Structural, petrological, and geochronological analysis of salt diapirs and their caprocks: implications for growth dynamics of salt diapirs in Iran

Sadegh Adineh

This PhD thesis explores the geological complexities of the Karmostaj, Siah Taq, and Paskhand salt diapirs in the Zagros Fold and Thrust Belt, focusing on their role as field analogues for studying caprock in Iranian salt diapirs within orogenic settings. The research aims to understand the origin, composition, deformation, and fluid interactions of the salt diapir caprock and how these elements influence the development of surrounding sedimentary structures. Utilizing a multidisciplinary approach, the study integrates field observations with structural, geochemical, stratigraphical, sedimentological, petrophysical, and petrographical analyses. Key findings include:

1. Origin of Salt Diapir Caprock: Investigating the carbonate caprock formed during the Late Ediacaran, the research highlights the impact of climatic shifts and the emergence of complex life on microbial carbonate deposition in nutrient-rich ocean environments. This period is crucial for understanding the early development of multicellular organisms and the geological context of caprock formation.

2. Re-examination of Caprock Formation: Challenging traditional interpretations of Iranian salt diapirs as salt glaciers, the study presents evidence of extensively deformed caprock, suggesting a need to revisit conventional understandings of these geological structures. It proposes new scenarios for diapir extrusion processes, emphasizing the importance of geophysical surveys.

3. Microscopic Porosity: Through mercury intrusion porosimetry and microstructural analysis, significant variations in caprock porosity were observed, attributed to geochemical and mechanical processes like sulphate reduction and deformation-driven recrystallization. This reveals the complex interactions influencing caprock integrity.

4. Reactivation of Salt Diapirs: Analyzing diapir reactivation during Zagros Folding through halokinetic sequences, the study provides insights into the growth dynamics of salt diapirs and their influence on sedimentation and regional tectonics, especially during the Oligocene-Miocene.

5. Dolomitization Processes: Investigating the Late Ediacaran-Early Cambrian dolomite rocks, the thesis explores the origins and diagenetic history of these rocks, highlighting the role of microbial activity, seawater evaporation, hydrothermal fluids, and volcanic activity in their formation and alteration.

6. LA-ICP-MS Dating: Testing the feasibility of LA-ICP-MS dating on dolomitic fragments, the research updates the timeline for carbonate caprock formation, extending it back to the Late Ediacaran to Cambrian period and providing new insights into post-Shuram glaciation hydrothermal veins and stromatolites.

Overall, the thesis offers a comprehensive understanding of the Iranian salt diapir caprock, emphasizing its significance in the context of Earth's geological evolution and the study of extreme climates and microbial life during the Late Ediacaran period.

Thesis Synopsis

The thesis is structured in Journal Format, being divided into eight chapters. Part I is the introduction, providing a background for the salt tectonics aspects involved in this research, objective of thesis, methods, and summery of manuscripts. Original research is presented in stand-alone papers in Part II, Part III, Part IV, Part V, Part VI, Part VII. Part III and IV have already been accepted and published in the Journal of Structural Geology; Part V will be submitted for Earth Surface processes and landforms; Part II has just been submitted to Gondwana Research; and Part VII will be subbmitted to the Q1 journals. Part VIII summarizes and concludes the thesis. The Appendix includes supplimentary, original two papers and another research paper co-authored with Cofrade et al., 2023. The work presented in this thesis follows a logical order that is also related to the chronological workflow developed during the project. Each research chapter consists of a self-contained paper, including a separate abstract, introduction, geological setting and/or methods, results, discussion and conclusion. The research chapters are briefly summarised below.

Part II: Evidence for a Late Ediacaran drastic global warming event in the ProtoTethys/ Panthalassic Ocean (Hormuz Complex, Zagros Fold-and-Thrust Belt, Southern Iran)

The manuscript examined the origin of the carbonate caprock associated with the Iranian salt diapir in the Zagros Mountains, Iran, which confirmed its sourced from Late Ediacaran deposition with is interbeded with salt diapir or deposited before salt deposition. Therefore, this paper is mainly focused on Late Ediacaran (Neoproterozoic) glaciation, exploring carbonate stringers with syn-glacial deposits (diamictites) and cap carbonates with stromatolites. The research combines sedimentary, geochemical, and isotopic analyses to understand the complex history of glaciation and subsequent hydrothermal activity in this region, which is the main source of the carbonate caprock of the salt diapir. This study is crucial for gaining insights into Earth's climatic and tectonic history during the Neoproterozoic era.

Part III: Composition and deformation patterns of the caprock on salt extrusions in southern Iran – Field study on the Karmostaj and Siah Taq diapirs

The manuscript focuses on geological studies of two prominent salt diapirs, Karmostaj and Siah Taq, in the Zagros Mountains, Iran. These diapirs, often referred to as "salt glaciers," exhibit distinct caprock formations mainly consisting of dissolution breccia and gypsum, with a complex structure influenced by shearing along gypsum-rich zones. The research aims to understand the deformation within the caprock and its interaction with underlying salt structures. The study includes detailed structural and lithological mapping, analysis of rock samples, and presents three hypothetical scenarios to explain the diapirs' extrusion process and the associated deformation history of their caprocks. This research is significant for understanding the geodynamics of salt extrusions and caprock formation in a region known for its unique salt tectonics. This paper proposes three hypothetical scenarios to explain the extrusion and deformation history of these diapirs and suggest geophysical surveys for further insights

Part IV: Reaction driven porosity development and weakening in salt caprock (southern Iran)

This manuscript presents a detailed study on the microscopic porosity of salt caprock in two salt diapirs, Karmostaj and Siah Taq, in southern Iran. The study focuses on various lithological types of salt caprock, employing mercury intrusion porosimetry and microstructural analysis. It reveals significant variation in porosity and median throat size across different rock samples. The research discusses the impact of sulphate reduction, hydrocarbon-rich fluids, deformation, and fluid-assisted weakening on the caprock. This study is pivotal in understanding the physical

properties of salt caprock, particularly its porosity and permeability, which are crucial for assessing the safety of storage facilities such as gas or radioactive nuclear waste in the salt diapirs.

Part V: Growth of a salt diapir in an anticline - A record from the Cenozoic halokinetic sequences in the Zagros Fold and Thrust Belt Iran

This manuscript investigates the halokinetic sequences adjacent to the Paskhand salt diapir in the Zagros Fold and Thrust Belt. It examines the irregular development of these sequences in response to the caprock of the diapir's growth in a compressional setting (Zagros Fold and Thrust Belt). The study involves detailed mapping of sedimentary packages and structural analysis, highlighting the reactivation and evolution of the caprock of the diapir and its interaction with host rock sediments. In addition, this research contributes significantly to our understanding of the dynamic interplay between salt diapirs and their surrounding structural deformation and irregular sedimentary deposition around the salt diapir during onset of the Zagros Folding.

Part VI: Evidences of hydrothermal fluids recorded in the Ediacaran cap dolostone of the Hormuz Complex, In southern Iran – Field study on the carbonate caprock of Paskhand salt diapir (Under preparation)

This manuscript focuses on the study of Late Ediacaran-Early Cambrian dolomite rocks in the Hormuz Complex, Iran, with an emphasis on understanding the processes of dolomitization and the impact of hydrothermal fluids. The study aims to set up a diagenetic paragenesis of the dolomite, determine the geochemical characteristics of these dolomites, document the characteristics of hydrothermal alteration, and propose a conceptual model for dolomitization. It reveals that the dolomite rocks were extensively altered by hydrothermal fluids, which is supported by petrographic examinations, isotope geochemistry, and clumped isotope analysis. The research identifies different types of matrix dolomites and dolomite cements, providing a detailed interpretation of their formation mechanisms. This study contributes to the understanding of the complex diagenetic history of the Hormuz Complex, including the role of hydrothermal activity during the Late Ediacaran period, and offers insights into potential hydrocarbon exploration targets within these extensively dolomitized rocks.

Part VII: Towards in situ U–Pb dating of carbonate caprock of the Iranian salt diapirs (Preliminary study)

The manuscript explores using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) for dating dolomite in the caprock of Iranian salt diapirs, extending techniques initially developed for calcite. It successfully applies LA-ICP-MS to date dolomitic rocks from various ages, revealing that the caprock formations were deposited during the Late Ediacaran to Cambrian period. This refutes the traditional view of carbonate caprock atop Iranian salt diapirs and indicates the Hormuz Complex is older than previously believed. The study highlights the methodological approach, including sample preparation, analysis, and characterization techniques, concluding that LA-ICP-MS U-Pb dating of dolomite significantly advances understanding of dolomitization processes and the geological history of sedimentary basins.

The synthesis of this PhD thesis provides a comprehensive exploration of the dynamics of salt diapirs and their associated carbonate caprocks within the Zagros Fold and Thrust Belt. Utilizing a multidisciplinary approach, it investigates the origins, structural dynamics, microporosity, halokinetic sequences, and geochronology of these formations, thereby enhancing our understanding of their geological and evolutionary significance.

Implications of the Research:

The thesis' findings have wide-ranging implications for the geological sciences, offering insights into orogenic processes, sedimentary basin development, and early microbial activity and carbonate precipitation during critical climatic transitions. The advancements in U–Pb dating techniques for dolomites and the understanding of hydrothermal fluid activities provide a solid framework for dating geological formations, crucial for reconstructing past environments and exploring conditions that supported early life.

Directions for Future Research:

The thesis lays the groundwork for future research avenues that promise to further illuminate the complexities of geological formations and their implications for Earth's history. Key areas include:

1. Carbonate Successions and Paleoenvironmental Reconstruction: Investigating carbonate successions for insights into Eocambrian glacial events and early life development, aiming to understand the paleoenvironmental conditions that facilitated biological diversification.

2. Systematic Survey of Halokinetic Sequences Across the Zagros: A comprehensive survey of halokinetic sequences to understand the timing and dynamics of deformation, contributing to our knowledge of regional geodynamic processes and sedimentary basin evolution.

3. Geochemical and Temporal Analysis of Replacement Reactions: Studying the timing and geochemistry of replacement reactions to gain insights into the conditions of early oceans and their role in supporting early biological activity, providing critical information on ancient marine environments.

In summary, this thesis not only sheds light on the formation and evolution of salt diapirs and carbonate caprocks in an orogenic setting but also establishes a foundation for future research aimed at deepening our understanding of geological processes. This research is poised to contribute to our quest for knowledge about life's origins on Earth and potentially elsewhere, opening new avenues for understanding Earth's environmental and biological evolution.