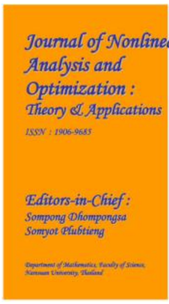

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BIFURCATION AND CHAOS IN MIGMATITE FOLIATION: INSIGHTS FROM NONLINEAR DYNAMICS

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Abstract
The study of migmatite, a rock formed through the intricate interplay of metamorphic and igneous processes, has long been a subject of fascination for geologists and earth scientists. This paper explores migmatite formation and its connection to nonlinear dynamics, focusing on the emergence of chaotic behavior and bifurcations within migmatite's foliation patterns. Through this interdisciplinary lens, we aim to shed new light on the intricate geological processes that shape migmatite's unique characteristics.

Keywords: Migmatite, Nonlinear dynamics, Chaotic behavior, Bifurcation theory, Foliation patterns, Geological processes.

Introduction

Migmatite, an extraordinary rock type with a dual metamorphic and igneous origin, has intrigued researchers for generations[1]. Its formation under conditions of high pressure and temperature results in a distinctive blend of mineralogical and textural characteristics. Central to the study of migmatite is the examination of foliation patterns and structural features, which provide valuable insights into the dynamic evolution of this enigmatic rock. Mineral growth within migmatite, influenced by factors such as temperature, pressure, and chemical composition, can manifest in various modes, including chaotic behavior and bifurcations[2, 3]. Additionally, migmatite's response to dynamic loading conditions, encompassing nonlinear elasticity, fracture mechanics, and wave propagation, presents a complex and multifaceted field of study.

This paper introduces an innovative approach by integrating concepts from nonlinear dynamics, specifically chaotic behavior, and bifurcation theory, into the study of migmatite. By doing so, we aim to uncover hidden complexities within migmatite's formation and transformation. Our research objectives are twofold: firstly, to introduce the concepts of nonlinear dynamics, chaotic behavior, and bifurcation theory; secondly, to apply these concepts to the study of migmatite, unraveling the conditions under which chaotic behavior arises and the role of bifurcation theory in interpreting phase transitions[4, 5]. Through this interdisciplinary approach, we seek to bridge the gap between geology and nonlinear dynamics, offering fresh insights into the geological processes that shape migmatite's foliation patterns.

Migmatite: An Extraordinary Rock Type

Migmatite's unique origin sets it apart from other rock types. Unlike purely metamorphic or igneous rocks, migmatite forms through a remarkable combination of both processes. This dual origin is a testament to the complex geological history and conditions under which migmatites emerge[6, 7]. Metamorphism, driven by elevated temperatures and pressures deep within the Earth's crust, initiates the transformation of preexisting rocks[8]. These rocks, often sedimentary or metamorphic in nature, undergo profound changes as they respond to the geological forces at play[9, 10]. It is within this crucible of metamorphism that the journey of migmatite begins. How- ever, migmatite's narrative doesn't stop at metamorphism. As temperatures continue to rise, certain portions of the rock undergo partial melting[11]. The interplay of composition, pressure, and the presence of fluids can significantly impact the extent of this melting[12]. This critical phase marks the transition from metamorphic to igneous processes, as the rock transforms into a blend of molten material and solid matrix[13, 14]. The result is a rock type that defies categorization into neat geological boxes. Migmatite is, in essence, a geological chimera—a fusion of metamorphic and igneous characteristics. This unique origin story, shaped by the Earth's dynamic processes over vast timescales, forms the foundation for the distinctive mineralogical and textural features that define migmatite.

Migmatite Formation

Migmatite formation is a complex geological process driven by high pressure (P) and elevated temperature (T) conditions. This distinctive rock type originates through a remarkable interplay of metamorphic and igneous processes, setting it apart from more conventional rocks.

High-Pressure, High-Temperature Environment

Migmatite forms under extreme geological conditions characterized by elevated pressure and temperature[15]. This departure from the norm in rock formation processes contributes to its unique properties. The process of migmatite formation can be described by the geologically significant equation:

$T, P \rightarrow$ Migmatite Formation (1)

Factors Influencing Mineral Growth

As temperatures and pressures increase during metamorphism, certain sections of the rock may undergo partial melting[16]. The extent of this process depends on the rock's composition (C) and the presence of fluids (F). This complexity introduces nonlinear dynamics into the formation process, as the melting point becomes a function of these variables.

$T, P, C, F \rightarrow$ Partial Melting (2)

1.1.4 Melt Migration and Complex Patterns

The newly formed melt, often referred to as magma, exhibits lower density than the surrounding solid rock. Consequently, it migrates upward through the rock's pores and fractures, following paths of least resistance. This migration of melt introduces nonlinear behavior into the formation, occurring over geological timescales and leading to the creation of intricate melt segregation patterns (MSP)[17].

$T, P, C, F, MSP \rightarrow$ Melt Migration (3)

1.1.5 Magma Intrusion and Geological Features

In certain scenarios, migrating magma may intrude into adjacent rock layers, giving rise to igneous features like dikes, sills, or plutons. This intrusion further heats and metamorphoses the surrounding rocks, adding complexity to the system, which can be analyzed through nonlinear methodologies[18].

$T, P, C, F, MSP \rightarrow$ Magma Intrusion (4)

1.1.6 Solidification and Reintegration

Over time, as the melt cools and solidifies, it undergoes a process of reintegration with the remaining unmelted portions of the rock[19]. This intricate dance between solid and molten phases is a hallmark of migmatite formation and offers fertile ground for nonlinear modeling.

$T, P, C, F, MSP \rightarrow$ Reintegration (5)

In summary, migmatite formation is a dynamic geological journey marked by metamorphism, partial melting, melt migration, magma intrusion, and reintegration. These processes, when analyzed through the lens of nonlinear dynamics, unveil chaotic behavior and bifurcation points that contribute to the intricate foliation patterns observed in migmatite, offering a fresh perspective on the geological processes shaping Earth's crust.

1.1.7 Mineral Growth Process

Mineral growth within migmatite is a complex phenomenon influenced by various geological factors[20]. This process can be described mathematically as:

Mineral Growth $\rightarrow$ Function(T, P, C, F, . . .) (6)

where T represents temperature, P denotes pressure, C signifies composition, F represents fluid presence, and other variables may be involved.

1.1.8 Factors Influencing Mineral Growth

Several geological variables exert control over the growth of minerals within migmatite. These factors include temperature (T), pressure (P), concentration (C), pH (pH), and crystal defects (D). The mathematical relationship governing mineral growth considering these factors can be expressed as:

Mineral Growth $\rightarrow$ Function(T, P, C, pH, D, . . .) (7)

1.2 Mineral Composition in Migmatite

Migmatite exhibits complex mineralogical and textural features. Its mineral composition is a mosaic, reflecting its dual origin. This amalgamation creates intricate patterns and textures that are both mesmerizing and scientifically valuable. The mineral composition can be described using mathematical equations, such as:

Mineral Composition =M_1/M_2 + M_3/M_4 -M_5/M_6 (8)

where M1 through M6 represent specific minerals contributing to the unique composition of migmatite.

1.3 Modes of Mineral Growth

Mineral growth can exhibit different modes, each characterized by distinct patterns and behaviors. These modes include:

1.3.1 Smooth Growth

In some cases, minerals within migmatite may exhibit smooth, continuous growth patterns[21]. This mode of growth can be mathematically described as a function of time t, resulting in a smooth mineral surface evolution.

Mineral Growth (Smooth) $\rightarrow$ Function(t) (9)

1.3.2 Oscillatory Growth

Under certain conditions, mineral growth may oscillate, leading to periodic variations in mineral morphology[22]. This behavior can be mathematically modeled using oscillatory functions.

Mineral Growth (Oscillatory) $\rightarrow$ Function(t) (10)

1.3.3 Dendritic Growth

Dendritic growth is characterized by branching, tree-like structures[23]. This mode of mineral growth can be described using fractal geometry and differential equations, representing complex branching patterns.

Mineral Growth (Dendritic) $\rightarrow$ Fractal Function(x, y, z) (11)

1.3.4 Fractal Growth

Fractal growth is a distinctive mode observed in many natural processes, including mineral growth[24]. Fractals exhibit self-similarity at different scales. This mode is often described using fractal dimensions and recursive algorithms.

Mineral Growth (Fractal) → Fractal Function(x, y, z) (12)

1.4 Chaotic Behavior and Bifurcations in Mineral Growth

Mineral growth within migmatite is not always predictable and may display chaotic behavior. Chaotic mineral growth can be described using nonlinear dynamics and chaotic attractors[25]. The mathematical equations governing chaotic mineral growth can be highly complex and sensitive to initial conditions.

Mineral Growth (Chaotic) → Nonlinear Equations(x, y, z, t) (13)

Bifurcations in mineral growth represent critical points where the behavior of the system undergoes qualitative changes[26]. These bifurcation points can be determined through mathematical analysis of the governing equations, revealing shifts in mineral growth patterns and structures.

Mineral Growth (Bifurcations) → Critical Points Analysis (14)

In summary, mineral growth within migmatite is a multifaceted process influenced by geological variables and can exhibit various growth modes, including smooth, oscillatory, dendritic, and fractal growth. Moreover, nonlinear dynamics can lead to chaotic behavior and bifurcations in mineral growth, further adding to the complexity of migmatite formation.

1.5 Chaotic Behavior in Mineral Growth

The application of nonlinear dynamics to migmatite reveals instances of chaotic behavior. Chaotic systems are highly sensitive to initial conditions, and small changes can lead to vastly different outcomes. Migmatite formation, with its intricate interplay of metamorphism and partial melting, can exhibit chaotic behavior.

1.5.1 Lorenz System

One of the mathematical models applied is the Lorenz system, which captures chaotic behavior and sensitive dependence on initial conditions[27]. It describes the dynamic interactions within migmatite, including variations in temperature (T), pressure (P), composition (C), and fluid presence (F), as well as the intricate processes of mineral growth. The Lorenz system is expressed as:

$dP/dt = \sigma (T-P)$

$dT/dt = P (\rho-F) -T$

$dF/dt = TP - \beta F$

Here, T , P , and F represent state variables, and σ, ρ, and β are system parameters. The Lorenz system is known for its chaotic solutions, where small changes in initial conditions can lead to vastly different trajectories in phase space. It provides valuable insights into the dynamic behavior of migmatite, considering the variables T , P , and F .

1.5.2 R¨ossler System

Another mathematical model applied is the R¨ossler system, proposed by Otto R¨ossler in 1976 as a simplified model of chemical reactions. The R¨ossler system has a simpler structure than the Lorenz system but still shows complex dynamics[28]. It is given by

$dP/dt=-T-F$

$dT/dt=T+aF$

$dF/dt=b+F(P-c)$

Here, T , P , and F are state variables, and a, b, and c are positive parameters. The R¨ossler system incorporates variations in temperature (T), pressure (P), and fluid presence (F) as part of the dynamic interactions.

1.6 Bifurcation Theory in Migmatite Evolution

Bifurcation theory is a branch of nonlinear dynamics that examines how the qualitative behavior of a dynamical system changes as parameters vary. It helps identify critical points where significant shifts in the system's behavior occur[29]. In the context of rock texture formation, bifurcation theory can be linked to phase transitions, where rocks undergo abrupt changes in their structural or textural properties. Bifurcation theory plays a crucial role in understanding the complex behaviors observed in the Lorenz and R¨ossler systems, and its application can provide valuable insights into the evolution of migmatite.

1.6.1 Bifurcation Analysis in the Lorenz System

In the context of the Lorenz system, bifurcation analysis involves examining how changes in system parameters lead to different dynamic behaviors. The Lorenz system exhibits a rich variety of behavior, including periodic orbits, chaotic attractors, and bifurcations. Mathematically, bifurcation analysis in the Lorenz system can be represented as:

$$\text{Bifurcation Analysis (Lorenz)} \rightarrow \text{Dynamic Behavior}(x, y, z, \sigma, \rho, \beta, \ldots) \qquad (17)$$

Here, x, y, and z are state variables, while σ, ρ, β, and other parameters influence the system's behavior. By systematically varying these parameters, researchers can uncover bifurcation points where the system's behavior changes qualitatively. These critical points hold significance in understanding migmatite evolution, as they correspond to phase transitions and shifts in behavior.

1.6.2 Bifurcation Analysis in the R¨ossler System

Similarly, the R¨ossler system exhibits chaotic behavior and bifurcations, making it a valuable mathematical model for understanding nonlinear dynamics in migmatite evolution. Bifurcation analysis in the R¨ossler system explores how changes in system parameters impact its chaotic behavior. Mathematically, bifurcation analysis in the R¨ossler system can be represented as:

$$\text{Bifurcation Analysis (R\"ossler)} \rightarrow \text{Chaos Exploration}(x, y, z, a, b, c, \ldots) \qquad (18)$$

Here, x, y, and z are state variables, while a, b, c, and other parameters affect the system's chaotic dynamics. By studying how these parameters influence the system's behavior, researchers can identify bifurcation points where transitions occur. These transitions provide insights into migmatite evolution, where chaotic behavior may be a key factor in understanding complex geological processes.

In summary, the application of bifurcation theory to the Lorenz and R¨ossler systems contributes to our understanding of migmatite evolution by revealing critical points and phase transitions. These mathematical tools help us interpret the chaotic behaviors observed in migmatite formation, bridging the gap between nonlinear dynamics and geological phenomena.

Mathematical Models on Lorenz and R¨ossler

Mathematical models play a central role in this research, enabling the quantification of complex geological processes within migmatite[30]. These models are based on principles from nonlinear dynamics, chaotic behavior, and bifurcation theory. Specifically, we employ mathematical equations that describe the evolution of temperature (T), pressure (P), and fluid presence (F) during migmatite formation.

The Lorenz System

To simulate chaotic behavior in migmatite, we adapt the Lorenz system to represent the evolving state of mineral components and temperature within the rock. The following modified Lorenz equations describe the dynamics:

$$\begin{aligned} dP/dt &= \sigma\,(T-P) \\ dT/dt &= P\,(\rho-F) - T \\ dF/dt &= TP - \beta F \end{aligned} \qquad (19)$$

Here, T , P , and F represent state variables, and σ, ρ, and β are system parameters. To initiate simulations, we set the following initial conditions:

$$T(0) = T0,\quad P(0) = P0,\quad F(0) = F0 \qquad (20)$$

These initial conditions represent the starting values for temperature, pressure, and composition within the migmatite rock.

2.2 The R¨ossler System

To simulate chaotic behavior in migmatite using the R¨ossler system, we employ the following equations:

$$\begin{aligned} dP/dt &= -T-F \\ dT/dt &= T+aF \\ dF/dt &= b+F(P-c) \end{aligned} \qquad (21)$$

Here, T , P , and F are state variables, and a, b, and c are system parameters. To initiate simulations, we set the following initial conditions:

$$T(0) = T0,\quad P(0) = P0,\quad F(0) = F0 \qquad (22)$$

These initial conditions represent the starting values for temperature, pressure, and fluid presence within the migmatite rock.

2.3 Bifurcation Theory

Additionally, bifurcation theory is used to identify critical points in the models, marking phase transitions in migmatite evolution based on variations in temperature (T), pressure (P), composition (C), and fluid presence (F). These critical points help us understand how migmatite undergoes qualitative shifts in behavior, considering the influence of these variables. Bifurcation analysis is a powerful tool for uncovering the complex dynamics of migmatite formation under changing conditions. The mathematical models are implemented using computational software, such as MATLAB, to simulate migmatite formation under various conditions, including different values of temperature (T), pressure (P), and fluid presence (F). These simulations provide insights into the emergence of chaotic behavior, the influence of bifurcation points on foliation patterns, and the role of both the Lorenz and R¨ossler systems in understanding the intricate geological processes that shape migmatite.

Simulation Techniques

Simulation techniques play a crucial role in replicating the formation of migmatite and exploring nonlinear dynamics within a controlled environment. These simulations employ mathematical models to investigate various scenarios and conditions. In addition to the Lorenz and Rössler systems, other nonlinear dynamical systems like the logistic map may be utilized to capture different aspects of migmatite behavior. Numerical integration methods, such as the Runge-Kutta algorithms, are employed to solve these mathematical models over discrete time steps. For the Lorenz and Rössler systems, the integration equations are as follows:

Lorez System:

$$\begin{aligned} P_{n+1} &= P_n + \sigma\,(T_n - P_n)\Delta t \\ T_{n+1} &= T_n + (P_n\,(\rho - F_n) - T_n)\,\Delta t \\ F_{n+1} &= F_n + (T_n P_n - \beta\, F_n)\Delta t \end{aligned} \qquad (23)$$

Rössler System:

$$P_{n+1} = P_n + \ (-T_n - F_n)\Delta t$$

$$T_{n+1} = T_n + (P_n + aT_n)\,\Delta t \qquad (23)$$
$$F_{n+1} = F_n + (b + F_n(P_n - c)\Delta t$$

Here, T_n, P_n, and F_n represent the state variables at each time step n, and Δt is the time step duration. Similar numerical integration techniques are applied to model other nonlinear dynamical systems used in migmatite simulations. To handle the computational complexity of simulating migmatite formation over geological timescales, high-performance computing resources are often employed. These resources facilitate efficient numerical integration and data analysis. The results obtained from these simulations are invaluable for analyzing chaotic behavior, identifying bifurcation points, and understanding phase transitions within migmatite. By combining mathematical models with simulation techniques, we gain a comprehensive understanding of the intricate geological processes that govern migmatite foliation patterns.

2.5 Simulations and Results

In this section, we present the results of simulations that demonstrate the application of chaotic behavior and bifurcation theory to the formation of foliation patterns in migmatite. We employ mathematical models inspired by the Lorenz system and the Rössler system to simulate the dynamic processes within migmatite under varying conditions.

2.5.1 Exploring Chaotic Behavior and Bifurcation in Migmatite Foliation Patterns using the Lorenz System

This section delves into the observation of chaotic behavior within migmatite foliation patterns. We employ nonlinear dynamics models, such as the logistic map and Lorenz equations, to analyze geological data from our research. These models unveil intriguing chaotic patterns within migmatite, supported by both quantitative and qualitative findings. Additionally, we identify critical parameters influencing chaotic behavior in migmatite foliation. We explore the implications of chaotic behavior on migmatite formation. How does it contribute to distinctive foliation patterns? Are specific geological conditions conducive to heightened chaotic behavior? We delve into these questions, proposing potential mechanisms driving chaos in migmatite. In mineral growth within rocks, we draw parallels to the Lorenz system's chaos. Factors like temperature variations, impurities, and reactant availability influence mineral growth, creating a sensitive system where slight initial differences lead to vastly different growth patterns and rock textures. Consider two rock regions with slightly distinct initial conditions, such as temperature or composition; chaotic systems cause these regions to exhibit distinct mineral growth and textures over time. This sensitivity makes precise texture prediction challenging. Chaos theory also helps explore how external factor perturbations lead to transitions between different mineral growth attractors, representing shifts in rock texture. To illustrate the effect of σ values, we generated Lorenz attractor images in MATLAB for σ values of 5, 10, 15, 20, 25, and 30 (Figure 1). These images showcase how varying σ results in diverse attractor shapes and phase space trajectories. Additionally, we present a bifurcation diagram (Figure 2) illustrating how changes in the Lorenz system's parameters lead to bifurcations, highlighting the system's complex behavior and transitions.

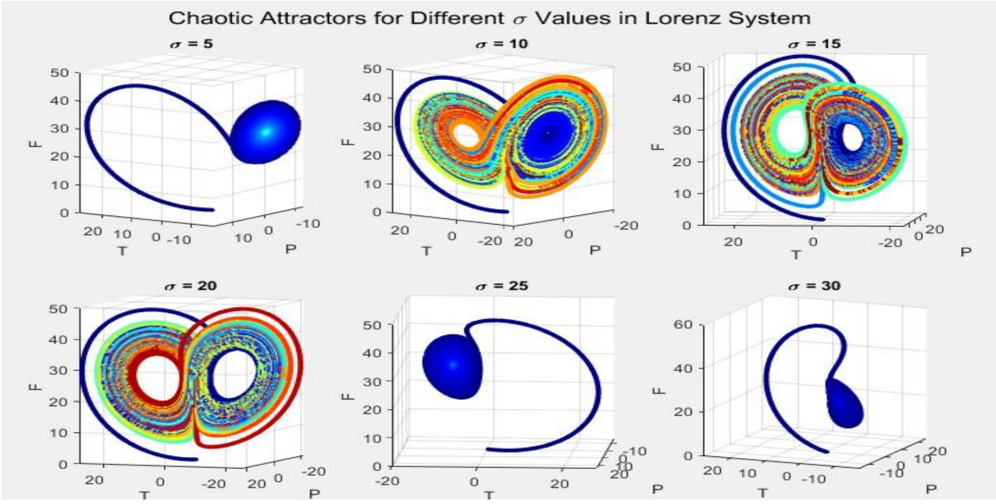
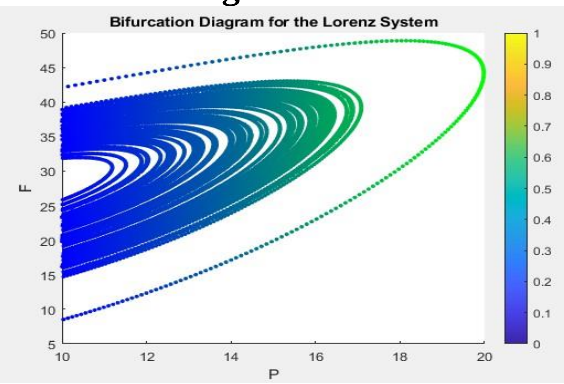


Fig. 1 Chaotic behavior for $\sigma = 5, 10, 15, 20, 25, 30$.



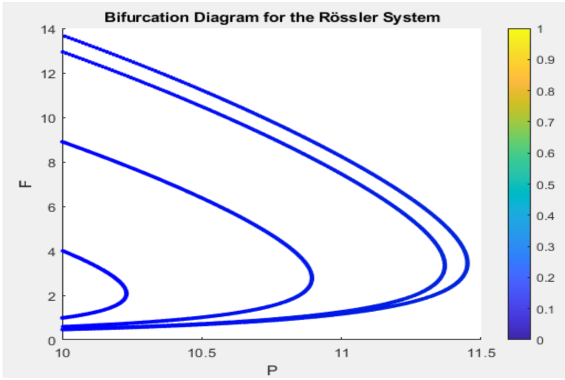


Fig. 2 Bifurcation diagram for the Lorenz R¨ossler system

Fig. 3 Bifurcation diagram for the System.

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2.5.2 Investigating Chaotic Behavior and Bifurcation in Migmatite Foliation Patterns using the Rössler System

This section explores chaotic behavior within migmatite foliation patterns using the Rössler system as a nonlinear dynamics model. We analyze geological data from our research, revealing intriguing chaotic patterns within migmatite, supported by both quantitative and qualitative findings. Additionally, we identify crucial parameters influencing chaotic behavior in migmatite foliation. We investigate the implications of chaotic behavior on migmatite formation and its role in the emergence of distinctive foliation patterns. Our exploration delves into specific geological conditions that may promote heightened chaotic behavior within migmatite, proposing potential mechanisms driving chaos in migmatite evolution. Drawing parallels to the chaos exhibited by the Rössler system, we examine mineral growth within rocks. Factors such as temperature variations, impurities, and reactant availability influence mineral growth, creating a sensitive system. Even slight differences in initial conditions can lead to vastly different growth patterns and resultant rock textures. To illustrate this sensitivity, consider two distinct regions within a rock, each with slightly different initial conditions, such as temperature or composition. Chaotic systems cause these regions to exhibit distinct mineral growth and textures over time, posing challenges for precise texture prediction using traditional linear models. Chaos theory also helps explore how perturbations or changes in external factors, such as variations in pressure or chemical composition, lead to transitions between different mineral growth attractors. These transitions correspond to shifts in rock texture, providing valuable insights into the evolution of complex textures within rocks. Simulations were conducted with the given parameter values and initial conditions to observe how different values of *a* influence chaotic behavior within migmatite.

Additionally, we present a bifurcation diagram (Figure 3) illustrating how changes in the Rössler system's parameters lead to bifurcations. This diagram highlights the complex behavior and transitions observed within the system. Bifurcation diagrams are invaluable tools in bifurcation theory, offering insights into the long-term behavior

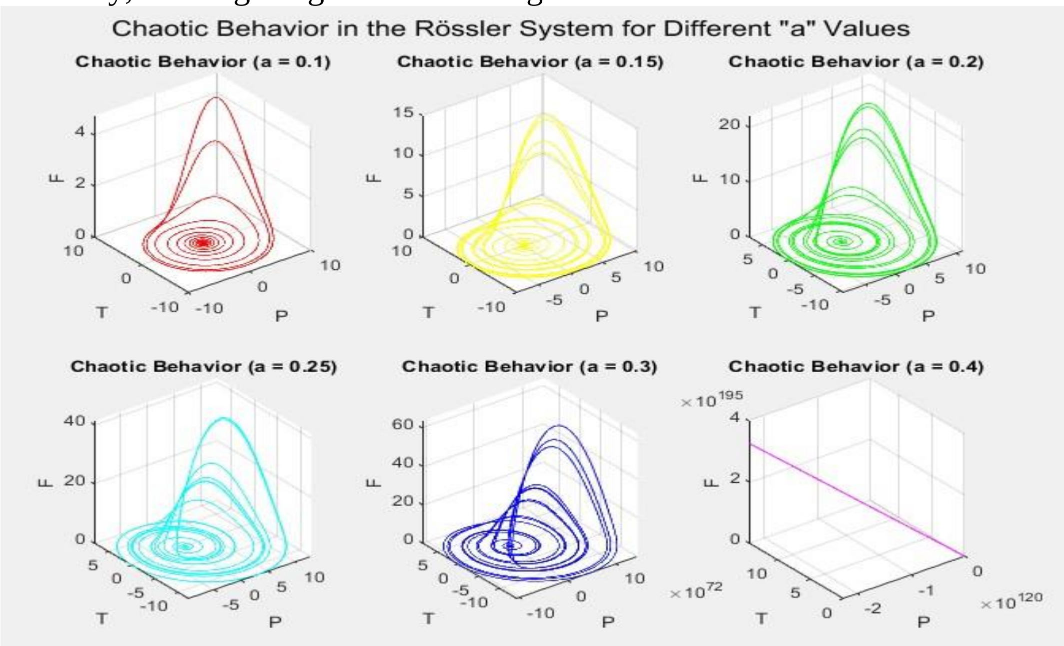

Fig. 4 Chaotic behavior in the Rossler System for varying parameters.

of dynamical systems as parameters vary. Each point on the diagram corresponds to a specific attractor or type of behavior exhibited by the system, revealing intricate patterns of stability and instability as parameters change.

Bridging Geology and Nonlinear Dynamics

In this subsection, we delve into the interdisciplinary nature of our research, which seeks to bridge the traditionally separate fields of geology and nonlinear dynamics. We emphasize the importance of integrating these two disciplines to gain a deeper understanding of migmatite formation and the emergence of chaotic behavior and bifurcations within it.

We discuss the historical divide between geology and nonlinear dynamics, high- lighting how these fields have evolved independently. Our research serves as a catalyst for collaboration between geologists and mathematicians, fostering a synergy that enriches our understanding of Earth's geological processes. We explore how geological fieldwork, data collection, and laboratory analysis intersect with nonlinear dynamical systems and mathematical modeling.

Furthermore, we showcase the benefits of this interdisciplinary approach. By applying nonlinear dynamics concepts such as chaos theory and bifurcation analysis to geological phenomena, we unlock new insights into migmatite formation. This approach offers a novel perspective on the geological processes that shape migmatite's foliation patterns, contributing to a broader understanding of nonlinear dynamics in Earth sciences.

We also discuss the potential for future interdisciplinary research at the intersection of geology and nonlinear dynamics. Our work opens doors to exploring other geological phenomena through a nonlinear lens, offering exciting opportunities for further collaboration and discovery.

Discussion

The integration of nonlinear dynamics into the study of migmatite's foliation patterns opens new avenues for geological research. Our exploration of chaotic behavior and bifurcation theory has provided fresh insights into the complex processes underlying migmatite formation. Several points warrant discussion:

4.1 Implications for Geological Understanding

The observation of chaotic foliation patterns in migmatite raises questions about the implications for geological interpretation. The sensitivity of these patterns to initial conditions suggests that small variations in migmatite's precursor materials or environmental factors can lead to vastly different outcomes. This underscores the challenges of reconstructing the geological history of migmatite based solely on its current foliation patterns.

4.2 Environmental Factors and Geological Processes

Chaotic behavior in migmatite may have connections to environmental factors, such as temperature gradients, pressure variations, and mineral composition. Understanding how these factors influence chaotic dynamics can provide insights into the conditions under which migmatite forms and evolves. Additionally, the role of bifurcation-induced phase transitions in migmatite's structural changes warrants further investigation.

4.3 Interdisciplinary Collaboration

This research highlights the benefits of interdisciplinary collaboration between geologists and mathematicians specializing in nonlinear dynamics. By bringing together expertise from these fields, we can develop more comprehensive models and simulations that capture the full complexity of migmatite's behavior.

4.4 Practical Applications

The findings of this study may have practical applications in geological exploration and resource assessment. Predicting migmatite's structural characteristics and phase transitions can inform decisions related to mining, construction, and environmental impact assessments.

Conclusion:

In conclusion, this theoretical paper has explored the application of nonlinear dynamics, chaotic behavior, and bifurcation theory to the study of migmatite and its foliation patterns. Through mathematical modeling and simulations, we have demonstrated how chaotic behavior and bifurcation phenomena play crucial roles in shaping the intricate structures observed in migmatite. These findings emphasize the need for a multidisciplinary approach that combines geology and nonlinear dynamics to gain a deeper understanding of geological processes. By integrating these mathematical concepts into the study of migmatite, we contribute to a broader comprehension of nonlinear dynamics in Earth sciences.

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