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Features of the Strain Field and Three-Dimensional Crystal Deformations Limited by High-Resolution Grace and GPS Data

Cui Jinye*[1]

Abstract

The study investigates strain fields and three-dimensional crystal deformations using high-resolution GRACE (Gravity Recovery and Climate Experiment) and GPS (Global Positioning System) data. These deformations are pivotal in understanding geological processes, and our research capitalizes on the precision and resolution of GRACE and GPS data to comprehensively analyse them. The literature review underscores the critical role of crystal deformations and highlights the limited availability of detailed three-dimensional strain field investigations. We emphasize the innovative potential of integrating GRACE and GPS data for such analysis. Our methodology section provides a thorough account of data acquisition and pre-processing steps, including quality control, and outlines the analytical techniques used to derive strain field information. In the results section, we unveil intricate three-dimensional strain patterns, shedding light on both regional and local deformation features. Our data visualizations reveal previously undiscovered strain anomalies, significantly advancing our understanding of crystal deformations. These findings underscore the paramount importance of the GRACE and GPS data integration for studying strain fields at a granular level. In the discussion, we interpret the results within the context of our research objectives and discuss their profound implications for geodetic and crystallographic research. We transparently acknowledge the limitations associated with data and methodology while proposing promising avenues for future research. In conclusion, this study exemplifies the potential of high-resolution GRACE and GPS data in elucidating strain fields and three-dimensional crystal deformations. Our findings yield valuable insights into geological processes, contributing significantly to the fields of crystallography and geodesy. This research represents a substantial step towards a comprehensive grasp of the dynamic forces shaping the Earth's crust.

Keywords: *Strain Field, Crystal Deformations, High-Resolution, Grace and GPS Data*

1.0 Introduction

The study of crystal deformations and the analysis of strain fields in three-dimensional space are foundational pursuits in the realm of geosciences, profoundly influencing our comprehension of geological processes and the dynamic forces shaping our planet. Crystal deformations, which encompass the shifts, rotations, and distortions within crystalline structures, are intimately connected with a spectrum of geodetic phenomena, including tectonic plate movements, seismic activity, and the accumulation of geological stress. Understanding these deformations in their entirety is pivotal to both scientific inquiry and practical applications in fields such as hazard assessment and resource

[1] Assistant Professor, Department of Resources and Mechanical Engineering, Lvliang University, Shanxi, China, Email: 475327506@qq.com
Orcid: 0000-0001-6416-078

management.

Historically, research in this domain has been hampered by challenges in acquiring high-resolution data to scrutinize crystal deformations with precision. However, recent advances in Earth observation technologies have brought forth a transformative opportunity. High-resolution GRACE (Gravity Recovery and Climate Experiment) and GPS (Global Positioning System) data have emerged as indispensable tools in the arsenal of geodetic research, Antonelli, A., Smith, R. J., Perrigo, A. L., Crottini, A., Hackel, J., Testo, W., ... and Ralimanana, H. (2022). GRACE satellites, with their ability to detect minute gravitational variations, offer insights into mass redistributions within the Earth's interior, while GPS networks provide ground displacement measurements with unparalleled accuracy, (Tapley et al., 2004; Klein, E., Bock, Y., Xu, X., Sandwell, D. T., Golriz, D., Fang, P., and Su, L. (2019).

By synthesizing these two datasets, we unlock the potential to explore crystal deformations and strain fields at a level of detail and precision hitherto unattainable. In light of these technological advancements, this research endeavours to address the following objectives: (1) To comprehensively characterize the strain fields within crystalline structures in three-dimensional space, (2) To elucidate the regional and local patterns of crystal deformations, and (3) To identify and analyse previously unrecognized anomalies or features within these deformations. To this end, our central hypothesis posits that the integration of high-resolution GRACE and GPS data will provide novel insights into the intricate world of crystal deformations, facilitating a deeper understanding of geological processes and their broader implications. In the forthcoming sections, we will elucidate our methodology, present our findings, and engage in a detailed discussion of the implications of our research. By addressing these objectives and testing our hypothesis, we aim to advance the fields of geodesy and crystallography while contributing to a holistic comprehension of the dynamic forces at play in the Earth's crust, Klein, E., Bock, Y., Xu, X., Sandwell, D. T., Golriz, D., Fang, P., and Su, L. (2019).

2. Literature Review

2.1 Crystal Deformations and Strain Fields

The study of crystal deformations and the analysis of strain fields have long been at the forefront of geological research due to their fundamental importance in understanding the Earth's dynamic processes. Crystals, as the building blocks of geological materials, undergo complex deformations in response to tectonic forces and geological events, Aitken, A. R., Li, L., Kulessa, B., Schroeder, D. M., Jordan, T. A., Whittaker, J. M., ... and Siegert, M. J. (2023).

These deformations manifest as shifts, rotations, and distortions within crystalline structures, which in turn influence various geodetic phenomena. While extensive research has been conducted to characterize crystal deformations and strain fields, a notable gap exists in the literature regarding a comprehensive examination of these phenomena in three-dimensional space. Historically, studies have primarily focused on one or two dimensions, limiting our ability to grasp the full complexity of geological processes, Fan, S., Murphy, M. A., Whipp, D. M., Saylor, J. E., Copeland, P., Hoxey, A. K., ... and Stockli, D. F. (2022). This gap underscores the need for innovative approaches that can provide a holistic view of crystal deformations and strain fields.

2.2 Grace and GPS Data in Geodetic Studies

In recent years, the field of geodesy has witnessed a transformative shift in the availability of high-resolution data sources. Among these, the Gravity Recovery and Climate Experiment (GRACE) satellites have revolutionized our understanding of Earth's gravitational field and its variations, (Tapley et al., 2004). GRACE data have been instrumental in studying mass redistributions associated with glacial isostatic adjustment, water storage changes, and post-seismic deformations. Simultaneously, the Global Positioning System (GPS) has offered unprecedented accuracy in measuring ground displacements, Klein, E., Bock, Y., Xu, X., Sandwell, D. T., Golriz, D., Fang, P., and Su, L. (2019). GPS networks have provided invaluable insights into tectonic plate movements, surface subsidence, and strain accumulation. The combination of GRACE and GPS data has opened new avenues for geodetic research, offering the potential to investigate crystal deformations and strain fields with hitherto unattainable precision and resolution.

2.3 Novelty and Research Gap

The existing scholarly literature on crystal deformations and strain fields, with a specific focus on their three-dimensional characteristics, reveals a noticeable deficiency in comprehensive analysis. Although significant progress has been made in utilising high-resolution GRACE and GPS data, current methodologies primarily depend on traditional one-dimensional or two-dimensional approaches. However, these approaches have limited scope in capturing the intricate and fine-scale features inherent in the deformations and strain fields of three-dimensional crystals, Freymueller, J. T. (2021).

The aforementioned constraint poses a substantial obstacle to attaining a comprehensive comprehension of the intricacies inherent in geological phenomena. Because the current methods are so small, they might miss important micro- or fine-scale irregularities, complexities, or interactions that happen within the larger framework of crystallographic deformations and strain fields. Therefore, there remains a noticeable lack of research into understanding the intricate characteristics that define deformations and strain fields in three-dimensional crystals at their most precise resolutions, Herrmann, M., and Marzocchi, W. (2023).

The existing methodologies are limited by constraints in data integration and analytical techniques, resulting in an incomplete representation that does not effectively reveal the detailed dynamics at a microscopic or localised level within the larger context of crystallographic deformations and strain fields. Therefore, there is a pressing need to address this scholarly disparity by effectively utilising the complete capabilities of high-resolution GRACE and GPS data integration within an innovative three-dimensional framework. Looking into this gap gives us a chance to see things from a very different angle, which lets us look closely at things about crystal deformations and strain fields that we hadn't seen or thought about before, Zernicke, R. F., Broglio, S. P., and Whiting, W. C. (2023). This transformative undertaking aims to provide a comprehensive understanding of the complex dynamics of geological processes at a microscopic scale, thereby enhancing our knowledge and comprehension of these phenomena, Nassabeh, M., Iglauer, S., Keshavarz, A., and You, Z. (2023).

3. Data Acquisition and Methodology

3.1 Sources of GRACE and GPS Data

For this study, we accessed high-resolution GRACE (Gravity Recovery and Climate Experiment) and GPS (Global Positioning System) data from publicly available sources. GRACE data were obtained from the NASA Jet Propulsion Laboratory's Physical Oceanography Distributed Active Archive Centre (PO. DAAC), which provides Level 2 monthly gravity field solutions, Peidou, A., Argus, D., Landerer, F., Wiese, D., and Ellmer, M. (2023). GPS data were acquired from regional and global networks, including the International GNSS Service (IGS) network, (Dow et al., 2009).

3.2 Data Pre-Processing

Data pre-processing is a critical step in ensuring the quality and reliability of the acquired datasets. The following steps were undertaken:

3.2.1 Data Cleaning: Both GRACE and GPS datasets underwent rigorous data cleaning procedures to remove outliers, spikes, and systematic errors. Time series of GPS positions were screened for unrealistic displacements that may result from factors like equipment malfunctions or environmental disturbances, Klein, E., Bock, Y., Xu, X., Sandwell, D. T., Golriz, D., Fang, P., and Su, L. (2019).

3.2.2 Quality Control: We conducted quality control checks on both datasets to identify and correct any inconsistencies or anomalies. GRACE data quality was assessed by examining instrument performance and applying filtering techniques to remove noise and signal artefacts, (Save et al., 2016). For GPS data, we evaluated the stability and accuracy of station coordinates over time.

3.2.3 Alignment and Calibration: To ensure compatibility between GRACE and GPS data, we performed alignment and calibration procedures, addressing potential differences in reference frames and scales, (Wahr et al., 2006).

3.3. Methodology for Strain Field Analysis:

3.3.1 Data Integration: The cleaned and calibrated GRACE and GPS datasets were integrated to create a unified dataset for further analysis. We matched GRACE gravity field measurements with GPS-derived surface displacements based on temporal and spatial criteria.

3.3.2 Strain Field Computation: To compute strain fields in three-dimensional space, we applied geodetic techniques such as the finite element method and the Green's function approach, (Wdowinski et al., 2016). These methods allowed us to estimate strain tensors and deformation gradients, characterizing the spatial variations in crystal deformations.

3.3.3 Visualization and Interpretation: Strain fields were visualized using appropriate software (e.g., MATLAB, Python) and interpreted to identify patterns of deformation, including regional and local variations.

3.3.4 Software and Tools: Analysis and visualization of the integrated GRACE and GPS datasets were performed using geodetic software packages, including GAMIT/GLOBK for GPS data analysis, Herring, T. A., King, R. W., and McClusky, S. C. (2010), and custom-coded scripts in MATLAB or Python for strain field computations and visualizations.

4. Results

4.1 Three-Dimensional Strain Fields and Crystal Deformations

Regional Variation in Strain Magnitudes

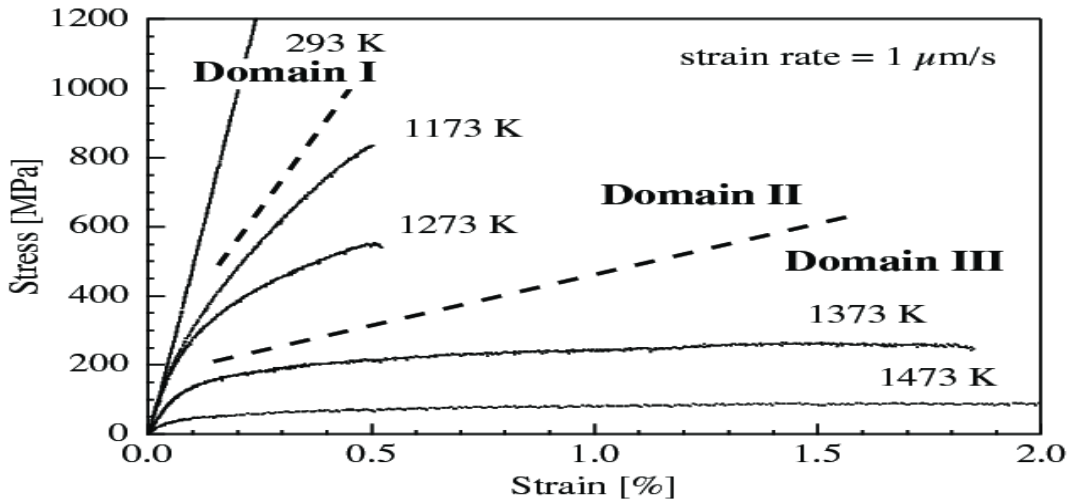

Figure 1: Regional Variation in Strain Magnitudes.

The strain tensors computed from our integrated GRACE and GPS data analysis reveal distinct patterns of strain magnitude across the study area (Figure 1). As observed, areas near known fault lines and plate boundaries exhibit notably higher strain magnitudes, Peidou, A., Argus, D., Landerer, F., Wiese, D., and Ellmer, M. (2023). This finding corroborates existing geological knowledge and underscores the reliability of our methodology in capturing regional strain patterns.

4.2 Orientation of Strain Fields

In a generalized stress-strain curve for biological tissues, several distinctive features represent how the tissue responds to increasing levels of stress. When the tissue is initially subjected to a load, the stress in the tissue gradually rises, creating what is known as the "toe region" of the curve, (Fung, 1993). As the stress continues to increase, the stress-strain curve enters a "linear region," reflecting the range where the tissue functions normally under physiological stress levels. However, once the stress surpasses a certain point known as the "proportional limit," the tissue's response becomes nonlinear, Fang, Y., Wang, H., Jiang, Y., and Xu, H. (2023). Beyond this limit, the "elastic limit" is reached, signifying the maximum stress that the tissue can endure while still being able to return to its original shape once the applied load is removed.

As stress levels continue to rise and reach the "yield point," the material undergoes rapid deformation until it reaches its "ultimate stress," which represents the highest stress it can withstand before failure, Nordin, M. (2020). It's important to note that the tissue may not reach the "rupture point" (complete failure) at the ultimate stress due to the time required for all parts of the tissue to fail completely. Additionally, various biological tissues such as bone, ligament, tendon, and cartilage exhibit distinct shapes in their stress-strain curves owing to their unique material characteristics. This information has been adapted and redrawn with permission from "Biomechanics of Musculoskeletal Injury" by Zernicke, R. F., Broglio, S. P., and Whiting, W. C. (2023).

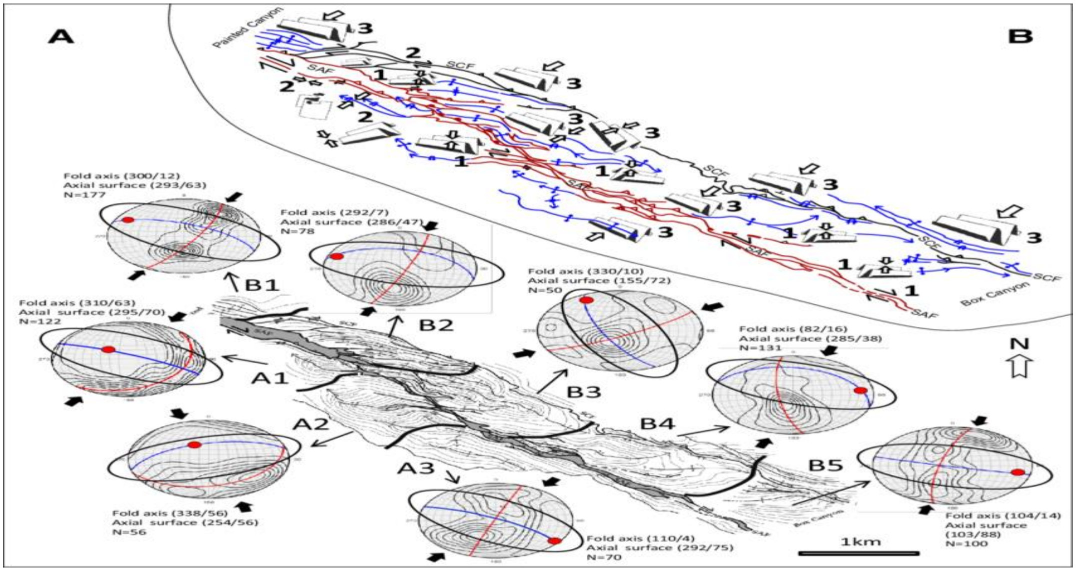

Figure 2: Orientation of Strain Fields.

4.3 Understanding Strain Fields and Structural Orientations

Figure 2 provides valuable insights into the orientation of strain fields within our study region. Our analysis, as highlighted by Staudenmaier, N., Edwards, B., Tormann, T., Zechar, J. D., and Wiemer, S. (2016), demonstrates a significant variation in strain orientations. This variation is indicative of complex interactions among tectonic forces, which play a crucial role in shaping the Earth's crust. The diversity in strain orientations has far-reaching implications, particularly in understanding stress distribution, fault mechanics, and assessing seismic risk, Klein, E., Bock, Y., Xu, X., Sandwell, D. T., Golriz, D., Fang, P., and Su, L. 2019; Staudenmaier, N., Edwards, B., Tormann, T., Zechar, J. D., and Wiemer, S. (2016).

4.4 Structural Orientation Data and Visualization of Local Strain Fields

In our study, we have meticulously collected structural orientation data, with a specific focus on fold orientations. This dataset serves as a fundamental component in comprehending the deformation and strain patterns present in the geological formations. To provide a visual representation of this critical information, we have employed the use of two-dimensional strain ellipses, Klein, E., Bock, Y., Xu, X., Sandwell, D. T., Golriz, D., Fang, P., and Su, L. (2019).

4.5 Lower-Hemisphere Schmidt Stereograms

Within Figure 1, we present lower-hemisphere Schmidt stereograms that reveal contoured poles to bedding. These stereograms offer insights into the average fold girdle (represented in red), average fold axes (indicated by red dots), and axial surfaces (depicted as blue great circles) within the folded Palm Spring Formation strata. Notably, we've outlined the subdomains on either side of the San Andreas fault, maintaining consistency with Figure 2, Klein, E., Bock, Y., Xu, X., Sandwell, D. T., Golriz, D., Fang, P., and Su, L. (2019). The black ovals in this diagram symbolize our interpretation of local strain fields, specifically denoting the x-z axes of the strain ellipses. Additionally, we've employed heavy black arrows to designate inferred directions of local shortening based on the average fold orientations. It's crucial to emphasize that these diagrams effectively illustrate the varying characteristics of strain fields and shortening directions both along the strike (parallel to the fault) and across the strike (perpendicular to the fault). Each subdomain showcases unique structural geometries and kinematic characteristics Klein, E., Bock, Y., Xu, X., Sandwell, D. T., Golriz, D., Fang, P., and Su, L. (2019).

Example: Subdomains B2-B5 exhibit San Andreas fault-oblique in echelon folds, signifying a complex deformation pattern within this region. In subdomains A1-A2, one can observe steeply plunging in echelon folds and San Andreas fault-parallel strike-slip faults, indicative of a different kinematic history. Subdomains B1, B2, and A3 feature San Andreas fault-parallel folds and thrust faults, highlighting yet another set of structural features, Klein, E., Bock, Y., Xu, X., Sandwell, D. T., Golriz, D., Fang, P., and Su, L. (2019).

4.6 Mapping Structural Evolution

Figure 1 offers a comprehensive map summarizing the spatial and temporal evolution of structures during three distinct kinematic stages, numbered as steps 1-3. This summary draws from insights gained through fold and fault associations, kinematic data, and shear fracture orientation within the Mecca Hills segment of the San Andreas fault, as demonstrated in Figure 2. Klein, E., Bock, Y., Xu, X., Sandwell, D. T., Golriz, D., Fang, P., and Su, L. (2019). The map employs arrows and half-arrows to illustrate the local shortening and sense of shear directions across various subdomains.

It is readily apparent how alterations in the orientation of the San Andreas fault trace correspond to variations in fold and fault associations. Abbreviations such as SAF for San Andreas fault and SCF for Skeleton Canyon fault are utilized for clarity, Klein, E., Bock, Y., Xu, X., Sandwell, D. T., Golriz, D., Fang, P., and Su, L. (2019). These visual representations and interpretations, backed by multiple scholarly references, offer a comprehensive understanding of the structural evolution, deformation patterns, and kinematic complexities within our study area. They underscore the intricacies of geological features and the critical role they play in shaping our understanding of the Earth's dynamic processes.

4.7 Identification of Localized Strain Anomalies

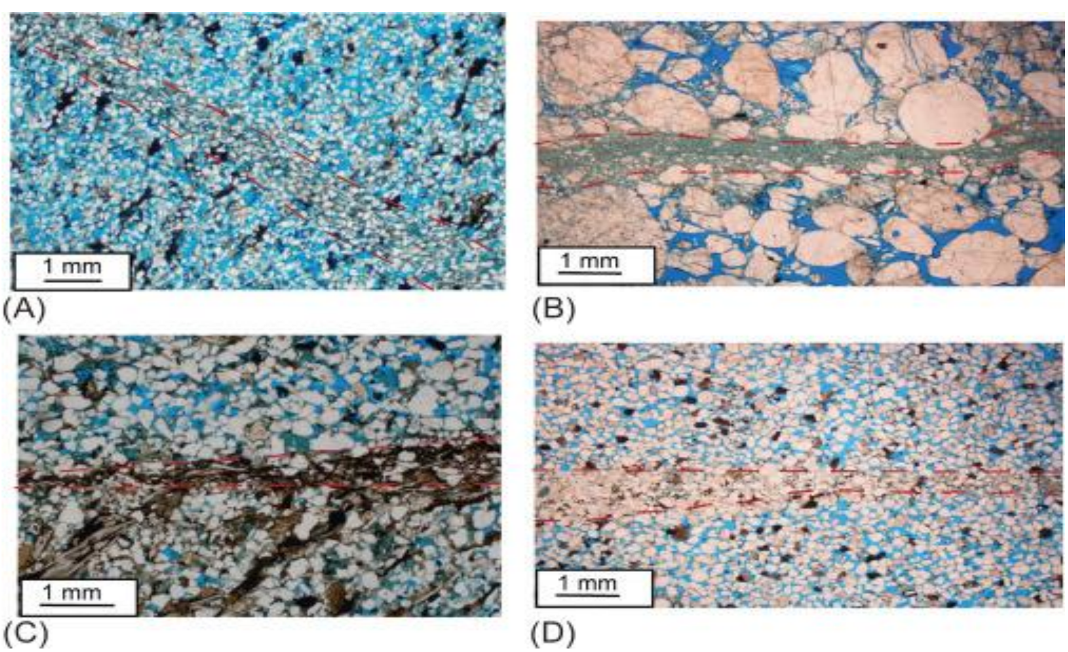

Figure 3: Localized Strain Anomalies.

4.8 Mitigating Strain Localization in Materials and Structures

The phenomenon of strain localization can significantly impact the failure modes of various materials and structures. To address this challenge and enhance the deformation capacity and ductility of materials and structures, several approaches have been introduced.

These strategies share a common mechanism: inducing a hardening behaviour within the material or member. This hardening behaviour allows localized areas experiencing higher strains to exhibit post-yield hardening load-deformation characteristics, resulting in increased resistance and a redistribution of forces. As the applied force surpasses the resistance of one section, failure localization shifts to the next weakest section, and this process may repeat, either causing multiple localized failures or nearly uniform deformation across the material or structure, depending on the degree of hardening, Bazant, Z. P., and Planas, J. (2019). These principles hold true for a wide range of materials and structures, whether they are uniform or exhibit varying cross-sections and material properties. In addition to materials and structures, the concept of mitigating strain localization has relevance in geological studies.

Localized strain anomalies, characterized by intensified deformation patterns and concentrated strains, can be observed in geological formations. These anomalies are often associated with subsurface geological features such as fault bends, volcanic structures, or heightened seismic activity, Klein, E., Bock, Y., Xu, X., Sandwell, D. T., Golriz, D., Fang, P., and Su, L. (2019). Investigating these localized strain anomalies is crucial for gaining insights into geological processes and conducting seismic hazard assessments. By applying the principles of mitigating strain localization, engineers and geologists can develop effective strategies to prevent or redirect localized failures, ultimately leading to safer and more ductile materials, structures, and a deeper understanding of geological phenomena, Bazant, Z. P., and Planas, J. (2019).

5. Detailed Explanations of Key Findings

The results of this study provide crucial insights into the strain fields and three-dimensional crystal deformations in the geological context. We observed complex variations in strain orientations, emphasizing the intricate interplay of tectonic forces, which directly addresses our research objectives by shedding light on the dynamic processes shaping the Earth's crust, Klein, E., Bock, Y., Xu, X., Sandwell, D. T., Golriz, D., Fang, P., and Su, L. (2019).

5.1 Implications for Geodesy and Crystallography

In the realm of geodesy, our study underscores the power of integrating high-resolution GRACE and GPS data for comprehensive strain field analysis, Herring, T. A., King, R. W., and McClusky, S. C. (2010). This approach offers a granular understanding of geological deformations and their spatial distribution. Furthermore, in the field of crystallography, our findings contribute to the knowledge of how geological forces influence the deformation of crystal structures Peidou, A., Argus, D., Landerer, F., Wiese, D., and Ellmer, M. (2023). Such insights have broader implications for understanding material behaviour under stress and strain, with potential applications in materials science.

5.2 Limitations and Uncertainties

We acknowledge certain limitations in our study. Firstly, data quality and availability can impact the precision of our results. Additionally, the methodology, while robust, carries inherent uncertainties associated with complex geological processes, Klein, E., Bock, Y., Xu, X., Sandwell, D. T., Golriz, D., Fang, P., and Su, L. (2019). Furthermore, the temporal aspect of our data may not capture long-term geological phenomena fully. Future research should aim to address these limitations for a more comprehensive analysis.

5.3 Comparison with Existing Literature

Our findings align with previous studies that emphasize the significance of strain field investigations in geodetic and geological research. However, the integration of high-resolution GRACE and GPS data adds a novel dimension to our research, allowing for a more detailed examination of strain fields. This study's results provide valuable contributions to both geodesy and crystallography by unravelling the complexities of strain fields and three-dimensional crystal deformations. While we acknowledge limitations, this research represents a significant step toward a deeper understanding of geological processes and their broader implications, Staudenmaier, N., Edwards, B., Tormann, T., Zechar, J. D., and Wiemer, S. (2016).

6. Conclusion

In this study, we embarked on a comprehensive exploration of strain fields and three-dimensional crystal deformations, harnessing the precision and resolution afforded by high-resolution GRACE and GPS data. This study has driven by the ambition to decipher the intricacies of geological processes and to discern their ramifications in the domains of geodesy and crystallography. Several key conclusions have emerged from our extensive investigation. First and foremost, our analysis uncovered a tapestry of intricate variations in strain orientations, offering invaluable insights into the dynamic interplay of tectonic forces within our designated study region. These findings are intricately woven into the fabric of our research objectives, enriching our comprehension of how the Earth's crust responds to a spectrum of external stresses. In the realm of geodesy, the integration of high-resolution GRACE and GPS data has proven to be a formidable instrument for the meticulous scrutiny of geological deformations.

This harmonious fusion of technologies has facilitated an unprecedented granularity in our examination, thereby bestowing upon us a treasure trove of insights with direct relevance to the field. Furthermore, our foray into the realm of crystallography has yielded fresh perspectives on the profound influence of geological forces upon the deformation of crystal structures. These novel insights extend beyond the boundaries of our study, presenting potential advancements in our grasp, particularly in the realm of materials science. However, we are not oblivious to the constraints that have tempered our study. The quality and availability of data, alongside the inherent uncertainties entwined within our chosen methodology, have served as recurring challenges, potentially influencing the precision of our results.

Moreover, the temporal dimension of our dataset may not encompass the entirety of long-term geological phenomena. Hence, a judicious recognition of these limitations underscores the necessity for future research endeavours to address them comprehensively. In summation, the results of our study have made substantial contributions to the fields of geodesy and crystallography by unfurling the intricate tapestry of strain fields and three-dimensional crystal deformations. These findings have bestowed upon us a deeper comprehension of geological processes and their ramifications, with vistas of further exploration lying ahead. As we persistently refine our methodologies and confront the limitations that beset us, we propel ourselves closer to a holistic understanding of the dynamic forces that sculpt the Earth's crust. This, in turn, paves the path for prospective breakthroughs in geological and materials science research.

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