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論文題目	Water and rock geochemical characterization to clarify fluid circulation process in transitional geothermal reservoir with a case study of the Wayang Windu field, West Java, Indonesia （水と岩石の地球化学的特徴抽出による遷移型地熱貯留層での流体循環プロセスの解明とインドネシア西ジャワ　ワヤン　ウインドゥ地区への適用）		

Formation process of transitional geothermal reservoir has not yet been fully understood due to complexities of hydrothermal fluid circulation and geologic structure. A transitional reservoir was defined as a zone with counter flow of condensates zones in vapor-dominated reservoir that overlays boiling liquid reservoir. To clarify the fluid origin and water-rock interaction (WRI) processes in the system, traditional isotope oxygen-18 and deuterium analysis was improved in order to clarify recharge zones of geothermal fluids, location of the boiling reservoir as the resource of vapor and liquid phases, and features of the most representative fluids in the reservoir called parent fluid. Parent fluid holds important role on controlling fluid circulation and its several processes occurred in the reservoir. Additional analyses of trace elements including rare earth elements and Sr isotopes were integrated in order to characterize hydrothermal flow in the shallower and deeper parts in details.

This doctoral dissertation begins with Introduction, including the research background, general notion of transitional geothermal reservoir, and objectives of this study in Chapter 1. An overview of geological settings and hydrogeology in Chapter 2 cover the highlights of regional and local geology of the study area, which significantly contributes to the characteristics of the reservoir as general information in the field study. The sampling locations and analytical methods of several instruments used in this study are also described in this chapter.

An investigation of the parental fluid, recharge elevation for production wells and surface manifestations, and the specification of a transitional zone by water to rock ratio (*W/R*) were described more in detail in Chapter 3. The water isotope ratios were corrected to remove effects of boiling in well bore and used for identifying the recharge elevations for geothermal fluids in reservoirs and surface manifestations. Clarification of the parent fluid was indispensable for understanding the origin of geothermal fluid and its subsequent flow processes. Geothermal flow patterns from meteoric recharge to discharge, including WRI, boiling, mixing, and evaporation processes, was successfully modeled with *W/R* ratios.

Another important highlight was that fluid evolutions from the reservoir to the surface or from the recharge areas to the reservoir were in a good agreement with the analysis results of fluid evolutions through the conservative elements Cl and B and additionally, alkali metal elements Li, Rb, and Cs in Chapter 4. However, the proposed methodology using alkali earth metals Ba and Sr, as well as transition metals (V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Zr, Mo, Cd, W) and p-block metals (Al, As, Sb, Pb) still need to be considered by speciation models with sufficient thermodynamic database. Nevertheless, the distribution of several trace elements from the surface fluids by interpolating the data with a spline revealed the roles of geological faults on the dilution and shallow water-rock interaction.

To deepen the understanding of shallow hydrothermal processes, another particular series of trace

elements: rare earth elements (REE) were analyzed from several types of rocks and fluids, including river waters, cold springs, hot springs, well fluids, well rocks, and host rocks from available references in Chapter 5. The process of mixing of meteoric water in oxic environments (referring to the local recharge or the shallow groundwater in Chapter 3) was shown by negative Ce anomalies in the gull-wing diagrams. The river, cold springs, and well fluids were assumed to have contact with oxic waters (meteoric recharge), meanwhile the hot springs have no interface with oxic waters. Geothermal fluid samples were revealed to have interaction of high temperatures chloride fluids with plagioclase in the reservoir (samples with positive Eu anomalies), fluid-alunite interaction, extensive hydrothermal alteration and precipitation of secondary minerals on their way to the surfaces, and undergo mixing with oxic waters.

As for the weathering process, $^{87}Sr/^{86}Sr$ ratio analyses in Chapter 6 revealed interactions of the recharge water with the unaltered volcanic and pyroclastic rocks in the study area. After meteoric water recharged the reservoir fluid, the ascending parent fluid mixed with different groundwater types that shared similar host rocks to appear as cold and hot springs. The results were well agreeable with the *W/R* ratios from Chapter 3. Two different types of aquifers could be differentiated to explain the genesis of cold springs with anthropogenic contaminant, and cold springs that shared the deeper aquifer with several hot springs. On the contrary, the hot springs originated from the aquicludes (perched aquifers) with no availability of oxic water in general. Matrix of *W/R* ratio to %MWE (meteoric water exchange) was also developed to trace the possible zones of meteoric recharge to the geothermal system.

Finally, the main results were summarized with a conceptual model in the last chapter. Chapter 7 also includes the relevant, necessary future works for applying my findings to development of other geothermal fields.

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（論文審査の結果の要旨）

地球温暖化防止のために温室効果ガス排出量の大幅な削減が喫緊の課題になっており，再生可能エネルギーを利用した発電の一層の増加が求められている。発電量の大きさと設備利用率の高さで地熱発電が世界的に急増し，特に地熱資源に恵まれたインドネシアでは地熱発電量の増加が国策にもなっている。近年，貯留層内で熱水から蒸気卓越部へと徐々に遷移するという新しい貯留層タイプが発見され，この開発が発電量の大幅増加に貢献すると期待されている。しかしながら，遷移型貯留層の涵養域，涵養域から貯留層までの流体流動，貯留層内外での水－岩石反応，熱水と天水との混合率，貯留層からの上昇流と地表への流出の経路などを含む流体循環機構と遷移型形成プロセスは未解明であり，持続的な地熱資源利用が困難な状況である。この問題に対して，本論文は地熱生産井や温泉水からの水と岩石サンプルの地球化学的分析により，水安定同位体・Sr 同位体，および主要成分と微量成分，希土類元素（REE）の濃度の統合解析法を開発した。これをインドネシアのワヤン　ウインドゥ地区に適用することにより，上記の課題を解明できたという初めての地熱資源学研究である。成果の概要は以下のようである。

1) 20 本の生産井で採取された水試料の水素・酸素同位体比データを貯留層内での値に補正し，地熱流体の涵養域の標高分布と場所，および水－岩石反応，沸騰，天水との混合過程を含む涵養域から流出域までの地熱流体の流動パターンを明らかにできた。この流動パターンは保存性元素の Cl と B，アルカリ金属元素の Li，Rb，Cs から推定される流動パターンと整合した。

2) 起源流体（parent fluid）は 320°C で沸騰し，水／岩石比が 0.2 以下で水―岩石反応が生じていること，および熱水貯留層の上部に位置する蒸気キャップ部での水／岩石比は 0.2～0.7 の範囲にあることが推定できた。

3) REE 分析により，塩化物イオンを高濃度で含む高温流体と貯留層内の斜長石との反応によって正の Eu 異常が生じ，この異常をトレースすることで貯留層から地表までの高温流体の経路を推定できた。一方，負の Eu 異常は，貯留層深部での Fe 酸化・水酸化鉱物と Ca 鉱物の共沈に起因することがわかった。

4) ^{87}Sr と ^{86}Sr の比より天水の混合率は冷泉で 90%，温泉で 59%，生産井水で 29～100%であるとともに，比から推定できる地熱流体の流動パターンは水素・酸素同位体比データに基づく結果を裏付けること，蒸気凝縮と蒸気過熱層の存在により遷移型貯留層が形成されることなどがわかった。

以上，本論文で提案された水・岩石の地球化学的分析法とデータ統合解析法の有用性，汎用性は高く，蒸気量が大きく発電に適した箇所へのボーリング掘削の成功確率を高めることに資する研究として，学術上，実際上寄与するところが少なくない。また，低炭素化社会に貢献し得るという社会的な意義も大きい。よって，本論文は博士（工学）の学位論文として価値あるものと認める。また，令和 2 年 2 月 19 日，論文内容とそれに関連した事項について試問を行い，申請者が博士後期課程学位取得基準を満たしている

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ことを確認し，合格と認めた。

　なお，本論文は，京都大学学位規程第 14 条第 2 項に該当するものと判断し，公表に際しては，全文公表日までの間，当該論文の全文に代えてその内容を要約したものとすることを認める。