第III部　結論および提言

第1章　結論

パラナ洪水玄武に伴う Cu-Ni-PGE 鉱床の広域探査を行うため、本年度は既存データ解析、衛星画像解析および地質調査を実施した。既存データ解析では洪水玄武岩、Noril'sk 鉱床および基盤岩の地質構造、衛星画像解析では JERS-1 の SAR 画像などが解析された。地質調査では主にパラナ洪水玄武岩の全岩分析、微量成分分析および同位体分析などの結果が解析された。

1－1　既存データ解析

洪水玄武岩については、白金属族元素（PGE）はその大部分が地球創生期に核に濃集しており、さらに、基本的に固相に濃集するため、分化が進んだ大陸地殻にはほとんど含まれていない。従って、洪水玄武岩中の PGE の起源はマントルに求めるのが妥当である。また、洪水玄武岩形成時には通常の火成活動と比べて大量のマグマを発生するため、大規模な溶融が起こり、通常は固相に濃集する PGE も、生成するメルト中に比較的多量に含まれる可能性が高い。これらのことから、PGE 鉱化作用をもたらす洪水玄武岩の起源マグマはマントルプリュームを起源とし、かつプリュームや周囲のマントル物質を大規模に部分溶融して発生したものが望ましいと考えられる。ただし、前述の条件は巨大火成岩岩石区（LIP）全般に言えることであり、PGE 鉱床の形成には、地殻の混染による珪酸塩成分および硫黄の供給や地域的なテクトニック・セッティングなど PGE 濃集を左右する要素の方が重要だと思われる。

Noril'sk 鉱床については、そのマグマはピクライト質～玄武岩質の組成で、硫黄に不飽和な PGE に富んだマグマであると考えられる。このようなマグマが地殻物質の混染作用を受けたことが原因で、不混和となった硫化物メルトが珪酸塩マグマから分離し、それがマグマ活動の中心域において大量の珪酸塩マグマと反応することにより銅、ニッケル、PGE を不混和硫化物メルト中に濃集したことが Noril'sk 鉱床の成因と考えられる。これらのことから、Noril'sk タイプの鉱床の生成条件として次の３点が掲げられる。（１）硫黄に不飽和なマグマの発生と地殻浅部への上昇、（２）地殻物質の混染作用による不混和硫化物メルトの生成、（３）不混和硫化物メルトが大量の珪酸塩マグマと反応すること。

更に、このような条件を満たす鉱床の探査指針として、以下の条件が掲げられる。（１）低 Ti タイプで PGE に富んだマグマが、溶岩または貫入岩として存在すること、（２）このようなマグマと関連して、地殻物質の混染作用の影響がみられ、かつ PGE に枯渇したマグマが溶岩または貫入岩として存在すること、（３）地殻の弱線が発達し、大量の珪酸塩マグマが地下から供給される火山活動の中心域であること、（４）地殻物質の混染を起こしやすい高温のピクライト質マグマが溶岩または貫入岩として存在すること。

パラナベーズンの地質については、パラナベーズンはゴンドワナ古大陸西部に形成された大陸内部ベーズンのひとつであり、潮汐重力異常からリソスフェアが薄く、マントルプリューム

が比較的浅所にある。パラナベーズンはオルドビス紀後期から白亜紀後期に堆積し、その堆積層はRio Ivai、Paraná、Gondwana I、Gondwana II、Gondwana III およびBauru スーパーシーケンスに区分される。Gondwana I はヘルシニアン造山運動直後の堆積層、GondwanaⅢは洪水玄武岩溶岩であり、厚い層厚を示す。ベーズンの堆積層の大部分は Paraná 州西部から San Paulo 州南西部の Paraná 川沿いを中心に堆積している。

大陸内部ベーズンはマントルプリュームがリソスフェアに入り込むと、リソスフェアは一瞬、縮み、プリュームの重さにより沈降し、ベーズンの堆積が始まると考えられている。ボーリングデータなどの解析からリソスフェアの収縮率（ε）が計算された。高ε帯はパラナ州西部から北西部を経てサンパウロ州南西部に至る NE-SW 方向のパラナ川沿いにみられる。これらの地域では多量のドレライトシル・岩脈の貫入、厚い玄武岩溶岩の噴出および厚いベーズンの正規堆積物がみられる。一方、重力異常については大陸内部ベーズンではリソスフェアが薄いため、米国の Midcontinet rift の例にみられるように高異常帯となる。パラナベーズンでは高残差重力異常が高ε帯とほぼ一致する地域にみられる。

パラナベーズンのテクトニクスについては Noril'sk、米国 Duluth 鉱床およびパラナベーズンについて考察した。共役なせん断裂罅は横ズレ運動の進行により、雁行状の２次せん断面からなる引張裂罅帯（Cymoid loop）を形成し、引張裂罅帯のせん断裂罅のひとつがリフト、他方がトランスフォーム断層に発展する。Duluth 鉱床の場合、重力異常および空中磁気異常から、2つのトランスフォーム断層の横ズレ運動により形成された引張裂罅帯に Duluth 複合岩体が貫入し、Cu-Ni-PGE 鉱床が形成された。その広域応力場は最大圧縮主応力軸（σ_1）が NE-SW 方向、最小圧縮主応力軸（σ_3）が NW-SE 方向とみられる。Noril'sk 鉱床の場合、鉱床は NNE-SSW 方向の右横ズレの Noril'sk- Kharayelakh 断層と NNW-SSE 方向の Kayerkansky-Pyasinsky 背斜に規制されている。NNW-SSE 方向は Gydansk- Omsk リフトの方向と一致することから、σ_1の方向とみられる。σ_3はσ_1の方向から Kayerkansky-Pyasinsky 背斜に直角な ENE-WSW 方向と推定される。Noril'sk 鉱床は NNE-SSW と NNW-SSE の両構造方向の交差部にあると同時に Nadezhinsky 玄武岩溶岩層の最も厚い部分、すなわち噴出中心に位置する。

パラナベーズンの断層、裂罅群をみると、リフト帯におけるひとつの広域応力場として解釈できる。Paraná 州西部から San Paulo 州南西部にかけてのパラナ川沿い地域は、NE-SW 方向に高ε帯、高重力異常帯、厚いドレライトシル・岩脈の貫入および厚いベーズンの堆積岩・洪水玄武岩の噴出がみられることから、リフト帯と推定される。応力場の方向は NE-SW 方向がσ_1である。NW-SE 方向の構造方向はリフトに直角でありσ_3となり、右横ズレのトランスフォーム断層とみられる。NW-SE 方向のせん断裂罅の中で、特に注目されるのは Ponta Grossa, Abreu-Mourao, Rio Piquiri など裂罅集中ゾーンである。このゾーンでは右横ズレ運動により引張裂罅ゾーン（Cymoid loop）が形成され、多量のシル、岩脈が貫入したものと推定される。パラナ川西部の引張裂罅ゾーンはトランスフォーム断層と NE-SW 方向のリフト帯、Ponta Grossa では ENE-WSW 方向のせん断裂罅との交点にシル、岩脈群が形成されている。その他、パラナベーズンでは ENE-WSW の構造方向も卓越している。この構造方向は基盤のクラトンと Brasilian-Pan African 変動帯を境しており、最大圧縮主応力軸σ_1と約 30°の角度で交わり、左横ズレの

せん断裂罅とみられる。このせん断裂罅は一般にドレライトのシル・岩脈を伴わない。

1－2　衛星画像解析

パラナベーズン中央部を東西方向に横断する範囲を対象にし JERS-1 の SAR（Synthetic Aperture Radar：合成開口レーダー）データを用いてデジタルモザイク画像を作成し、地質構造の判読・解析を行った。調査地域の面積は約 500,000 km^2 で、これをカバーする JERS-1/SAR データ 131 シーンを使用した。調査地域はパラナベーズンを東西方向に横断する地域であり、地域の大部分はジュラ紀から白亜紀にかけて噴出した洪水玄武岩が広く覆っている。また古生代の堆積岩類と基盤の花崗岩類が対象地域の北東部に分布する。地質構造の解析・判読では、リニアメント（断層を含む）と環状構造を抽出した。

調査地域北東部の Ponta Grossa Arch には古生代の堆積岩と基盤の花崗岩類が分布しており、洪水玄武岩のフィーダーと考えられている多数のドレライト質の岩脈群が存在する。岩脈群は NW-SE 系で最大 80 km 程度の走向延長を持っており、これらは判読画像上で明瞭なリニアメントとして抽出されている。これは相対的に浸食に対する抵抗性の弱い堆積岩中では岩脈群が尾根状の連続地形をなすためと考えられる。しかし、基盤の花崗岩類中に存在する岩脈群は抽出されていない。これは岩脈群と花崗岩類の浸食に対する抵抗性に大きな差がないため、岩脈群が尾根状地形を呈さないためであると考えられる。洪水玄武岩分布域については対象地域中央部において NE-SW 方向のまとまったリニアメント群が抽出された。これらは既存の地質図上では全く記載されていないものであり、注目すべきものである。洪水玄武岩分布域のリニアメント密度は、堆積岩区域に比べると非常に低い。特に、対象地域の中でパラナ川を中心とした低地においては、基盤中の NE-SW 系の地塁・地溝構造が空中磁気探査、重力探査によって推定されているが、これに対応するリニアメントは SAR 画像上では抽出されていない。これは基盤構造は洪水玄武岩の分布に大きな構造的影響を与えておらず、また洪水玄武岩噴出以降、本地域においては大きな構造運動がなかったことを示している可能性がある。

環状構造に関しては、地質図上の環状構造と明確な対応を持つものとして、Lages 地区に存在するアルカリ複合岩体が明瞭に抽出された。

1－3　地質調査

今年度の調査により、パラナベーズン洪水玄武岩類は低 Ti タイプ（Gramado、Esmeralda）、Transitional タイプ（Paranapaneme-Ribiera）および高 Ti タイプ（Pitanga、Urubicí）に分類された。３タイプの溶岩は次のような地化学的特徴を有している。

（１）低 Ti タイプの Esmeralda は、Th, Ta, Y, Zr の含有量と Nd 同位体比から最も未分化である。（２）低 Ti タイプの Gramado と Esmeralda は相対的に Th、U、Rb 等の地殻濃集元素を多く含んでいる。この傾向は Gramado において特に著しい。このことは Sr と Nd 同位体によっても示された。（３）高 Ti タイプと Transitional タイプのマグマは、大陸地殻上部物質の影響は

小さいものと考えられ、マントル起源のマグマが直接地表に噴出した可能性が考えられる。（4）各タイプのマグマは、マントル物質の部分溶融の違いによって生成された可能性が高い。このうち、低 Ti タイプのマグマが最も部分溶融の程度の大きく、大陸地殻上部物質をさまざまな程度に同化したものと考えられる。（5）Transitional タイプの Paranapanema-Ribeira の Pt と Pd の平均含有量はそれぞれ 9.7ppb、15.5ppb であり、各タイプのうち、最も高い含有量を示す。この含有量は Noril'sk 鉱床の最も PGE に富んだ溶岩よりも大きい。低 Ti タイプのマグマ（Gramado、Esmeralda）は、これに次いで高い Pt、Pd 含有量を示しており、地殻物質混染の影響が大きい Gramado については、PGE に枯渇した試料と枯渇していない試料が存在する。一方、高 Ti タイプの Pitanga の Pt、Pd の含有量は非常に低い。以上のように溶岩の化学組成の検討から、パラナベーズン地域には Noril'sk タイプの正マグマ性硫化物鉱床を生成し得る、高い PGE 含有量を有するマグマが存在することが明らかになった。

貫入岩類に関しては、主要成分、微量成分の分析結果から Lomba Grande 地区のシルの組成幅は広く、ピクライト質～デイサイト質のシルが存在する。一方、Ponta Grossa Arch のシルと岩脈の組成幅は狭くすべて玄武岩質であることが明らかになった。また溶岩類と同様に、前者は後者に比べて Th、U、Rb に富んでいた。これは溶岩類で示された低 Ti タイプのマグマの特徴と同じである。Pt、Pd 含有量に関しては、Lomba Grande 地区北東部と東部に存在する厚さ 130m 以上の大規模シル（玄武岩質～安山岩質）が比較的高い含有量を示し、特に北東部シルでは Pt 20ppb 以上の試料も認められた。これに対し同じ Romba Grande 地区中央部に存在するピクライト質～玄武岩質および安山岩質～デイサイトシルは Pt、Pd に枯渇しており、特に安山岩質～デイサイトシルは Pt、Pd をほとんど含まない。Ponta Grossa Arch のシルと岩脈の Pt、Pd は、ばらついた値を示し、Pd: 20ppb を越えるものから非常に枯渇したものまで存在する。

以上のように本年度実施した溶岩、貫入岩の地化学的検討から、パラナベーズン地域には Noril'sk タイプの正マグマ性硫化物鉱床を生成し得る、高い PGE 含有量を有するマグマ（Paranapanema-Ribeira など）が存在することが明らかになった。さらに低 Ti タイプの Gramado の一部試料では地殻物質の混染と PGE の枯渇が認められた。また Ponta Grossa Arch の一部の岩脈、シルでは、地殻物質の混染作用は明確ではないものの、PGE の枯渇が認められた。

EPMA の結果からは、Ponta Grossa Arch と Romba Grande 地区北東部のシル、岩脈に微量ながら黄銅鉱が含有されることが明らかになった。特に Ponta Grossa Arch のシル、岩脈から微量の閃亜鉛鉱とニッケルを含有するコバルト砒素鉱物が検出されており、興味深い。

第２章　第２年次調査への提言

第１年次調査は洪水玄武岩分布域の主に中央部で調査が実施された。第１年次の調査により、洪水玄武岩の溶岩および貫入岩の分析値を基に、それらのマグマの地球化学的な特徴が明らかにされた。また Noril'sk 鉱床および Duluth 鉱床の例を念頭に、どのようなマグマおよび地質的条件が Cu-Ni-PGE 鉱床をもたらすかについても考察された。

第２年次の調査は第１年次調査に引き続き、地域全域を対象に調査を実施するが、特に分析試料が十分でない地域北部および南部で、地質調査と分析試料の採集を行う。分析試料は地表および石炭探査ボーリングの溶岩、貫入岩から採集する。分析項目および元素は第 1 年次との継続性を考慮しほぼ同じ内容とする。

Paraná 州の MINEROPAR および Rio Grande do Sul 州の CPRM は沢砂地化学探査を実施している。両調査の分析結果は洪水玄武岩の化学的組成を比較的、良く反映している。沢砂地化学探査は露頭の少ない地域に対して有効であり、露頭調査の補助的方法として適宜、実施する。

パラナベーズンおよび基盤岩の地質および地質構造の調査から、洪水玄武岩の活動が広域的応力場に支配されていると推察された。ベーズン堆積物および基盤岩の地質構造については第１年次に引き続き調査を行い、鉱床賦存が期待される洪水玄武岩の噴出位置について解析を行う。

衛星画像解析は第１年次に引き続き、パラナベーズンの地質および地質構造を明らかにするため、JERS-１の SAR 画像および TM 画像の解析を行う。

PETROBRAS が所有するボーリングコアおよび物理探査資料については引き続き、関係方面に働きかけ、その入手に努めることとする。

第２年次の調査結果は、第 1 年次の調査結果とまとめて総合的に解析する。結論として、パラナベーズンにおける Cu-Ni-PGE 鉱床賦存の可能性を考察し、その探査指針を提示し、更に探査有望地を抽出する。

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巻　末　資　料

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