatic processes that can lead to eruptions. This study focuses on Fentale Volcano, located in the Northern Main Ethiopian Rift, which is an active volcano that has experienced periodic eruptions and unrest. Limited geodetic monitoring has restricted comprehensive understanding of deformation patterns at the volcano due to the shortcomings of traditional methods. Meanwhile, InSAR enables effective and cost-efficient analysis over large areas. We utilized InSAR data from the Sentinel-1 satellite mission to analyze ground surface deformation patterns from both ascending (2015-2017) and descending (2015-2022) orbits obtained through the COMET-LiCSAR portal. Therefore, the analysis results were revealed complex patterns of ground uplift, subsidence, and lateral displacement, with mean deformations of -7.36 mm for ascending data and -3.66 mm for descending data. The maximum annual uplift and subsidence velocities were recorded at 17 cm/yr and -23 cm/yr for ascending data, and 50 cm/yr and -43 cm/yr for descending data, respectively. These findings indicate ongoing active deformation, suggesting dynamic magmatic processes within the volcano. Validation of displacement measurements showed a high coefficient of determination (R^2 = 0.87) between the ascending and descending datasets. This research demonstrates the effectiveness of Sentinel-1 InSAR for long-term monitoring of volcanic ground deformation, enhancing our understanding of Fentale Volcano's behavior and the associated hazards for nearby communities.

Keywords: *Fentale Volcano, Ground Deformation, InSAR, Main Ethiopian Rift, Sentinel-1, volcano monitoring*

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List of Abbreviations

ALOS	Advanced Land Observation Satellite
COMET	Centre for the Observation and Modelling of Earthquakes, Volcanoes and Tectonics
CSV	Common-Separated Values
DEM	Digital Elevation Model
D-InSAR	Differential interferometric Synthetic Aperture Radar
EARS	East African Rift System
ENVISAT	Environmental Satellite
ESA	European Space Agency
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
InSAR	Interferometry Synthetic Aperture Radar
LiCS	Looking inside the Continents from Space
LOS	Line of sight
MER	Main Ethiopian Rift
PS-InSAR	Persistent Scatterer Interferometric Synthetic Aperture Radar
SAR	Synthetic Aperture Radar
SBAS	Small Baseline Subset
SRTM	Shuttle Radar Topography Mission
TOPS	Terrain Observation with Progressive Scans

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Volcanic activity is a critical geological phenomenon that significantly impacts both the environment and human society. The Main Ethiopian Rift, where Fentale Volcano is located, is characterized by active tectonic processes, including volcanic eruptions and seismic events. This rift system represents a zone where the African Plate is gradually splitting into two smaller plates, creating a complex interplay of geological forces (Ebinger et al., 2000). Understanding the dynamics of volcanic systems in this region is essential for effective hazard assessment and risk mitigation, especially given the historical significance of eruptions and the potential -for future volcanic activity.

Fentale Volcano has a notable history of eruptions, with significant activity recorded during the late Quaternary period. This volcano is characterized by fumarolic activity, indicating ongoing magmatic processes beneath the surface (Mohr, 1962; Chernet et al., 1998). These features make Fentale an important focus for volcanic monitoring, as the deformation of the ground surface serves as a crucial indicator of volcanic unrest. Ground surface deformation often precedes volcanic eruptions, making it a vital parameter for understanding and predicting volcanic behavior (Dzurisin, 2007). By monitoring these deformation patterns, researchers can gain insights into the movement of magma and the pressure changes within the volcanic system, ultimately contributing to enhanced volcanic hazard assessments.

Historically, monitoring volcanic deformation has relied on conventional geodetic techniques such as Global Positioning System (GPS) and traditional leveling surveys. While these techniques provide valuable data, they are often limited in spatial coverage and temporal resolution, making it challenging to capture the full dynamics of volcanic behavior over large areas (Massonnet & Feigl, 1998). The sparse geodetic networks in many volcanic regions, including Fentale, further exacerbate these challenges, resulting in a fragmented understanding of volcanic processes and behaviors.

Advancements in remote sensing technology, particularly the development of Interferometric Synthetic Aperture Radar (InSAR), have revolutionized the field of volcanic monitoring. InSAR allows for the detection of ground deformation over extensive areas with millimeter precision, regardless of weather conditions (Hooper et al., 2012). The launch of the Sentinel-1 satellite constellation by the European Space Agency (ESA) in 2014 has significantly enhanced the capabilities of InSAR by providing free and open access to high-resolution Synthetic Aperture Radar (SAR) data with a rapid revisit time. This development has made it possible to conduct systematic monitoring of ground deformation at a global scale, providing researchers with a powerful tool for analyzing volcanic activity (Hooper et al., 2019; Morishita et al., 2020).

The utilization of InSAR technology is particularly relevant for Fentale Volcano, where traditional monitoring methods have fallen short. The ability to analyze large datasets generated by Sentinel-1 opens new avenues for understanding the volcano's behavior and the underlying magmatic processes. By employing InSAR, researchers can identify spatial deformation patterns, analyze the temporal evolution of these patterns, and enhance the predictive capabilities regarding volcanic unrest.

In summary, the study of ground surface deformation at Fentale Volcano using InSAR data is not only timely but necessary due to the combined factors of ongoing volcanic activity, the limitations of traditional monitoring methods, and the advancements in remote sensing technology. This research seeks to fill the knowledge gaps surrounding the volcano's behavior, ultimately contributing to improved monitoring, hazard assessment, and risk mitigation strategies for the communities residing in the vicinity of Fentale Volcano.

1.2 Statement of problem

Volcanic activity along the Main Ethiopian Rift presents considerable hazards to the surrounding communities, with the potential for catastrophic events such as explosive eruptions, lava flows, pyroclastic flows, and lahars (Tilling, 1989). Among the active geological features in this region, Fentale Volcano stands out due to its history of eruptions and persistent fumarolic activity, indicating ongoing magmatic and hydrothermal processes beneath the surface (Mohr, 1962; Chernet et al., 1998). As such, monitoring the behavior of Fentale Volcano is critical for understanding the underlying volcanic dynamics and mitigating associated risks.

The ongoing magmatism and rifting processes in the Ethiopian Rift generate complex, regional deformation fields that necessitate systematic mapping to effectively characterize volcanic hazards. Despite the recognized importance of monitoring ground surface deformation, the spatial distribution and temporal evolution of these deformations at Fentale Volcano remain inadequately understood (Hutchison et al., 2019). Ground deformation monitoring is essential, as it provides critical insights into subsurface magmatic systems, which can serve as indicators of volcanic unrest and potential eruption scenarios (Dzurisin, 2007). An improved understanding of these deformation patterns can significantly enhance risk assessment and preparedness for communities living in proximity to the volcano.

Historically, the monitoring of ground deformation at Fentale Volcano has been hampered by a lack of comprehensive geodetic instrumentation and insufficient data availability. Conventional in-situ techniques, such as GPS and leveling surveys, are limited in their spatial coverage and often prohibitively costly to deploy across expansive volcanic regions (Massonnet & Feigl, 1998). As a result, previous studies have struggled to accurately capture the dynamic behavior of Fentale Volcano, leading to a fragmented understanding of its volcanic activity and an incomplete assessment of associated hazards. The reliance on sparse geophysical monitoring networks has left critical knowledge gaps that need to be addressed to ensure effective risk mitigation strategies.

In light of these challenges, the advent of InSAR technology, particularly the recent availability of open-access Sentinel-1 Synthetic Aperture Radar (SAR) data, offers a promising solution to the limitations posed by conventional monitoring methods. InSAR enables the mapping of ground deformation with millimeter precision over broad geographic areas, facilitating comprehensive monitoring of volcanic processes (Massonnet & Feigl, 1998). By harnessing this advanced remote sensing technique, researchers can overcome the constraints of traditional geodetic approaches, allowing for more effective assessments of deformation patterns and their relationship to volcanic activity.

The primary problem addressed by this research was the urgent need to characterize the spatial and temporal patterns of ground surface deformation at Fentale Volcano using Sentinel-1 InSAR data. This study aims to leverage the capabilities of InSAR technology to transcend the limitations of conventional monitoring methods and fill the existing knowledge gaps regarding the volcano's behavior. By utilizing this remote sensing approach, the research seeks to enhance the understanding of deformation signals and their correlation with volcanic processes, thereby improving monitoring efforts, hazard assessments, and risk mitigation strategies in regions where geophysical monitoring networks are limited.

1.3 Objective of the Study

1.3.1 General Objective

The main objective of this study was to monitoring the ground surface deformation of Fentale Volcano using Sentinel-1 InSAR Data.

1.3.2 Specific Objectives

To identify the spatial distribution and patterns of ground surface deformation in the study area using Sentinel-1 InSAR data.

To analyze the temporal evolution of ground surface deformation around Fentale Volcano over time using Sentinel-1 InSAR data.

1.4 Research Questions

What are the deformation patterns observed in Fentale Volcano using Sentinel-1 InSAR data?

How does the temporal evolution of ground surface deformation contribute to understanding Fentale Volcano's activity?

1.5 Scope of the Study

The scope of the study was focused on the monitoring of ground surface deformation of Fentale Volcano in the Northern Main Ethiopian Rift. The study utilizes Sentinel-1 InSAR (Interferometric Synthetic Aperture Radar) data to analyze the spatial distribution and temporal evolution of ground deformation. The analysis includes both ascending and descending datasets from 2015 to 2022. The study aims to understand the behavior of Fentale Volcano, including uplift, subsidence, and lateral displacement, and to contribute to the identification of potential hazards associated with the volcano. The research specifically focuses on the use of Sentinel-1 InSAR data for long-term monitoring of volcanic areas and enhancing preparedness and response strategies for volcanic activity in the region of Fentale Volcano.

1.6 Significance of the Study

The significance of the study lies in its contribution to the understanding and management of volcanic hazards, specifically focusing on Fentale Volcano in the Northern Main Ethiopian Rift. The study aims to monitor ground surface deformation using Sentinel-1 InSAR data, providing valuable insights into the spatial distribution and temporal evolution of deformation patterns. By utilizing the capabilities of InSAR data, the significance of this thesis research on monitoring ground surface deformation of Fentale

Volcano using Sentinel-1 InSAR data can be classified into five groups based on its scientific achievements. Firstly, by analyzing ground surface deformation, the study enhances our understanding of the behavior of Fentale Volcano. This information is crucial for assessing volcanic hazards and identifying potential risks to nearby communities and infrastructure. It allows for a more accurate evaluation of the volcano's activity level and potential eruption scenarios. Secondly, the research contributes to the development of effective monitoring systems and early warning mechanisms. By utilizing Sentinel-1 InSAR data, the study enables a detailed analysis of ground surface deformation, providing timely information on changes occurring at the volcano. This data can be integrated into existing monitoring frameworks to enhance preparedness and response strategies for volcanic activity in the region. Thirdly, the study validates the use of Sentinel-1 InSAR data for long-term monitoring of volcanic areas. By comparing the results with previous studies, it demonstrates the reliability and usefulness of this remote sensing technique in capturing spatial and temporal deformation patterns. This supports the establishment of a continuous monitoring system for Fentale Volcano and other volcanic regions.

Fourthly, the research contributes to the scientific knowledge and understanding of volcanic activity in the Ethiopian Rift Valley. It adds to the existing literature on ground surface deformation and geodetic monitoring techniques, particularly in the context of volcanic areas. The methodology and findings can serve as a reference for future studies and related research endeavors.

Overall, the study's significance lies in its potential to improve volcanic hazard assessment, facilitate early warning systems, support long-term monitoring efforts, and advance scientific knowledge in the field of volcanology.

1.7 Limitation of the Study

The present study acknowledges and recognizes several limitations that were encountered during the research process. These limitations include: data availability acquiring an adequate amount of Sentinel-1 data within the download quotas posed a significant challenge. This limitation may have affected the comprehensiveness and accuracy of the study's findings. Processing complexity developing advanced InSAR skills through self-learning is a time-consuming process. The researchers had to invest a considerable amount of time in acquiring the necessary expertise to analyze and interpret the data correctly.

Temporal/spatial resolution, the study faced challenges related to temporal baselines, which resulted in increased decorrelation over vegetation. Additionally, the spatial resolution of the data might have limited the detection of small-scale features, potentially impacting the precision of the results. Atmospheric artifacts tropospheric delays can introduce errors in InSAR measurements. Software constraints the advanced analysis of InSAR data required proficiency in MATLAB and Python coding. The researchers had to overcome the learning curve associated with these programming languages, which added complexity to the study. Lack of ground data the absence of in-situ measurements hindered direct validation of the study's findings. Instead, the researchers had to rely on indirect validation by comparing their results to previous studies. This reliance on indirect validation introduces some level of uncertainty. Despite the researchers' efforts to address these limitations systematically, it is important to acknowledge that some uncertainties may persist due to the inherent limitations of data availability, software tools, and the scope of a single study. These limitations should be considered when interpreting and generalizing the study's results.

1.8 Organization of the Thesis

This thesis is deals with the space technology datasets measurement for monitoring ground surface deformation in volcanic area and organized in five chapters: the first chapter Provide about the background information on the topic, statement of the problem, objectives of the study, research questions, scope, significance and the limitation of the study. This sets the context and outlines the purpose and focus of the research. Chapter two is an extensive reviews and synthesizes previous studies relevant to the research topic to establish the current state of knowledge and identify gaps of literature pertaining to the need for ground surface deformation monitoring, the causative factors of ground surface deformation with monitoring ground deformation techniques.

Chapter three; it is describe the study area, data sources and materials used. Presents the methodology and procedures employed to achieve the research objectives. Chapter four; Presents the key findings and outputs of the research. Includes maps, graphs and tables to illustrate results. Analyzes and discusses the results in relation to the objectives and research questions. Chapter five presents to summarizes the main conclusions drawn from the study and provides recommendations for future work and applications of the research.

CHAPTER TWO

LITERATURE REVIEW

This literature review examines the use of Interferometric Synthetic Aperture Radar (InSAR) data for monitoring ground surface deformation at Fentale Volcano in Ethiopia. The review covers the importance of volcanic deformation monitoring, the principles of InSAR technology, and the application of InSAR to study Fentale Volcano.

2.1 Background

Volcanic activity was recognized as a powerful natural phenomenon characterized by the movement of magma, gases, and various materials from beneath the Earth's crust to its surface. This activity often resulted in ground surface deformation, which served as a critical indicator of the underlying magmatic dynamics (Dzurisin, 2007; Sigmundsson, 2006). Understanding ground surface deformation was particularly essential in regions with active volcanism, such as the Main Ethiopian Rift, where the complex interactions between tectonic forces and volcanic activity created a dynamic geological environment.

Fentale Volcano, situated within this rift, had a significant history of eruptions, with notable activity recorded as recently as 1820 (Abebe et al., 2007; Acocella & Korme, 2002). The patterns of ground deformation observed at Fentale were crucial for assessing volcanic hazards and developing effective monitoring strategies capable of providing early warnings to local communities. As magma accumulated within the volcanic system, it exerted pressure on the surrounding rocks, leading to deformation of the ground surface. This deformation often manifested as inflation prior to an eruption and deflation afterward (Segall, 2010; Pinel et al., 2011).

Traditional monitoring methods, including Global Positioning System (GPS) measurements and leveling surveys, offered limited spatial and temporal coverage (Massonnet & Feigl, 1998). This limitation prompted interest in advanced remote sensing techniques such as Interferometric Synthetic Aperture Radar (InSAR), which provided millimeter-precision measurements of ground changes over extensive areas (Hooper et al., 2012). The introduction of the Sentinel-1 satellite constellation by the European Space Agency significantly enhanced the capacity for systematic monitoring of ground deformation at Fentale, facilitating more effective volcanic hazard assessments (Hooper et al., 2019).

The application of InSAR technology to Fentale Volcano yielded important insights into its volcanic processes. Previous studies employing InSAR successfully revealed significant deformation patterns associated with magma movement at Fentale (Biggs et al., 2011, 2013; Hutchison et al., 2016). By analyzing these deformation patterns, researchers could gain a deeper understanding of the relationship between magmatic processes and surface expressions, ultimately improving monitoring and risk management strategies.

In conclusion, the study of volcanic ground surface deformation at Fentale Volcano using InSAR data proved vital for enhancing the understanding of volcanic behavior and improving hazard assessments in the region.

2.2 The Concept of Volcanoes

Volcanoes, awe-inspiring natural wonders, captivated humanity for centuries, playing a significant role in shaping the Earth's surface. Understanding volcanoes and their associated ground surface deformation was crucial for predicting potential hazards. Volcanic activity resulted from internal movements within the Earth, transporting magma, gases, and ash to the surface, where eruptions occurred through vents or fissures (Tilling, 2009).

Vents served as openings for explosive eruptions, forming conical volcanoes, while fissures allowed for gentle outpourings of lava, creating lava plateaus (Tilling, 2009). Explosive eruptions could leave large craters, or calderas, which sometimes filled with water to form lakes, such as Ethiopia's Lakes Zuquala, Wonchi, and Dendi. Future eruptions within these calderas could lead to the formation of new volcanic cones (Guffanti & Mayberry, 2008).

Additionally, magma that crystallized underground formed various geological structures, including batholiths, laccoliths, dikes, and sills (Tilling, 2009). InSAR technology employed satellite-based synthetic aperture radar to measure ground surface deformation by comparing radar images over time. This understanding of volcanic concepts was essential for interpreting geodetic observations related to subsurface magmatic processes at Fentale Volcano, ultimately aiding in the prediction of eruptions and assessment of hazards.

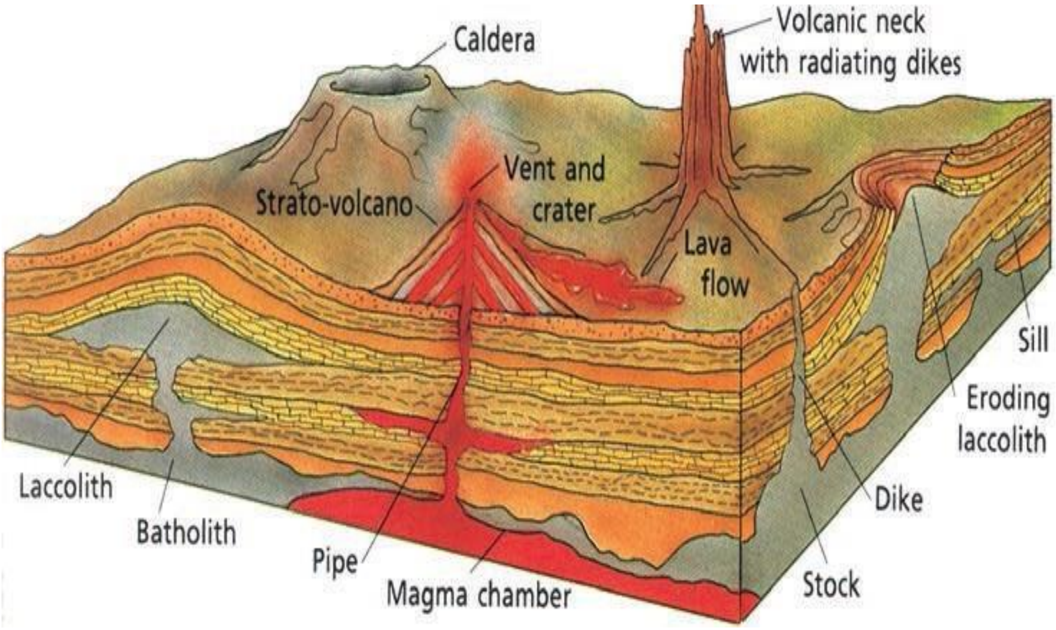

Figure 1 Types of volcanic intrusion and extrusion features

2.3 Volcanic Hazard in Ethiopia

Ethiopia, known for its rich cultural heritage and diverse landscapes, faced significant natural hazards, including volcanic eruptions. The country was home to 59 Holocene volcanoes, primarily distributed along the Main Ethiopian Rift and the Afar Depression (Abebe et al., 2007; Siebert et al., 2010). Many of these volcanoes exhibited mafic characteristics with effusive eruptions, while some had the potential to produce large ignimbrites (Abebe et al., 2007; Brown et al., 2015a). Although historical records of explosive eruptions were limited, the possibility of future Plinian eruptions could not be ruled out (Lenhardt & Oppenheimer, 2014).

The high exposure risk faced by the population posed a significant challenge. Over 1.5 million people lived within a 10-kilometer radius of a volcano, increasing their vulnerability (Brown et al., 2015a). Fentale Volcano, one of the most active volcanoes in Ethiopia, demonstrated ground surface deformation indicative of magma movement, which could lead to explosive eruptions and other hazards, such as pyroclastic flows and ash fall (Brown et al., 2015a).

To mitigate these risks, investments in enhanced instrumentation and public education were deemed crucial (Alcántara-Ayala, 2002). Effective monitoring systems and raising awareness among communities could significantly reduce the impacts of volcanic hazards. Understanding volcanic risks in Ethiopia was essential for ensuring the safety of the population, and advanced techniques like Sentinel-1 InSAR provided valuable insights into volcanic processes and eruption indicators.

2.4 Ground Surface Deformation

Ground surface deformation referred to the changes in the shape, elevation, and movement of the Earth's surface due to various natural processes, including tectonic activity, volcanic activity, and human-induced factors. Understanding ground surface deformation was essential for assessing geological hazards such as earthquakes, volcanic eruptions, and landslides, as well as for monitoring the stability of infrastructure and the environment (Massonnet & Feigl, 1998).

At Fentale Volcano, ground surface deformation represented a significant phenomenon that provided valuable insights into the volcanic processes occurring beneath the Earth's surface. This deformation involved alterations in the shape, elevation, and movement of the ground, manifesting over varying timescales. Ground deformation could take several forms, including uplift (vertical displacement), subsidence (vertical sinking), lateral displacement, and tilting of the Earth's surface. These changes were critical for understanding the behavior and dynamics of volcanic systems, aiding scientists in monitoring and interpreting volcanic activity (Segall, 2010).

The causes and patterns of ground surface deformation were crucial for assessing potential hazards associated with Fentale Volcano. By analyzing deformation data, researchers could gain insights into magma movement beneath the surface, indicating an impending eruption. This understanding helped improve monitoring strategies and hazard assessments, ultimately contributing to the safety and preparedness of communities living near the volcano (Hooper et al., 2012).

2.5 Causes of Ground Deformation

The primary cause of ground deformation at volcanoes was the movement of magma within the Earth's crust. As magma rose towards the surface, it displaced the surrounding rocks, leading to changes in the shape and elevation of the land. Several interconnected factors influenced the extent and nature of ground deformation, particularly at Fentale Volcano.

Magma Intrusion and Accumulation played a significant role in this process. Fentale Volcano was characterized by a magma chamber or reservoir beneath its surface. As magma ascended from deeper within the Earth, it intruded into the surrounding rocks, causing them to deform and uplift. The accumulation of magma exerted considerable pressure on the overlying rocks, resulting in ground surface deformation that could manifest as uplifted areas or even the formation of volcanic domes (Bishop et al., 2013).

Magma Migration further contributed to ground deformation. The movement of magma through fractures, conduits, and other pathways led to interactions with surrounding rocks, causing them to shift, crack, and deform. The direction and rate of magma migration influenced the deformation patterns observed at Fentale Volcano, revealing critical insights into volcanic activity (Tibaldi et al., 2012).

Another vital factor was Volcanic Gas Emissions. Gases such as water vapor, carbon dioxide, and sulfur dioxide, dissolved within the magma at high pressures and temperatures, played a crucial role in ground deformation. As magma approached the surface and pressure decreased, these gases escaped, creating pathways for magma migration and contributing to ground surface deformation. Additionally, the interaction of volcanic gases with groundwater could produce steam, further impacting ground deformation (Allard, 1997).

Tectonic Forces also influenced ground deformation at Fentale Volcano, situated in the tectonically active East African Rift. The movement of tectonic plates and associated stress could create fractures, faults, and structural features affecting magma behavior. This interaction between volcanic activity and tectonic forces contributed to the complex patterns of ground surface deformation observed (Ayele et al., 2007).

Lastly, Hydrothermal Systems, which involve circulation of hot water and steam, played a role in shaping ground deformation. The interaction between hydrothermal fluids and surrounding rocks could lead to alteration and weakening of materials, resulting in either subsidence or uplift of the ground surface, depending on the hydrothermal processes occurring at the volcano (Miller et al., 2006).

In summary, ground surface deformation at Fentale Volcano was a multifaceted phenomenon influenced by magma intrusion and migration, volcanic gas emissions, tectonic forces, and hydrothermal systems. By studying and monitoring these processes, scientists could gain a deeper understanding of volcanic activity, thereby enhancing safety measures for nearby communities.

2.6 Monitoring Ground Deformation

Ground surface deformation monitoring plays a crucial role in understanding volcanic activity and assessing the associated risks. By quantifying the spatial and temporal patterns of ground deformation, scientists can gain valuable insights into the behavior of volcanoes and their potential for eruption. Various techniques are used to monitor ground surface deformation associated with volcanic activity. These techniques can be broadly classified into two categories: geodetic and remote sensing methods. Geodetic methods involve the direct measurement of ground displacements using instruments such as GPS (Global Positioning System) receivers, tilt meters, and leveling surveys. GPS receivers provide precise measurements of ground movement by tracking the positions of multiple satellites. Tilt meters measure changes in the tilt of the ground, which can indicate the movement of magma beneath the surface. Leveling surveys involve measuring the height differences between fixed points on the ground to detect changes in elevation (Dzurisin, 2007).

Remote sensing methods utilize satellite-based sensors to measure ground deformations over large areas. One of the most widely used remote sensing techniques for volcanic monitoring is Interferometric Synthetic Aperture Radar (InSAR). InSAR uses radar signals to create high-resolution maps of ground displacement by measuring the phase difference between two radar images acquired at different times. This technique allows for the detection of even subtle deformations over wide areas (Massonnet & Feigl, 1998). By continuously monitoring ground deformations, scientists can detect precursory signals that indicate the potential for an eruption. Changes in ground elevation, tilting, or the opening of surface cracks can be early warning signs of volcanic unrest. Timely detection of these signals allows for the implementation of appropriate measures to mitigate risks and protect nearby communities (Dzurisin, 2007).

Ground surface deformation monitoring provides insights into the complex processes occurring beneath volcanoes. By analyzing the patterns and rates of deformation, scientists can infer the movement and accumulation of magma, the geometry of subsurface reservoirs, and the pathways through which magma ascends to the surface. This information improves our understanding of volcanic systems and aids in the development of accurate models for eruption forecasting (Lundgren & Samsonov, 2019). Accurate monitoring of ground surface deformation allows for the assessment of volcanic hazards and risks. By combining data from multiple monitoring techniques, such as seismic monitoring, gas analysis, and thermal imaging, scientists can develop comprehensive hazard maps and risk assessments. This information is vital for emergency response planning, evacuation strategies, and the development of effective mitigation measures (Berardino et al., 2002). Fentale volcano, located in Ethiopia, is an active volcano that has been the subject of extensive ground surface deformation monitoring using geodetic and remote sensing techniques. In particular, the application of InSAR using Sentinel-1 satellite data has provided valuable insights into the volcano's deformation history. By analyzing radar acquisitions spanning from 2014 to 2020, researchers have detected ground displacements indicative of magma accumulation and/or migration beneath Fentale volcano.

The spatial and temporal deformation patterns have been mapped, allowing for a better understanding of the volcano's plumbing system dynamics. These findings complement existing monitoring data and enhance eruption forecasting capabilities, contributing to improved risk assessments and emergency response planning for Fentale volcano (Berardino et al., 2002; Lundgren & Samsonov, 2019). Generally, ground surface deformation monitoring is a critical component of volcanic monitoring efforts. By utilizing geodetic and remote sensing techniques, scientists can accurately measure and analyze ground deformations associated with volcanic activity. This monitoring provides early warning of eruptions, improves our understanding of subsurface processes, helps assess hazards and risks, and aids in the development of effective mitigation strategies. The case study of Fentale volcano in Ethiopia demonstrates the practical application of these monitoring techniques and their contribution to eruption forecasting and emergency response planning.

2.6 Space Geodetic Techniques for Monitoring Ground Surface Deformation

There are different space geodesy techniques like GNSS, LLR, SLR, VLBI, GRACE, Satellite Altimetry and InSAR to determine the ground surface deformation. Ground surface deformation monitoring is a critical aspect of understanding geological processes and assessing potential hazards. In recent years, space geodetic techniques have revolutionized the field by enabling systematic and high-precision monitoring of surface deformation over large and inaccessible areas. In this thesis research focus on the utilization of Interferometric Synthetic Aperture Radar (InSAR) using data from the

Copernicus Sentinel-1 mission to study ground surface deformation, specifically at Fentale volcano.

2.6.1 Synthetic Aperture Radar

Synthetic Aperture Radar (SAR) is a crucial technology utilized by satellites to capture images of the Earth's surface using microwave pulses. Unlike optical sensors, SAR is not affected by weather conditions or sunlight, making it an ideal tool for monitoring ground surface deformation (Massonnet & Feigl, 1998). SAR sensors record both the amplitude and phase of the backscattered signals, providing valuable information about surface scattering properties and processes like lava deposition (Arnold et al., 2017; Dietterich et al., 2012; Wadge et al., 2011). The phase component of SAR data is particularly important for precise deformation measurements. It encodes the path delays between the sensor and the target, allowing scientists to accurately measure ground surface elevation changes (Massonnet & Feigl, 1998).

In the case of Fentale volcano, the Sentinel-1 mission operates in a polar sun-synchronous orbit, acquiring regular imagery of the volcano in both ascending and descending geometries. The C-band sensor on board Sentinel-1 has a repeat cycle of 6 days, which is reduced to 12 days when both Sentinel-1A and -1B are operational (Torres et al., 2012). For the specific study of Fentale volcano, interferograms are generated from Sentinel-1 TOPS (Terrain Observation by Progressive Scans) data spanning from 2015 to 2022. These interferograms are created by comparing the phase differences between acquisitions, which encode elevation changes. Through advanced timeseries analysis techniques, the spatiotemporal deformation field can be mapped, providing valuable insights into the dynamics of the volcano's plumbing system (Massonnet & Feigl, 1998). By characterizing ground displacements related to magmatic processes, InSAR enhances the monitoring and understanding of Fentale volcano, supporting integrated hazard assessments and emergency response planning.

The results obtained from the InSAR analysis using Sentinel-1 TOPS data contribute to a comprehensive understanding of Fentale volcano's behavior. By mapping the spatiotemporal deformation field, scientists can identify areas of significant ground displacement, monitor the evolution of deformation patterns over time, and gain insights into the dynamics of the volcano's plumbing system. This information is crucial for integrated hazard assessments, which aid in the development of effective emergency response plans to mitigate potential risks associated with volcanic activity. In conclusion, Synthetic Aperture Radar (SAR) technology, specifically the use of Sentinel-1 TOPS data, plays a vital role in monitoring ground surface deformation at Fentale volcano. The amplitude and phase information captured by SAR sensors provide valuable insights into surface scattering properties, lava deposition, and precise deformation measurements. By generating interferograms and analyzing the spatiotemporal deformation field, InSAR enhances our understanding of the volcano's plumbing system dynamics, supporting hazard assessments and emergency response planning.

2.6.2 SAR Interferometry

Synthetic Aperture Radar interferometry (InSAR) is a powerful technique used to measure surface deformation by analyzing the phase differences between co-registered SAR images (Massonnet & Feigl, 1998). In the context of this study, interferograms are generated from Sentinel-1 TOPS data spanning the period from 2015 to 2022. The process involves multiplying the phase component of the master image by the complex conjugate of the slave image, which allows for the determination of phase differences between acquisitions. These phase changes encode the range displacement between the satellite and the ground, along with some inherent noise. One important consideration in SAR interferometry is the correction of phase artifacts induced by baseline separation. SAR satellites follow slightly different orbits, resulting in variations in the baseline distance between acquisitions.

These variations introduce additional phase artifacts that need to be corrected using precise orbit data (Hanssen, 2001). By accounting for these baseline-induced artifacts, the accuracy of the interferometric measurements can be improved. At Fentale volcano, the interferometric phase signals obtained through InSAR analysis reveal the deformation of the volcanic edifice, which is directly related to magmatic processes occurring in the subsurface. The high coherence of natural targets, such as rock outcrops, allows for the mapping of ground displacements with millimeter precision over large areas surrounding the volcano. This level of precision is crucial for understanding the spatial distribution of deformation and its relationship to the volcano's magmatic system. To isolate the temporal deformation signals from interferometric data, a technique called Small BAseline Subsets (SBAS) analysis is employed. This technique effectively mitigates topographic and atmospheric artifacts, allowing for the extraction of meaningful temporal deformation patterns (Berardino et al., 2002). By applying the SBAS technique, researchers can focus on the variations in ground deformation over time, which provides valuable insights into the inflation and deflation behavior of Fentale volcano's magmatic system. The primary objective of this research is to enhance our understanding of Fentale volcano's magmatic system by characterizing its spatially and temporally varying inflation and deflation behavior through InSAR analysis. By mapping and analyzing the deformation patterns, scientists can gain valuable insights into the underlying processes driving volcanic activity.

These findings contribute to integrated monitoring efforts and support hazard assessments, which are crucial for assessing the potential risks associated with volcanic activity and developing effective mitigation strategies. In conclusion, Synthetic Aperture Radar interferometry (InSAR) is a powerful technique used to measure surface deformation. In the context of Fentale volcano, InSAR analysis of Sentinel-1 TOPS data allows for the generation of interferograms, which reveal the deformation of the volcanic edifice related to magmatic processes. By employing techniques such as baseline correction and SBAS analysis, researchers can accurately map and analyze the spatial and temporal variations in ground deformation. These insights contribute to a better understanding of Fentale volcano's magmatic system and support integrated monitoring efforts and hazard assessments.

2.6.3 Principles of Interferometric SAR for Monitoring Deformation at Fentale Volcano

Interferometric Synthetic Aperture Radar (InSAR) is a powerful technique employed in this study to characterize deformation at Fentale volcano. The principles of InSAR were first demonstrated in the 1990s and have since become a widely used method for measuring changes in the radar signal path length between acquisitions (Massonnet et al., 1993, 1995). By analyzing the phase differences in repeat-pass interferograms generated from co-registered SAR images, deformation signals can be extracted. The availability of Sentinel-1 data, which has been acquired every 6-12 days since 2014, provides an ideal dataset for this study.

Fentale volcano is located in the Afar region, which is an active rift zone. InSAR is particularly well-suited for monitoring in this region due to the challenges associated with accessibility. Conducting field-based measurements in remote and hazardous volcanic areas can be difficult and dangerous. However, satellite geodesy, such as InSAR, offers a safe and accessible alternative for widespread and long-term monitoring (Walters et al., 2011). The regular acquisitions of Sentinel-1 data also support responsive research, allowing for the rapid detection and analysis of signals related to volcanic unrest. This capability is crucial for monitoring volcanic activity and assessing potential hazards. By utilizing InSAR, researchers can detect and analyze deformation signals in near real-time, enabling a better understanding of the evolving behavior of Fentale volcano (Hamling et al., 2017).

In this research, InSAR is employed to study the multi-temporal deformation at Fentale volcano using two main analysis techniques: Small BAseline Subsets (SBAS) and Persistent Scatterer (PS) time series analysis. The SBAS technique mitigates topographic and atmospheric artifacts, allowing for the isolation of meaningful temporal deformation signals. On the other hand, PS analysis focuses on the identification and analysis of persistent scatterers, which are stable radar targets that provide valuable information about ground deformation over time. The insights gained from this study using InSAR analysis contribute to the scientific understanding of Fentale volcano's deformation behavior. By characterizing the spatial and temporal variations in deformation, researchers can improve hazard assessments in this remote region.

Understanding the patterns and dynamics of deformation is crucial for assessing the potential risks associated with volcanic activity and developing effective mitigation strategies. In conclusion, the principles of Interferometric Synthetic Aperture Radar (InSAR) are utilized in this study to monitor deformation at Fentale volcano. By analyzing the phase differences in repeat-pass interferograms generated from co-registered SAR images, deformation signals can be extracted. The availability of Sentinel-1 data, along with the advantages of satellite geodesy, enables widespread and long-term monitoring in the challenging and remote Afar region.

The regular acquisitions of Sentinel-1 data also support responsive research, allowing for the rapid detection and analysis of volcanic unrest signals. The utilization of InSAR, combined with SBAS and PS time series analysis, provides valuable insights into Fentale volcano's deformation behavior and contributes to improved scientific understanding and hazard assessments in this remote region.

2.6.4 Differential SAR Interferometry

Differential SAR Interferometry (DInSAR) is a valuable technique employed in this study to characterize deformation at Fentale volcano. DInSAR takes advantage of the phase differences between co-registered SAR images acquired at different times (Massonnet & Feigl, 1998). By forming interferograms from repeat-pass Sentinel-1 TOPS data spanning the period from 2014 to 2020, researchers can analyze the changes in phase to infer surface deformation. To assess the quality of the interferograms and determine the level of phase noise, the normalized coherence γ is calculated from the complex pixel intensities (Zebker & Villasenor, 1992). This coherence measurement provides insights into the reliability of the phase information and helps identify areas with high noise levels. Additionally, topographic contributions are removed using a SRTM Digital Elevation Model (DEM), allowing for the isolation of the deformation phase.

Phase unwrapping is a critical step in DInSAR analysis. It involves reconstructing the integer number of wavelengths between pixels to obtain a continuous representation of the deformation field (Goldstein et al., 1988). Unwrapped interferograms provide spatially continuous information about deformation with millimeter precision, enabling researchers to accurately map and analyze the surface changes at Fentale volcano. One challenge in SAR interferometry is the presence of atmospheric artifacts, which can introduce errors in the deformation measurements. To mitigate these artifacts, interferometric time series analysis is conducted using the Small BAseline Subsets (SBAS) technique (Berardino et al., 2002).

By analyzing a series of interferograms over time, researchers can separate the temporal deformation signals from the atmospheric noise, allowing for a more accurate characterization of the deformation patterns. DInSAR has a high sensitivity to subtle surface displacements, with the capability to detect displacements as small as 2.8 cm using C-band SAR (Synthetic Aperture Radar) data. This level of sensitivity enables the monitoring of subtle unrest and provides valuable information about the dynamics of Fentale volcano's magmatic system.

By conducting time series analysis of the DInSAR interferograms, researchers can gain insights into the deformation processes driven by magmatic activity in Fentale's plumbing system. Understanding the spatial and temporal variations in deformation is crucial for improving eruption forecasting and supporting integrated hazard and risk assessments for the surrounding communities.

The findings of this study contribute to a better understanding of the volcanic processes at Fentale volcano and aid in the development of effective strategies for mitigating volcanic hazards. In summary, Differential SAR Interferometry (DInSAR) is utilized in this study to characterize deformation at Fentale volcano. By analyzing the phase differences between co-registered SAR images, interferograms are formed, and the deformation phase is isolated. Phase unwrapping allows for the reconstruction of a continuous deformation field with millimeter precision. Through the use of the SBAS technique, atmospheric artifacts are mitigated, and the temporal deformation signals are extracted. DInSAR high sensitivity enables the detection of subtle surface displacements, providing valuable insights into the magmatic processes at Fentale volcano. The results of this study contribute to improved eruption forecasting and support integrated hazard and risk assessments for the surrounding communities.

2.6.5 Persistent Scatterer SAR Interferometry

Persistent Scatterer (PS) SAR Interferometry is a powerful technique employed in this study to analyze surface deformation at Fentale volcano. Originally developed for urban environments (Ferretti et al., 2000, 2001), the PS technique has proven to be effective in volcanic settings as well (Lundgren & Samsonov, 2019). In this research, the PS approach is applied to a time series of Sentinel-1 TOPS images spanning the period from 2014 to 2020. The PS technique identifies pixels with stable backscatter, which are dominated by a single scattered (Ferretti et al., 2011). These stable pixels are referred to as Persistent Scatters (PS). By identifying these PS points, researchers can track their behavior over time and analyze the deformation patterns. The PS method generates interferograms using a common master image to minimize decorrelation (Sousa et al., 2008).

This approach ensures that the interferograms are generated with minimal loss of coherence, allowing for a more accurate analysis of the deformation signals. At maximum resolution, the likelihood of a single scattered increases, making it easier to identify and track the PS points (Perissin et al., 2011). Time series analysis of the PS phases enables the quantification of deformation with millimeter precision (Ferretti et al., 2011). By analyzing the phase information of the PS points over time, researchers can gain valuable insights into the surface deformation processes at Fentale volcano. To mitigate atmospheric artifacts, the PS analysis is combined with the SBAS technique (Lundgren & Samsonov, 2019). The SBAS technique, as mentioned earlier, allows for the separation of temporal deformation signals from atmospheric noise. By combining the PS and SBAS approaches, researchers can obtain a more accurate and reliable characterization of the deformation patterns at Fentale volcano. Stable rock outcrops surrounding Fentale volcano host abundant PS points that are suitable for monitoring subtle surface displacements driven by magmatic processes (Perissin & Rocca, 2006). These stable rock outcrops serve as reliable scatters for the PS analysis, providing valuable information about the deformation behavior of the volcano. Characterizing the spatial and temporal deformation patterns through PS/SBAS InSAR analysis improves the understanding of Fentale volcano's plumbing system dynamics and eruption precursors. By analyzing the deformation signals obtained from the PS points, researchers can gain insights into the processes occurring beneath the surface of the volcano.

This information is crucial for improving our understanding of volcanic activity and enhancing eruption forecasting capabilities. In conclusion, the Persistent Scattered (PS) SAR Interferometry technique is applied in this study to analyze surface deformation at Fentale volcano. By identifying and tracking the behavior of Persistent Scatters (PS) over time, researchers can quantify deformation with millimeter precision. The PS analysis is combined with the SBAS technique to mitigate atmospheric artifacts and improve the accuracy of the deformation measurements.

The stable rock outcrops surrounding Fentale volcano provide abundant PS points suitable for monitoring subtle surface displacements driven by magmatic processes. The analysis of the spatial and temporal deformation patterns through PS/SBAS InSAR analysis enhances our understanding of Fentale volcano's plumbing system dynamics and eruption precursors.

2.6.6 Small BAseline Subsets (SBAS) SAR Interferometry

The Small BAseline Subsets (SBAS) SAR Interferometry technique is a valuable tool utilized in this study to analyze the Sentinel-1 InSAR time series and isolate deformation signals associated with magmatic processes at Fentale volcano. SBAS is specifically designed to mitigate artifacts that can limit conventional DInSAR analysis (Berardino et al., 2002). The SBAS technique forms a network of interferograms by selecting image pairs with short spatial and temporal baselines. The use of short baselines helps minimize decorrelation and atmospheric delays, which can manifest as apparent range changes in the interferograms.

By selecting image pairs with short baselines, researchers can reduce the impact of these artifacts and obtain more accurate deformation measurements. One of the key features of the SBAS technique is its ability to model and correct for atmospheric delays using their spatial and temporal characteristics (Lundgren et al., 2003). This is crucial in areas with significant atmospheric disturbances, such as volcanoes. By accurately modeling and correcting for atmospheric delays, researchers can improve the reliability of the deformation measurements and isolate the true deformation signals. The SBAS technique employs a least-squares inversion of the wrapped interferometric phases to solve for line-of-sight displacement rates at each pixel. This inversion process allows researchers to quantify the magnitude and direction of the deformation at each pixel with high precision. Additionally, temporal filtering is applied to separate transient volcanic signals from steady tectonic trends (Lundgren et al., 2003).

This temporal filtering helps identify and isolate the deformation signals specifically related to volcanic activity at Fentale volcano. In this study, the SBAS technique is applied to the Sentinel-1 data from 2015 to 2022. By utilizing the SBAS approach, researchers can characterize the deformation history of Fentale volcano in detail. The spatial filtering techniques further reduce noise and enhance the accuracy of the deformation measurements. This allows for the identification and isolation of subtle unrest signals that can be directly related to the dynamics of the volcano's subsurface plumbing system. The insights gained from the SBAS analysis support integrated monitoring efforts and contribute to more accurate hazard and risk assessments.

By understanding the deformation patterns and processes at Fentale volcano, researchers can better assess the potential hazards associated with volcanic activity and develop effective strategies for mitigating risks to the surrounding communities. In summary, the Small BAseline Subsets (SBAS) SAR Interferometry technique is utilized in this study to analyze the Sentinel-1 InSAR time series and isolate deformation signals related to magmatic processes at Fentale volcano.

SBAS mitigates artifacts that limit conventional DInSAR analysis by forming a network of interferograms with short spatial and temporal baselines. Atmospheric delays are modeled and corrected using their spatial and temporal characteristics. The least-squares inversion of wrapped interferometric phases allows for the quantification of deformation rates at each pixel, while temporal filtering separates volcanic signals from tectonic trends. The SBAS analysis characterizes Fentale's deformation history in detail and provides valuable insights into the volcano's subsurface plumbing system dynamics. These insights support integrated monitoring efforts and contribute to more accurate hazard and risk assessments.

2.6.7 Applications of InSAR for Monitoring Volcanic Deformation

InSAR techniques have proven effective for characterizing a range of surface deformation processes. As early applications demonstrated for earthquakes and volcanoes, it provides a powerful remote sensing tool (Funning et al., 2005; Massonnet et al., 1995). Monitoring volcanic deformation is particularly well-suited given InSAR's synoptic view and ability to detect subtle signals indicative of subsurface processes (Ebmeier et al., 2012). Time series analysis techniques like SBAS isolate transient volcanic events from background trends (Lundgren et al., 2003).

This research aims to characterize deformation transients at Fentale volcano in Ethiopia's Main rift using Sentinel-1 InSAR. Understanding the volcano's plumbing system dynamics through InSAR-derived displacement fields supports integrated hazard and risk assessments. Results also contribute to scientific knowledge of rifting processes in this seismically and volcanically active region. While fieldwork access is limited, satellite geodesy provides a means to systematically monitor Fentale volcano and improve forecasting abilities through remote quantitative analysis.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Description of the study area

The study area is located on the northern Main Ethiopia Rift, which includes the Fentale volcano and surrounding areas. It is located between East Showa State in the Oromia region, North Showa State in the Amhara region, and the southern Afar region, and its coordinates are 8.88 to 9.06 latitude and 39.8 to 40.05 longitude. The altitude is 800 ~ 1900 m above sea level. The area is about 96 km from Adama and 200 km from Addis Ababa. Fentale volcano is surrounded by three towns: Metehara, Haro-Adi and Sabure, and is located on the Djibouti railway line at 957 meters above sea level. Haro Adi Fentale Woreda is located near Metehara, next to the Metehara sugar factory, and Sabure is in the northern part of the study area. The climate of the region is classified as arid and semi-arid, with mean monthly temperatures ranging from a minimum of 12.8 to 20.9°C and a maximum of 31 to 36.7°C. These temperature ranges reflect the generally hot and dry conditions in the area. Fentale Volcano is part of an active Main Ethiopian Rift, known for its geological and volcanic activity, which poses a potential threat to nearby communities. In this study, we use Sentinel-1 InSAR technology to characterize surface deformation, improve our understanding of the dynamics of the Fentale magmatic system, and assess the associated risks to local populations. The main goal of this study is to determine the relationship between volcanic activity and ground deformation to improve risk assessment and monitoring in this geologically active region.

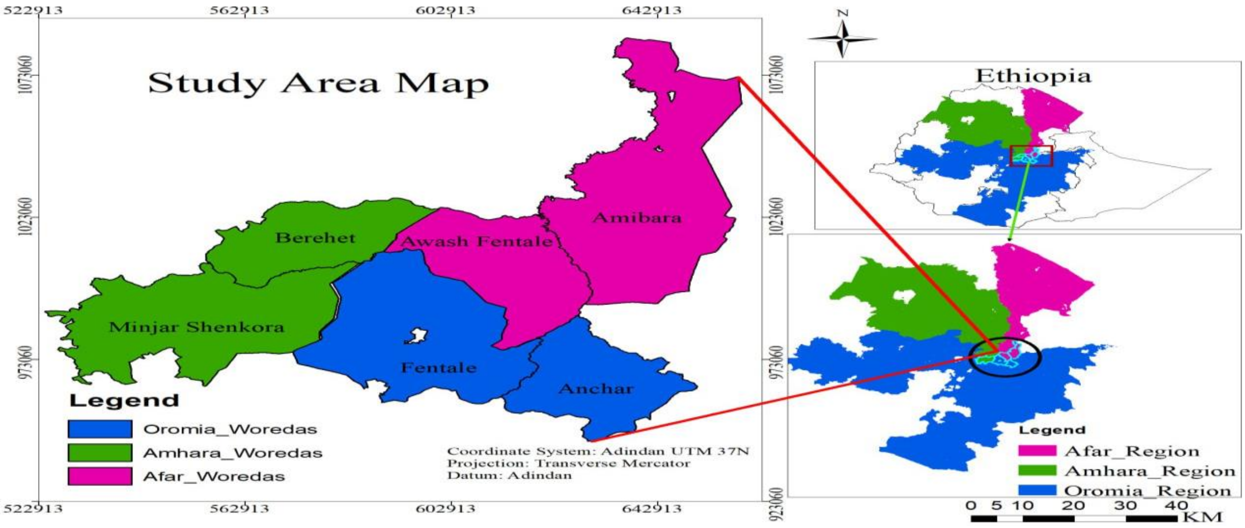

Figure 2 Location map of the study area

3.2 Geology

The Main Ethiopian Rift (MER) is part of the East African Rift System, where a new plate is emerging (Wood & Guth, 2022). The MER shows all stages of rift evolution from initiation to termination (Ebinger, 2005). The MER represents a classic continental rift environment in which a magma-dominated portion is separated into multiple rift-dominated zones (Keranen et al., 2004).

Fentale is located in the Dophan-Fentale Magmatic Segment. Fentale Volcano is located north of the MER. The volcanic activity of Fentale has produced many different types of explosives. In addition to trachyte and rhyolite lavas, inimbrites and ash deposits attest to a history of Plinian and Apliniean explosive eruptions at an early stage of evolution (Gibson, 1967). The 3.5 km caldera was formed by a massive collapse, which was probably associated with a massive silica eruption. Post-caldera lava erupted along annular fissures and reemerged domes (William et al., 2004).

Geochemical data indicate that the Fentale magma formed by melting of continental lithosphere with increasing crustal contamination over time (Abebe et al., 2007). The isotopic signatures also suggest the involvement of depleted and abundant mantle sources. Space bursts are controlled by N-S trending regional faults. Transient eruption episodes coincide with increasing elongation and extensional control phases along these structures (Acocella et al., 2002).

In this study, we use Sentinel-1 InSAR to characterize the deformation of the Fentale surface due to volcanic and tectonic processes. The spatiotemporal deformation patterns provide insight into the volcanic conduit system and stress distribution during rifting. Fentale's understanding of disturbance mechanisms supports integrated monitoring and informs risk/threat assessments in Main Ethiopian Rift (MER) work areas limited by these data.

InSAR geodesy helps overcome accessibility limitations for systematic and long-term monitoring of volcanic activity. Characterizing the permanent deformation patterns of Fentale through InSAR time series analysis will provide new insights into how active magmatic processes interact with surface deformation on different time scales. This, in turn, helps to better mitigate volcanic hazards to local communities.

3.3 Sentinel-1 InSAR Data

Sentinel-1 radar data, which operates in the C-band at a wavelength of approximately 5.6 cm, was acquired through a collaboration between the European Space Agency (ESA) and the European Commission. This data is important in determining surface deformation. This information is collected by two satellites, Sentinel-1A and Sentinel-1B, launched in 2014 and 2016 respectively. As part of the EU's Copernicus programme, the satellite provides free and public access to radar images that allow a complete view of the region at short repetition intervals of 6 or 12 days.

The biggest advantage of Sentinel-1 data is that it can provide images in all weather conditions, day and night (Albino & Biggs, 2021). One of the most important applications of Sentinel-1 data is radar interferometry (InSAR), which detects ground motion by comparing the phase delay between two radar images. InSAR technology can easily monitor various surface deformations such as subsidence, uplift and lateral movement. This information is essential for many fields, including geology, geophysics and environmental monitoring (Albino & Biggs, 2021).

Regarding coverage in Africa, the return time for Sentinel-1 data has improved significantly over the years. From January 2015 to January 2017, the minimum recurrence period was 24 days. However, from January 2017 to December 2019, this interval was shortened to 12 days, allowing more frequent updates of radar images and improved monitoring of surface changes across the continent (Albino & Biggs, 2021).

The LiCSBAS platform uses the open access LiCSAR product, allowing users to save processing time and disk space when extracting results from InSAR time series analysis. By integrating LiCSBAS with CSV data downloaded from the COMET-LiCSAR portal processor, researchers can efficiently analyze interferograms and obtain valuable information about ground deformation over time (Watson, Andrew R. et al., 2024). The free availability of Sentinel-1 data has greatly benefited researchers, providing critical data for monitoring ground deformation at the Fentale volcano.

For this study, the researchers accessed Sentinel-1 InSAR data through the COMET-LiCSAR Volcanoes and Magma Deformation portal. The researchers collected ascending (2015–2017) and descending (2015–2022) Sentinel-1 InSAR data from the LiCSAR portal (Lazeck, Milan et al., 2020). LiCSAR provides access to interferograms processed from Sentinel-1 satellite data. The analysis focused on specific Sentinel-1 data frames selected to cover the Fentale volcanic region, namely the downscaling data 079D_08094_131313 and the upscaling data 087A_08102_131312.

The acquired Sentinel-1 InSAR data provided important information about the surface deformation of Pentale volcano, including latitude and longitude displacement measurements, coherence values, and elevation data. This dataset spans a specific time period and contains spatially distributed measurements across the volcano. Using the Sentinel-1 InSAR data, the researchers were able to thoroughly analyze the spatial and temporal patterns of surface deformation of Pentale volcano to better monitor and assess volcanic activity.

In conclusion, the researchers visited the LiCSAR portal to download targeted frames of Sentinel-1 InSAR data for the Fentale volcanic region, which provide important information about surface deformation and help assess volcanic activity.

Table 1 sentinel-1 dataset used in this study

Sensor	Sentinel-1	Sentinel-1
Band	C	C
Wavelength	~5.6 cm	~5.6 cm
Acquisition mode	Descending	Ascending
Imaging mode	IW	IW
Polarization	VV	VV
Time span	2015-2022	2015-2017
Frame ID	079D_08094_131313	087A_08102_131312

3.4 Software Used

In the Fentale volcano surface deformation monitoring study using Sentinel-1 InSAR data, a variety of software, including Matlab, Python, ArcGIS and Microsoft Office, were used to facilitate the analysis, visualization and documentation of the data.

Matlab helped to map the spatial distribution of surface deformation, and Python helped to visualize the temporal evolution of deformation. ArcGIS was used to map the study area using Shapefiles to provide geospatial context. Microsoft Office was used to organize and write the research document, ensuring clear communication of the research methodology.

Table 2 Software were used in this study

Software	Purpose	Features
MATLAB	Mapping ground surface deformation	Data acquisition and preprocessing,interpolation and grid generation, visualization and mapping, analysis and interpretation
Python	Plotting temporal evolution of ground surface deformation	Data acquisition and preprocessing, data visualization, analysis and interpretation
ArcGIS	Mapping the location of the study area using shape file	Creation and manipulation of shape files, import of spatial data, digitization of study area boundaries, customization of maps, export of maps
Microsoft Office	Organizing and documenting the study	Microsoft Word for creating comprehensive documents, Microsoft Excel for data organization and analysis, Microsoft PowerPoint for creating presentations, Microsoft OneNote for note-taking and organization

3.5 Data Pre-Processing

Data preprocessing is an important step in a research project that involves converting raw data into a suitable format, cleaning the data, and checking for quality (Smith, 2010). By taking these steps, researchers can ensure the accuracy and reliability of the results, resulting in more reliable results. In this case, the researchers decided to convert the data into Comma Separated Values (CSV) format (Johnson et al., 2018). A text format commonly used to store tabular data. data. Converting the data to CSV format makes it compatible with a variety of tools and platforms, making it easy to import and manipulate (Smith, 2010). The CSV file contains important information such as latitude, longitude, displacement (mm), coherence, and height (m).

This format ensures that the required data is stored and organized in a structured manner before researchers enter the data into the MATLAB software for further analysis (Johnson et al., 2018). MATLAB is a powerful software widely used in the scientific community for data analysis and visualization. This provides researchers with a variety of processing capabilities. By importing CSV data into MATLAB, researchers can use an extensive library to perform complex analyses that provide accurate and meaningful results. The next important step in data preprocessing is importing the data into MATLAB.

Data cleaning and quality control are checks. This step is designed to identify and correct any errors, inconsistencies, or biases in the data set that may affect the accuracy of the analysis (Smith, 2010). During this process, various methods are used to ensure the integrity and reliability of the data. Missing values can occur for several reasons, including sensor failure or data transmission errors. To overcome this problem, researchers often use interpolation to estimate missing values based on surrounding data points. For the analysis of surface deformation, researchers used cubic spline interpolation (Smith, 2010).

Cubic Spline Interpolation is a mathematical technique that estimates missing values by fitting a smooth curve to the available data points. This was help to fill in the gaps in the data set and provide a more complete picture of the surface deformation of Fentale Volcano. By reducing the impact of missing values, researchers can obtain a more accurate analysis of the spatial distribution and temporal evolution of surface deformation.

3.6 Spatial Analysis of Ground Surface Deformation

Spatial distribution analysis is a method that allows researchers to study the patterns and spatial variability of surface deformation in a study area. Researchers can use a variety of data sources, such as satellite observations and InSAR displacement data, to obtain information about latitude, longitude, and line of sight (LOS) displacement at multiple locations in the study area. The latitude and longitude coordinates indicate the spatial location where the measurement was made, and the displacement values indicate the amount of surface movement in millimeters at each location.

Threfore, Spatial distribution analysis plays an important role in surface deformation studies. By plotting displacement values on a map and visualizing the spatial distribution of deformation, researchers can identify areas of uplift, subsidence, and lateral displacement. The spatial distribution of surface deformation was analyzed by examining deformation maps derived from InSAR processing. The color-coded maps show different types of ground movement, including uplift (red), lateral movement (green), and subsidence (blue).

By setting appropriate color constraints, we focused on specific ranges of deformation to better understand volcanic activity. These models provide valuable insight into fundamental geological processes and help monitor volcanic activity, assess hazards, and mitigate risks. To begin the analysis, the data.csv was imported into MATLAB using the training matrix function. This allowed us to generate the necessary columns for latitude, longitude, and LOS displacement. Get a first idea of the spatial distribution of surface deformation by viewing the data points in a scatter plot in MATLAB.

Spatial distribution analysis involves identifying areas of significant surface uplift, subsidence, and lateral displacement. This analysis can be performed using rise and decline data, which provides a different perspective on transformation patterns. The Ascending data represent measurements taken as the satellite moves from south to north, while the Descending data represent measurements taken as the satellite moves from north to south. A close examination of this graph reveals areas of significant uplift, subsidence, and lateral displacement.

These observations provide important information about the fundamental processes that drive volcanic activity. By correlating these spatial patterns with geological features, such as fault lines or magma chambers, we can gain a deeper understanding of the volcano's behavior. By analyzing scatter plots and examining the spatial distribution of displacement values, we were able to identify areas of uplift, subsidence, and lateral displacement. Areas with positive offset values indicate uplift, and areas with negative offset values indicate subsidence. Lateral displacements were observed where the displacement values deviated from the vertical direction. To further analyze the spatial pattern of surface deformation, the displacement values were interpolated into a fixed grid.

This was done using the Griddata function in MATLAB, resulting in a smooth deformable surface. By creating contour plots of the interpolated deformation surfaces, we were able to visualize patterns of uplift and subsidence in the study area. To improve the interpretability of the contour plots, thresholds were set at 10 mm, -10 mm, and 5 mm to avoid areas of significant uplift, subsidence, and lateral movement.

The interpolated displacement values were compared to these threshold criteria to generate a binary mask in MATLAB. These masks were then overlaid on a contour plot using different colors to distinguish regions of interest. Contour plot of a deformed surface interpolated with a nested binary mask.

By characterizing and visualizing the surface motion patterns, we were able to identify individual areas that exhibit uplift, subsidence, and lateral movement. Areas of uplift indicated by areas above the 10 mm threshold indicate the presence of subsurface volcanic activity.

Therfore, the spatial distribution analysis method used in this study significantly improved our understanding of the deformation behavior of Pentale volcano. In addition to spatial analysis, summary statistical analysis of surface deformation data is very important. This provides quantitative insight into the nature of the deformation pattern and helps in interpreting the data. The mean and median quantify the central tendency of the surface motion. The standard deviation describes the variability of the data. The minimum and maximum limits define the overall range of observed variation. By calculating these summary statistics, we can gain a deeper understanding of the deformation behavior of Fentale Volcano.

Overall, combining spatial analysis techniques with comprehensive statistical analysis provides a comprehensive understanding of the deformation patterns and volcanic processes of Fentale Volcano.

3.7 Temporal Analysis of Ground Surface Deformation

Temporal analysis is a technique that allows researchers to study the evolution of surface deformation over time. By analyzing time series of interferograms, images created by comparing multiple radar images of the same area taken at different times, researchers can track the progression of deformation patterns and identify temporal changes. To study the temporal changes in surface deformation, upwelling and downwelling datasets were analyzed separately.

As calculated several parameters: maximum velocity, minimum velocity, maximum rise velocity, maximum sink velocity, mean displacement, median displacement, standard deviation of displacement. These parameters provide insight into the rate and magnitude of surface deformation over time. Transient analysis plays an important role in the field of volcanology.

Transient analysis allows researchers to track the progression of surface deformation over time. Time series analysis of interferograms allows the detection of changes in the shape and height of the volcano's surface. These changes can provide valuable insight into fundamental volcanic processes and help researchers understand volcanic dynamics.

One of the main advantages of temporal analysis is the ability to determine temporal changes in surface deformation. By comparing interferograms taken at different times, researchers can detect changes in deformation patterns. These temporal fluctuations can indicate a period of increased volcanic activity or may be a precursor to a volcanic eruption.

3.8 Validation Displacement Measurements

The performed a comparative analysis to validate the displacement measures in the rise and decline datasets. To assess the correlation between the two datasets, we plotted a scatter plot of the line-of-sight (LOS) displacement values for overlapping pixels. To confirm the reliability of the measurements and ensure that the results meet the standards set in InSAR studies, a high coefficient of determination (R^2) was calculated.

3.9 Methodology

Sentinel-1 SAR data were the main input for this study and processed by the COMET-LiCSAR system to generate the required InSAR products. To achieve the research objectives and provide insight into the behavior of Fentale Volcano, spatial and temporal analyses of surface deformation were performed. This methodological approach allows a comprehensive study of surface deformation around Fentale Volcano using the capabilities of Sentinel-1 InSAR data and the advanced processing techniques provided by the COMET-LiCSAR system.

The methodology used in this study included the analysis of Sentinel-1 InSAR data to monitor and analyze the surface deformation of the Fentale Volcano. The study focused on two periods: Ascending data from 2015 to 2017 and descending data from 2015 to 2022. The analysis involved visualizing the spatial distribution using color-coded maps and examining temporal changes using velocity and displacement measurements. Analyze the spatial distribution of surface deformation, creating color-coded maps showing ground uplift, lateral displacement, and subsidence at Fentale Volcano.

This map provides a visual representation of the spatial pattern of variation. Additionally, calculate the mean displacement, median displacement, and standard deviation for the rise/fall data to understand the magnitude and variability of deformation over time. Combining advanced InSAR data processing, spatial and temporal analysis, and rigorous validation, this comprehensive methodology provides a detailed understanding of the ground deformation patterns at Fentale Volcano. Insights from this analysis were essential for improving volcano hazard assessments and the safety and preparedness of nearby communities.

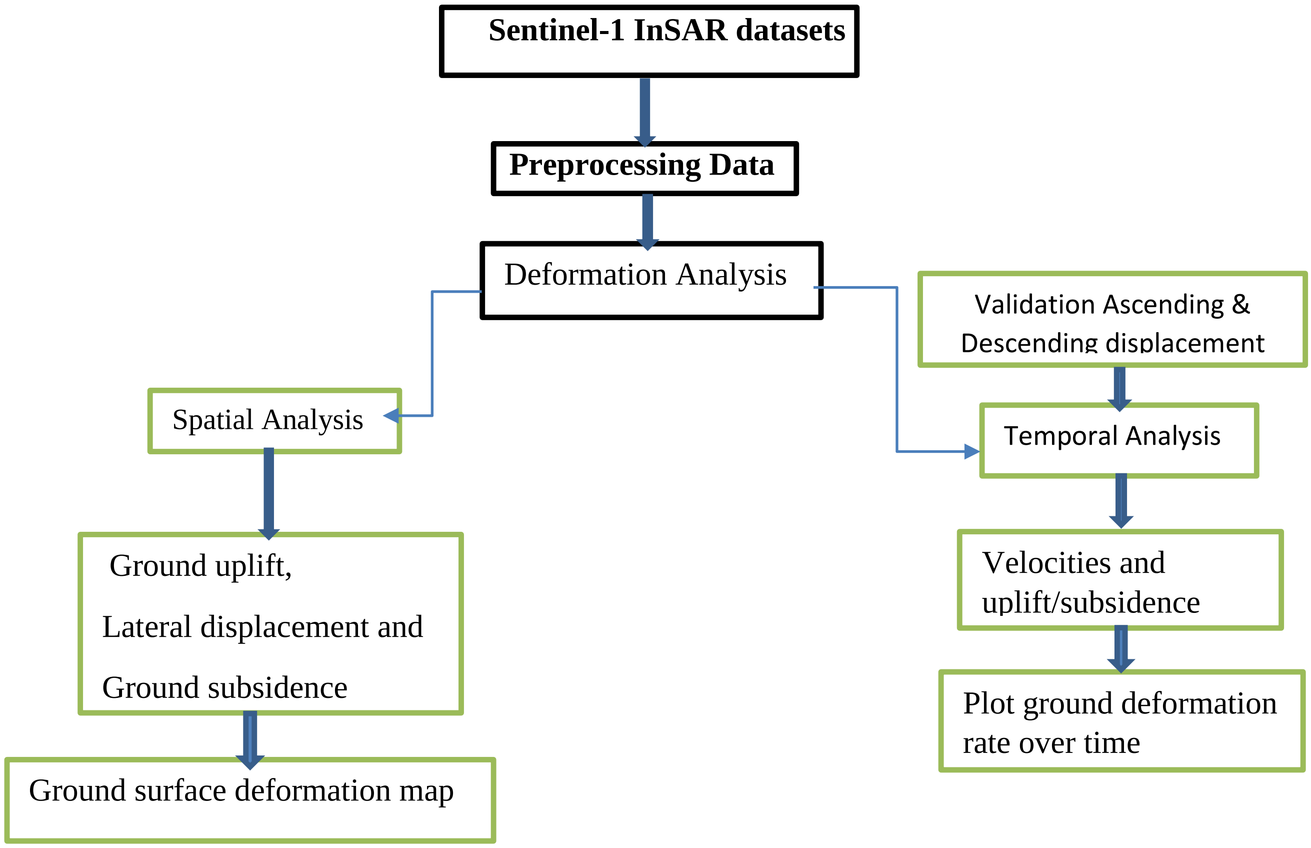

Figure 3 Conceptual frame work of data processing

CHAPTER FOUR

RESULTS AND DISCUSSION

In this paper, we investigated the surface deformation of Fentale volcano using Sentinel-1 InSAR data from the Northern Ethiopian Rift Valley. The aim of this study was to increase understanding of the spatial and temporal patterns of deformation and their relationship to volcanic activity in the region. Analysis of Sentinel-1 InSAR data processed by the LiCSAR system provided key insights into the behavior of Fentale volcano. Sentinel-1 interferograms can be accessed via the COMET-LiCS Sentinel-1 InSAR Portal (COMET-LiCS Portal). The public availability of LiCSAR InSAR data has enabled more in-depth studies of volcanic and tectonic phenomena in the region.

Using advanced LiCSAR methods and algorithms, the study provides reliable and accurate measurements of surface deformation. Researchers obtained specific Sentinel-1 images of the Fentale volcanic region, focusing on the descending datasets 079D_08094_131313 and ascending datasets 087A_08102_131312. From 2015 to 2022. The Sentinel-1 InSAR data provided valuable information on ground surface deformation at Fentale Volcano, including Latitude, longitude, displacement, coherence values, and altitude data.

The dataset covered a specific time period and consisted of spatially distributed measurements across the volcano, allowing for a comprehensive understanding of how the study area is changing over time. The displacement values obtained from the dataset indicate the magnitude and direction of ground movement, while coherence values provide information on the quality and consistency of the radar signal. Elevation data helps researchers assess changes in the topography of the study area. These datasets were evaluated using Matlab code, and Python code was developed to investigate the deformation of the ground surface of Fentale Volcano and its surrounding area.

The results of the Sentinel dataset illustrated the deformation patterns of the study area. The analysis of the Sentinel-1 dataset has provided valuable insights into the deformation patterns of the study area. The dataset, processed using the LiCSAR system, has allowed researchers to observe and understand the changes occurring on the ground surface over time. The study area, which includes the Fentale Volcano in the Northern Main Ethiopian Rift, exhibits significant volcanic and tectonic activity. By analyzing the Sentinel-1 dataset, researchers have been able to identify and document the deformation patterns in this region. Through the analysis of the Sentinel-1 dataset, researchers have observed various deformation patterns in the study area, such as uplift, subsidence, lateral movement, or a combination of these effects. Studying the deformation patterns of Fentale Volcano has revealed significant volcanic and tectonic activity in the region. The spatial distribution and temporal evolution of ground surface deformation have been documented, providing a deeper understanding of the volcano's behavior. This information is crucial for assessing potential hazards and mitigating risks in the surrounding region.

4.1 Spatial Distribution and Patterns of Ground Surface Deformation

The spatial distribution of ground surface deformation was analyzed for the ascending and descending datasets. Figures 3 and 4 illustrate the deformation patterns observed during these periods. The analysis revealed distinct spatial distribution patterns of ground surface deformation surrounding Fentale Volcano. The spatial distribution of ground surface deformation provides valuable insights into the areas experiencing uplift, lateral displacement, and subsidence. Areas in close proximity to the volcano exhibited higher levels of deformation, indicating localized volcanic activity.

The deformation patterns displayed both vertical and horizontal displacement, suggesting complex volcanic processes at play. By analyzing the ascending and descending figures provided, we can gain valuable insights into the spatial patterns of ground surface deformation in the study area. These figure consists of three distinct graphs overlaid on a map, each representing a different zone of deformation: subsidence, uplift, and stability. For the ascending dataset, the color limits were set between -20 mm and 20 mm. Ascending Figure 3 provides us with a comprehensive view of the ground surface deformation patterns observed between 2015 and 2017.

The graph corresponding to the area of subsidence reveals a striking pattern of sinking ground surfaces. Predominantly colored in blues, this zone indicates significant subsidence across the region. This substantial sinking of the ground surface raises questions about the underlying processes driving this phenomenon.

In contrast to the area of subsidence, the graph representing the area of uplift showcases a different set of spatial patterns. The prevailing colors in this graph are reds, indicating ground rise. However, it is important to note that the magnitudes of uplift are generally lower compared to subsidence. This suggests that while uplift is occurring, it is not as pronounced as the sinking observed in the subsidence zone. The area of stability, as depicted in the graph, exhibits minimal color variation. This indicates that little to no vertical displacement is occurring in this zone. While the subsidence and uplift zones experience significant changes in ground surface elevation, the stability zone remains relatively unaffected.

Similarly, for the descending dataset, the color limits were set between -30 mm and 30 mm. Descending Figure 4 provides us with a more recent snapshot of ground surface deformation patterns, spanning from 2015 to 2022. Similar to the ascending figure, this figure consists of three graphs representing subsidence, uplift, and stability. The subsidence graph in the descending figure reveals a continuation of the sinking trend observed in the ascending figure. The blues dominate the graph, indicating ongoing subsidence in the study area.

It is intriguing to note that the magnitudes of subsidence appear to vary over time, suggesting a dynamic subsurface environment. The uplift graph in the descending figure showcases a similar pattern to the ascending figure. Reds dominated the graph, indicating localized areas of ground rise. However, as previously mentioned, the magnitudes of uplift are generally lower compared to subsidence. This reinforces the notion that uplift processes in the study area are not as pronounced as subsidence. The stability zone in the descending figure remains relatively unchanged, exhibiting minimal color variation. This suggests that the area of stability has maintained its non-deforming nature over the years. Understanding the factors contributing to this stability is crucial for comprehending the overall deformation patterns in the study area.

The ascending and descending figures collectively provide a comprehensive visualization of the spatial patterns of ground surface deformation around Fentale Volcano. It is evident that the study area exhibits spatial heterogeneity, with distinct zones of subsidence, uplift, and stability.

The statistical analysis of the ground surface deformation data at Fentale Volcano provides insights into the relationships between variables. The statistical measures such as mean displacement, median displacement, and standard deviation of displacement. The statistical measures that further enhance our understanding of the data. The mean displacement represents the average shift in millimeters across the study area. The median displacement represents the middle value that separates the higher and lower displacements.

The standard deviation of displacement quantifies the variability or spread of the displacement values. It provides us with information about the diversity of deformation patterns. The ascending data shows a general subsidence trend, while the descending data indicates slight subsidence. The mean displacement values also differ (Table 3), indicating a greater degree of subsidence in the ascending data compared to the descending data. Additionally, the standard deviation of displacement values is higher in the descending data, indicating a greater degree of variability in the deformation patterns.

Table 3 Summary Statistics of Ground Surface Deformation

Data Type	Mean Displacement (mm)	Median Displacement(mm)	Standard Deviation (mm)
Ascending	-7.36	-7.54	18.81
Descending	-3.66	-4.85	38.25

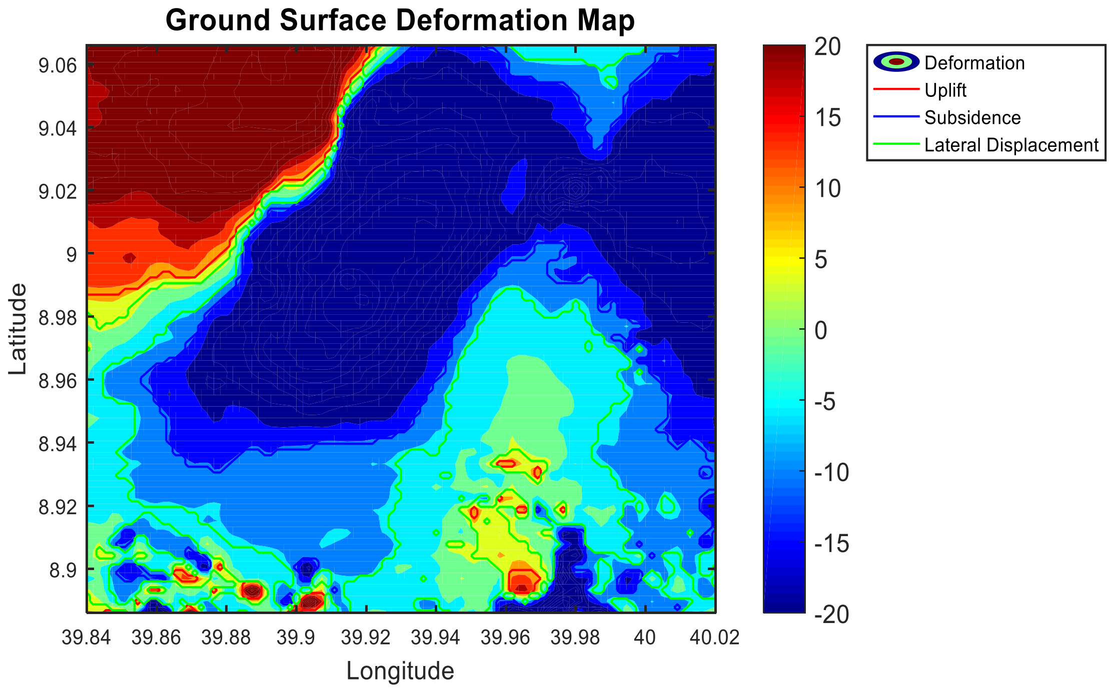

Figure 4 shows the spatial distribution of ground surface deformation map from ascending data (2015-2017)

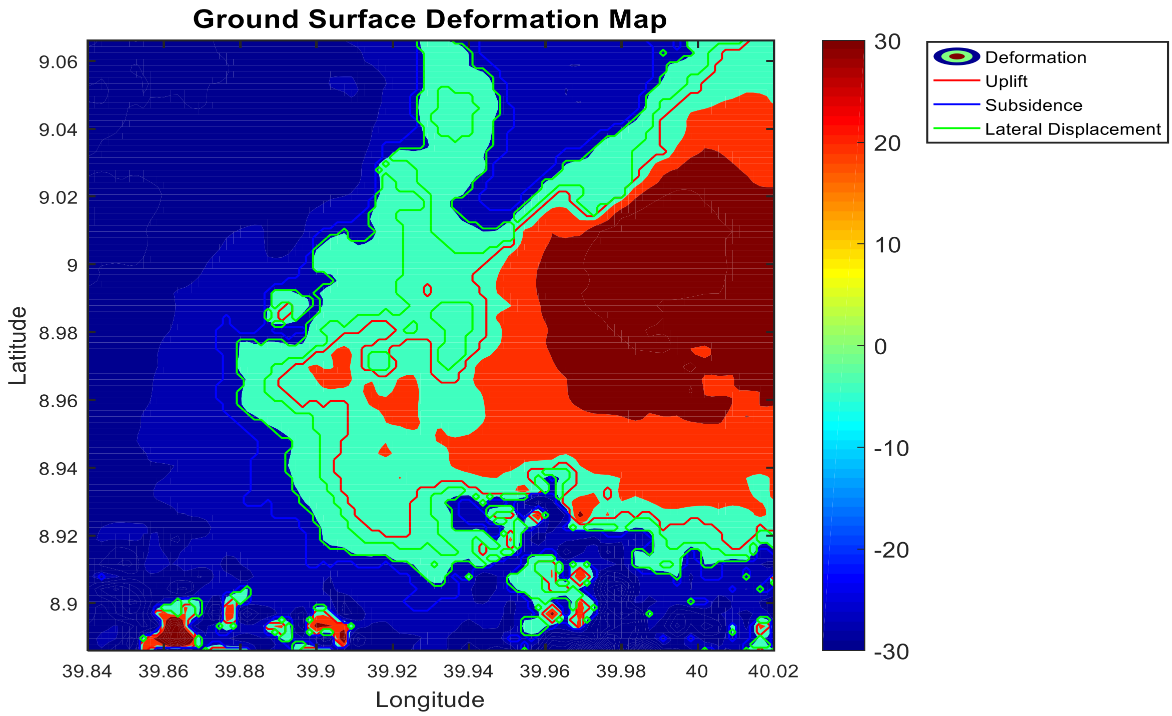

Figure 5 presents the spatial distribution of ground surface deformation map from descending data (2015-2022)

4.2 Temporal Evolution of Ground Surface Deformation

The temporal analysis of ground deformation patterns at Fentale Volcano unveils critical insights into the dynamics of volcanic activity over the seven-year study period. Time-series analysis of the InSAR data revealed significant ground deformation events that correlate with historical periods of volcanic unrest. The analysis of displacement velocities during both ascending (2015-2017) and descending (2015-2022) periods provided a nuanced understanding of the temporal evolution of ground movement. Figures 5 and 6 depict the changes in deformation over time.

The maximum uplift rate recorded during the ascending data period reached 17 cm/year in 2016, while the maximum subsidence rate was measured at -23 cm/year during the same period. Notably, the descending data revealed a maximum uplift rate of 50 cm/year in 2017 and a maximum subsidence rate of -43 cm/year recorded in 2021. These findings illustrate the fluctuating nature of volcanic activity, with periods of significant uplift often accompanying substantial subsidence.

During the initial years of the study (2015-2017), the uplift rates were relatively moderate, suggesting a period of gradual volcanic unrest. However, the later years (2018-2022) exhibited a marked increase in uplift rates, particularly in 2021, indicating a potential escalation in volcanic activity. The data reflect the dynamic nature of ground movement at Fentale Volcano, where periods of uplift and subsidence coexist, contributing to the overall complexity of the volcanic behavior.

The contrast between ascending and descending data provides a comprehensive understanding of the three-dimensional nature of ground deformation. Regions of uplift are generally concentrated around the summit of the volcano, while subsidence is more prevalent on the flanks.

This pattern underscores the intricate interplay of volcanic processes at Fentale Volcano. The identified peaks in uplift and subsidence rates are not uniform across the volcano, with certain areas experiencing rapid changes while others remain relatively stable, emphasizing the necessity for continuous monitoring and further investigation into the mechanisms driving these changes.

Table 4 Maximum Uplift and Subsidence Rates (Ascending and Descending Data)

Data Type	Maximum Uplift Rate (cm/year)	Maximum Subsidence Rate (cm/year)	Year
Ascending	17	-23	2016
Descending	50	-43	2017/2021

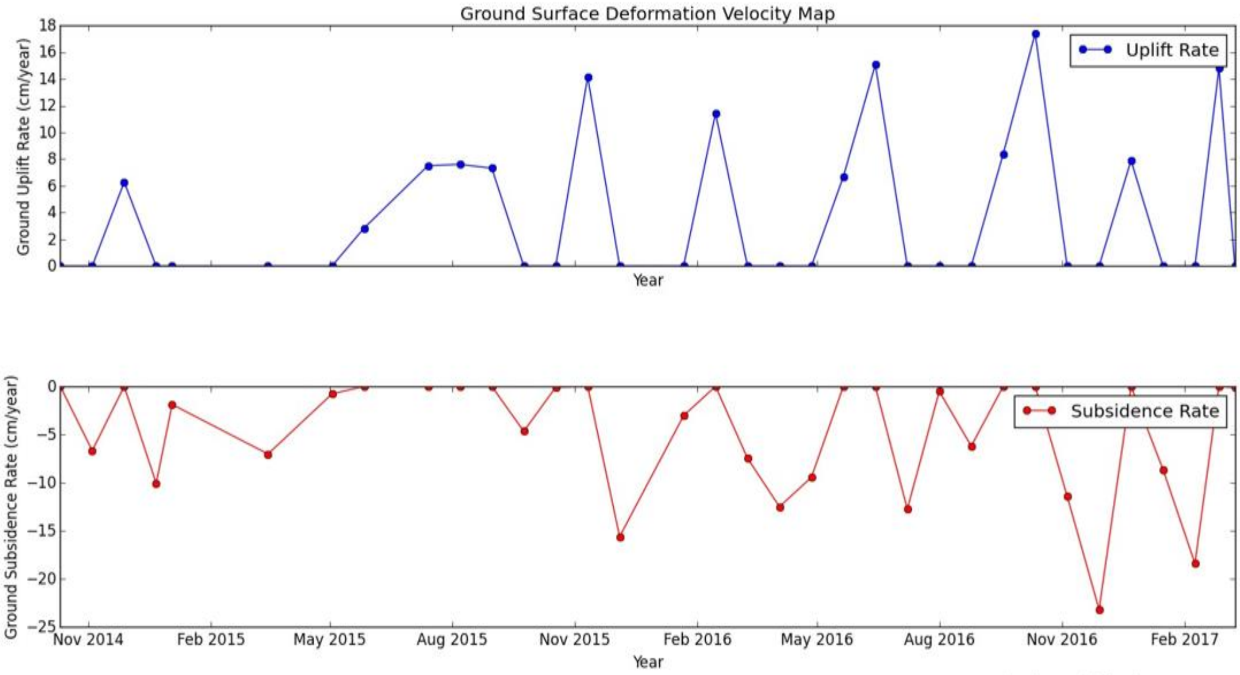

Figure 6 Temporal evolution of ground surface deformation rate study over time for ascending data (2015-2017)

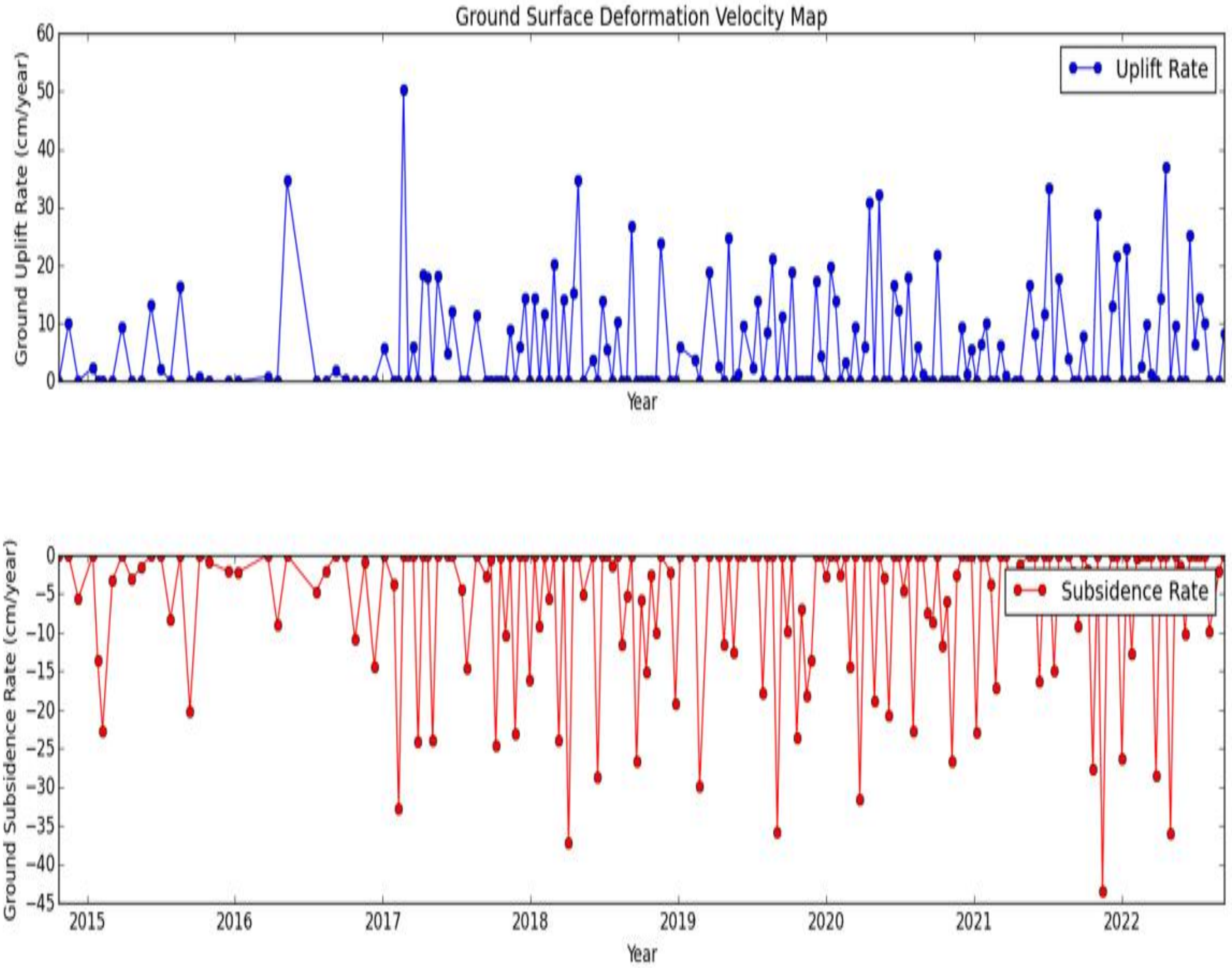

Figure 7 Temporal Evolution of ground Surface deformation rate study over time for descending data (2015-2022)

4.3 Validation of displacement measurements

The results from the ascending and descending datasets were compared to validate the displacement measurements and provide a comprehensive understanding of the ground surface deformation at Fentale Volcano. The comparison of the ascending and descending Sentinel-1 InSAR data provides a robust validation of the displacement measurements data can be explained by the regression equation: $y = 0.29x + 2.47$, with a high coefficient of determination ($R^2 = 0.87$) between the two datasets. To validate the displacement measurements obtained from the ascending and descending Sentinel-1 InSAR data, a scatter plot of the Line of Sight (LOS) displacement values from overlapping pixels was generated. In the case of the ground surface deformation analysis, the R-squared value suggests that the regression equation captures a strong level of correlation between the variables.

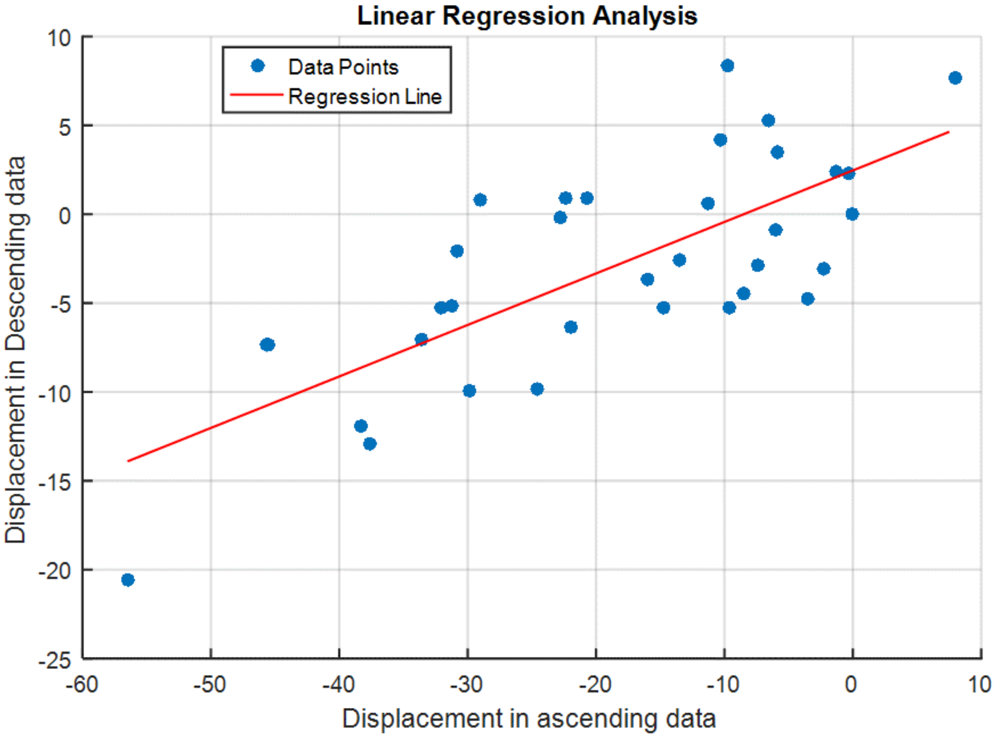

Figure 8 shows the scatter plot of LOS displacement values from overlapping pixels in the ascending and descending data

4.4 DISCUSSION

The main objectives of this study were to utilize Interferometric Synthetic Aperture Radar (InSAR) data to monitor and analyze ground surface deformation at the Fentale Volcano. By examining both ascending and descending datasets over various timeframes, the study aimed to uncover the spatial and temporal patterns of volcanic deformation. This systematic approach enhanced the understanding of the underlying magmatic processes and potential volcanic hazards. Such foundational research is essential for informing risk assessments and developing adequate preparedness strategies for local populations.

The findings revealed a complex interplay of ground uplift, subsidence, and lateral displacement at Fentale Volcano. Notably, the analysis identified maximum uplift rates of 50 cm/year during the descending observation period, alongside significant subsidence rates of -43 cm/year. Moreover, the mean deformations observed were -7.36 mm for the ascending dataset and -3.66 mm for the descending dataset, indicating a pronounced trend of ground displacement (Ayele et al., 2016; Biggs et al., 2011). These results underscored ongoing volcanic activity and suggested dynamic magmatic processes within the volcanic system.

Furthermore, the observed patterns of deformation can be interpreted as indicators of active magmatic movement beneath the volcano. The substantial uplift rates suggested that magma was accumulating in shallow reservoirs, potentially leading to increased pressure and future eruptive events (Pritchard & Simons, 2002). Conversely, the significant subsidence rates indicated the withdrawal of magma, which may correlate with prior volcanic unrest in the region (Hooper et al., 2012). This duality of uplift and subsidence highlighted the complex nature of volcanic systems, where simultaneous processes could occur, reflecting the dynamic state of the underlying geology.

In comparison with existing literature, these findings resonated with previous studies conducted in the region, such as those by Ayele et al. (2016) and Biggs et al. (2011), which also documented patterns of ground deformation associated with volcanic activity in the Ethiopian Rift. However, the maximum deformation rates identified in this study, particularly the substantial uplift and subsidence values, suggested an intensification of volcanic unrest compared to earlier reports. Importantly, the enhanced resolution and temporal coverage provided by Sentinel-1 InSAR data enabled a more nuanced mapping of deformation patterns, thereby contributing to a deeper understanding of the processes at play (Albino & Biggs, 2021).

Moreover, the implications of these findings are profound, not only for the scientific community but also for local populations residing near Fentale Volcano. The identification of significant uplift and subsidence patterns indicated that the volcano is an active system, necessitating continuous monitoring to inform risk assessment and preparedness strategies (Ding, 2014; Tizzani et al., 2007).

Understanding these dynamics could aid local authorities in implementing timely interventions, thereby enhancing community resilience in the face of potential volcanic hazards. Furthermore, these results emphasized the importance of integrating InSAR data with other geophysical monitoring techniques, such as seismic and GPS measurements, to create a comprehensive hazard assessment framework (Morishita et al., 2020). Despite these substantial contributions, it is essential to acknowledge limitations. The reliance on InSAR data, while powerful, may be subject to atmospheric noise and other external factors that could influence the accuracy of displacement measurements (Albino & Biggs, 2021).

Additionally, the study's focus on specific timeframes may limit the broader understanding of long-term volcanic behavior. Consequently, future research should address these limitations by incorporating diverse geophysical methods and extending the temporal analysis to capture a more comprehensive view of volcanic dynamics. Looking ahead, future research should prioritize the integration of InSAR data with other geodetic techniques to enhance the understanding of ground deformation at Fentale Volcano. Extended time series analysis, coupled with advanced atmospheric correction methods, could provide deeper insights into the volcano's behavior and potential hazards (Hooper et al., 2012).

Furthermore, exploring the socio-economic impacts of volcanic activity on local communities can inform the development of effective risk management strategies (Ding, 2014). By addressing these areas, researchers can contribute to a more robust framework for monitoring and mitigating the risks associated with volcanic systems in the Ethiopian Rift and beyond.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

Ground surface deformation monitoring is indeed one of the most essential aspects of volcano monitoring and hazard assessment. The analysis of Sentinel-1 InSAR data revealed significant ground surface deformations at Fentale Volcano. The study aimed to understand the spatial distribution and temporal evolution of deformation patterns at the volcano using ascending data from 2015-2017 and descending data from 2015-2022. In this regard, the spatial distribution maps revealed complex patterns of uplift, subsidence and lateral displacement across the volcano, indicating heterogeneous deformation occurring due to subsurface volcanic vs magmatic processes. Subsidence was found to be dominant across much of the study area, with localized zones of significant uplift also observed. This suggests the volcano is undergoing both inflation and deflation at different locations. Another also, the temporal evolution analysis showed deformation rates and velocities vary over time. Periods of accelerated uplift/subsidence were detected, providing insights into the evolving subsurface magmatic system. As a result, comparison of ascending and descending InSAR datasets provided a more comprehensive characterization of the multi-dimensional deformation field. This aided improved understanding of the complex spatial and temporal patterns.

Statistical analysis quantified the mean, median and variability of displacement values, improving understanding of deformation behavior. These results demonstrate ongoing active deformation at Fentale Volcano. Comparisons with previous studies validated the use of Sentinel-1 InSAR data for long-term monitoring of volcanic areas. The research contributes to a better understanding of volcanic activity and helps identify potential hazards associated with Fentale Volcano. The findings of this study have important implications for the development of effective monitoring systems and early warning mechanisms. By utilizing Sentinel-1 InSAR data, detailed analysis of ground surface deformation can be conducted, aiding in the understanding and management of volcanic hazards.

5.2 RECOMMENDATIONS

While this study provides valuable insights into ground surface deformation at Fentale volcano through InSAR analysis, some limitations were identified that could be addressed in future work, needs to be focused on expand in-situ geodetic measurements, establishing a dense GPS/GNSS network and conducting regular leveling surveys would allow validation and refinement of InSAR time-series modeling. This is particularly important for capturing transient or localized deformation signals. Increase SAR dataset density, leveraging additional free and open SAR datasets, such as Sentinel-1, Sentinel-2 optical imagery and altimetry from Sentinel-3, could improve temporal resolution and coherence. Commercial satellites like TerraSAR-X and COSMO-SkyMed offer higher resolution but are not open-access. Incorporate groundwater data, given the hydrothermal activity at Fentale, integrating groundwater level and quality data could provide insights into links between subsurface fluid processes and deformation. This may help distinguish magmatic vs. hydrothermal signals.

Atmospheric corrections, future work should investigate advanced DInSAR techniques like Small BAseline Subsets and Stacked InSAR which mitigate atmospheric noise through temporal decorrelation. This would improve sensitivity to subtle deformation. Continued long-term monitoring, Sustained InSAR time-series analysis over decades utilizing all available SAR missions could detect pre-eruptive signals and aid forecasting of volcanic behavior. Addressing these aspects would enhance the spatio-temporal resolution and integration of geophysical datasets, advancing our understanding of Fentale volcano dynamics and hazard assessment capabilities. Continued collaborative efforts are also recommended.

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APPENDICES

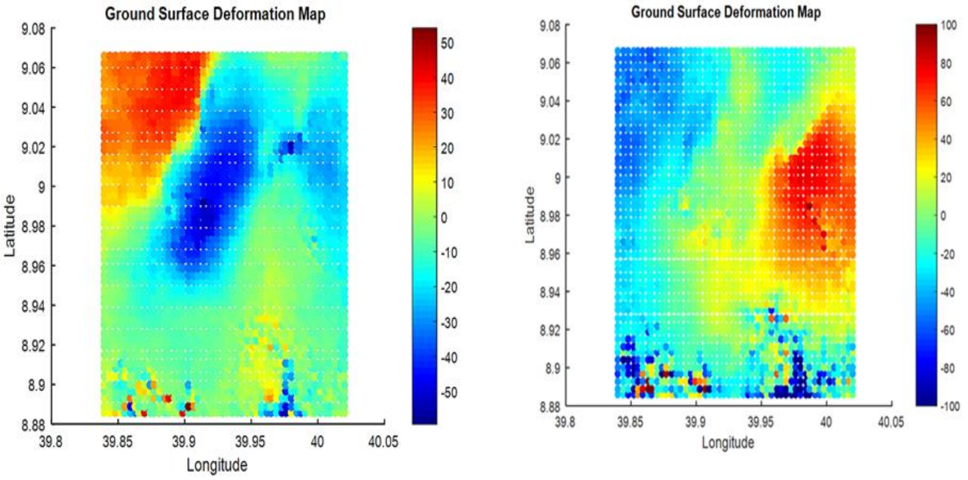

Figure 9 showcases a scatter plot of the ground surface deformation data ascending (2015-2017) and descending (2015-2022) measurements

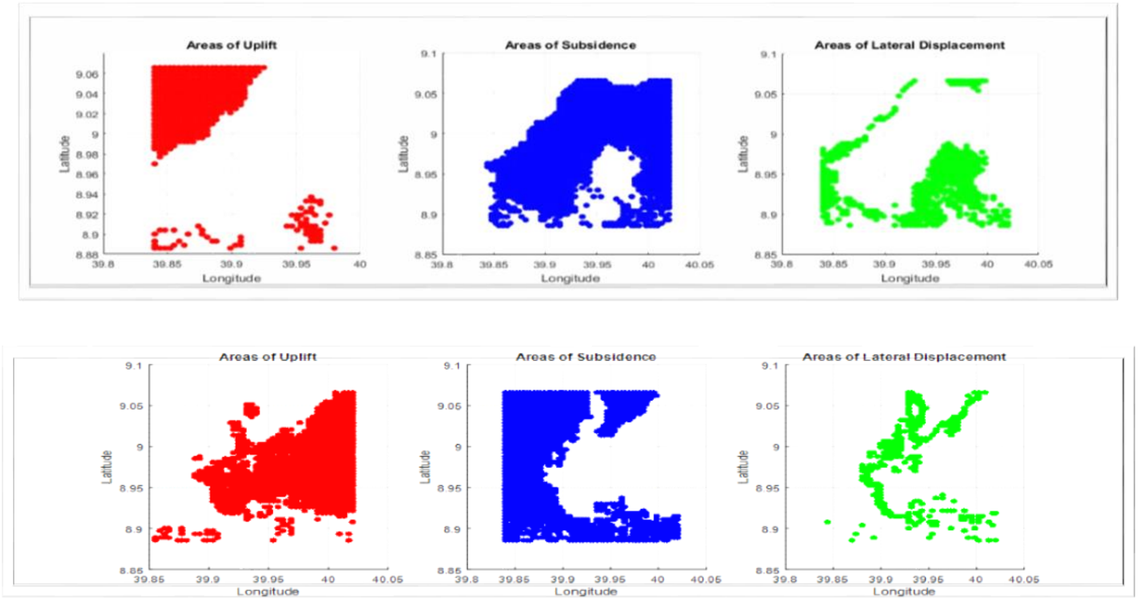

Figure 10 Identify areas of significant uplift, subsidence, and lateral displacement of ascending and descending respectively

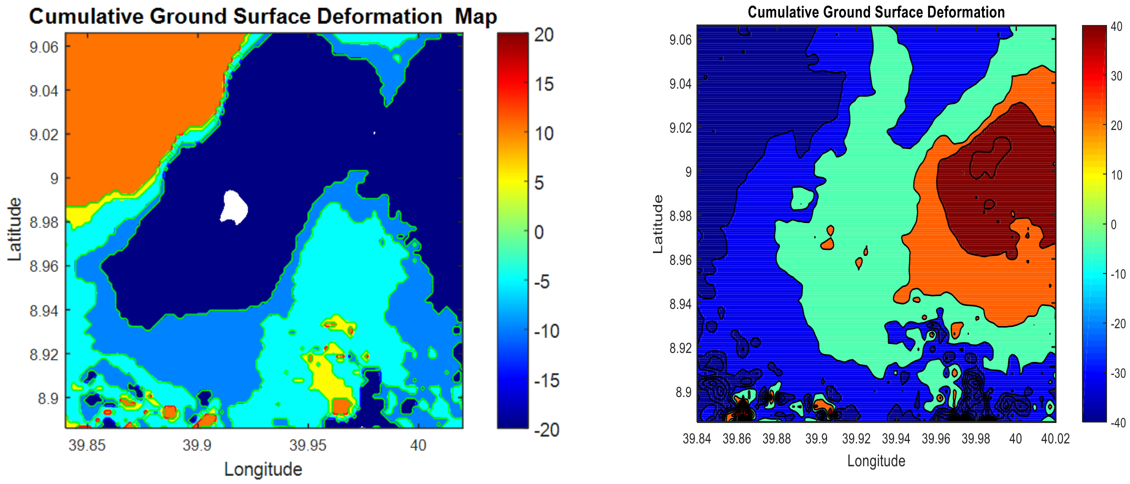

Figure 11 cumulative ground surface deformation data ascending and descending measurements

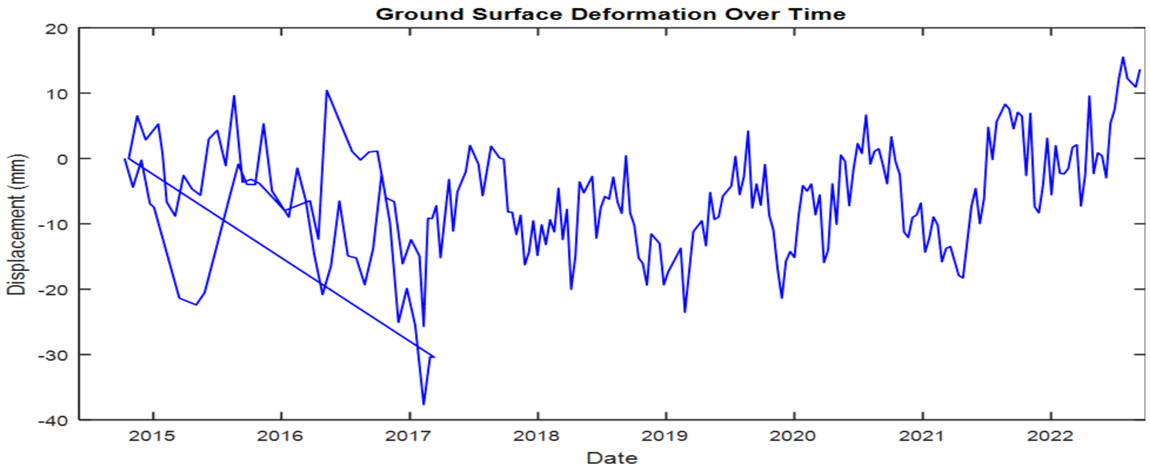

Figure 12 visually represents the combination of ascending and descending data, providing a holistic view of the ground surface deformation at Fentale Volcano