Prepared in cooperation with the
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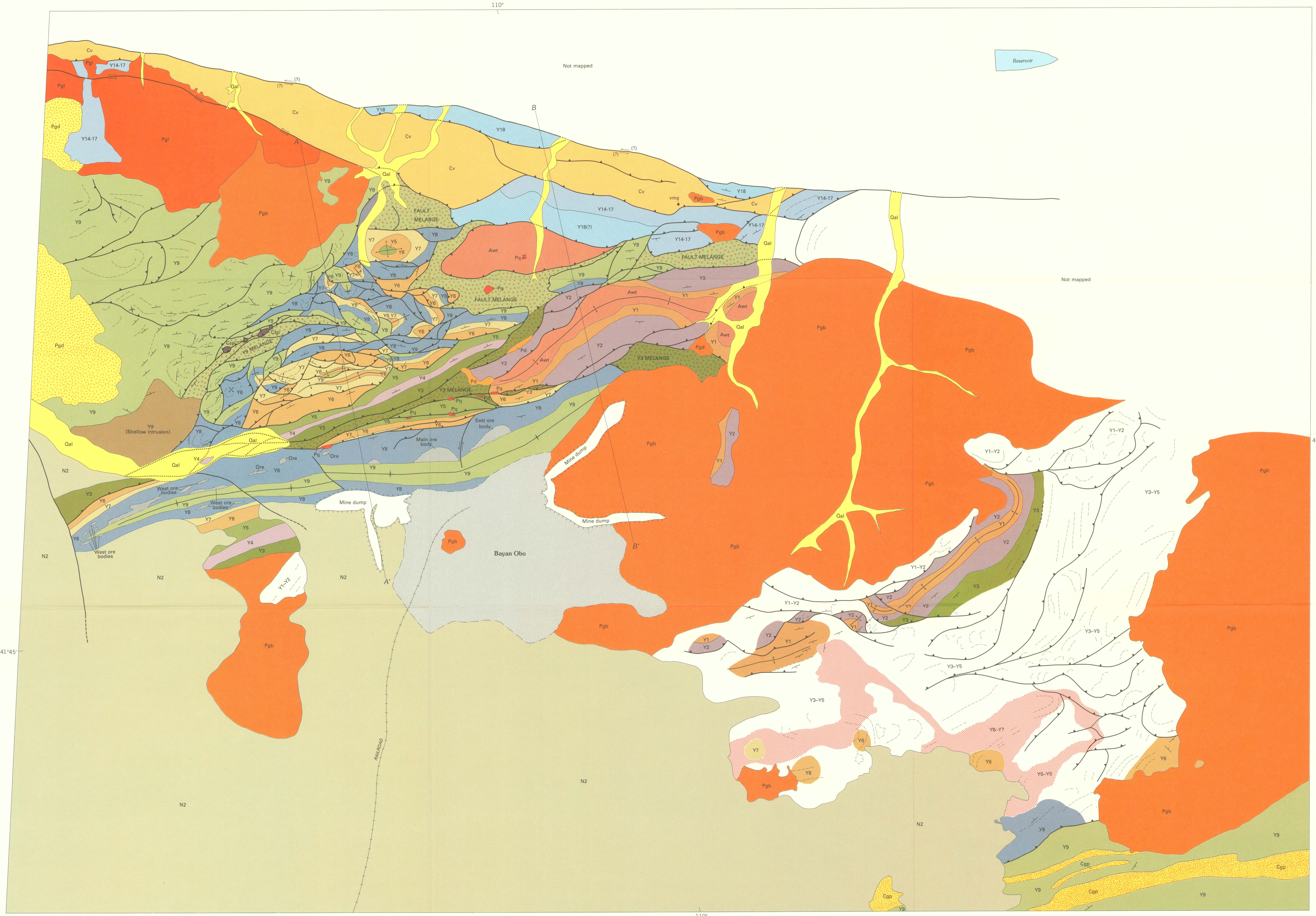

SCALE 1:50,000

Geologic compilation based on an enlargement; to scale 1:50,000, of a Satellite Pour P'Observation de la Terra (SPOT) image no. K266 J266 860427 and field work, September 4-21, 1988.

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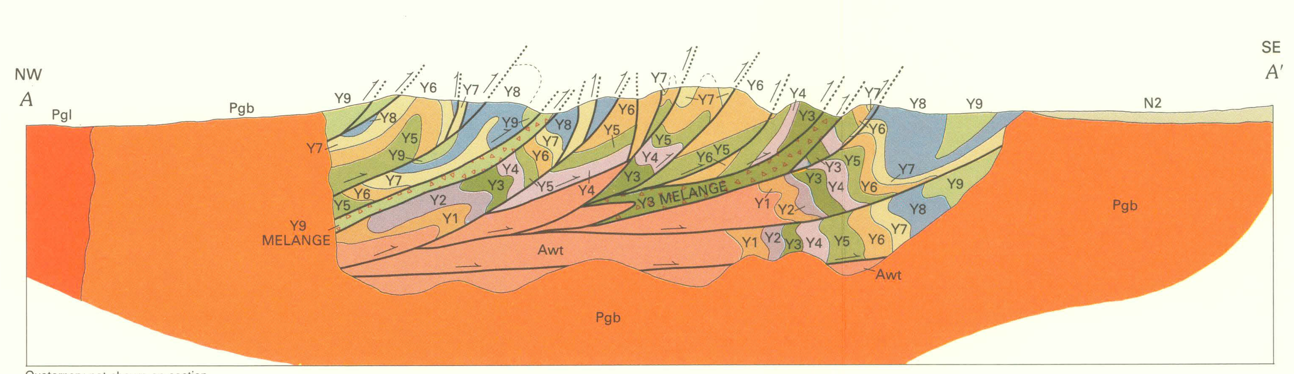
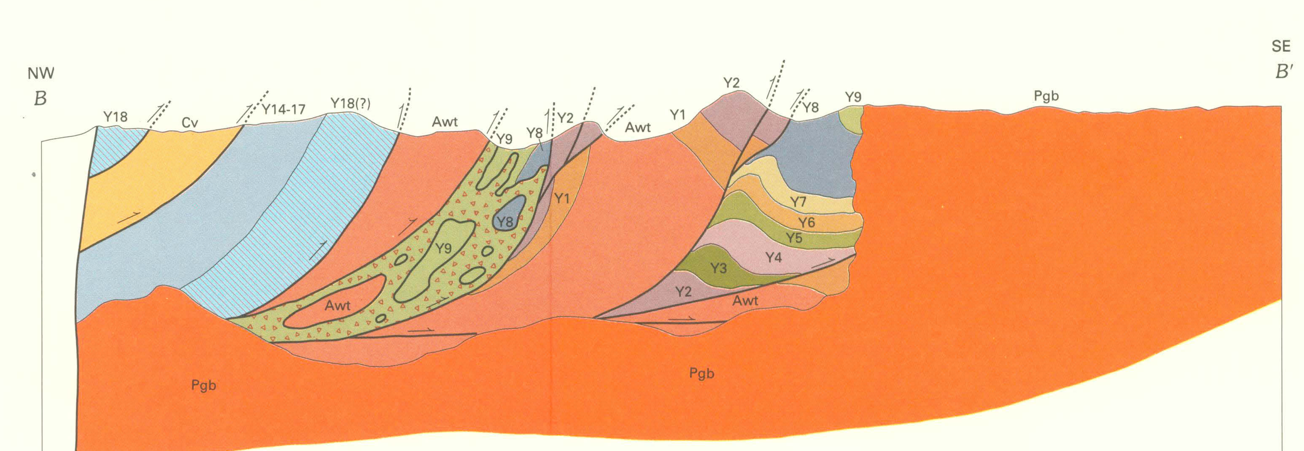
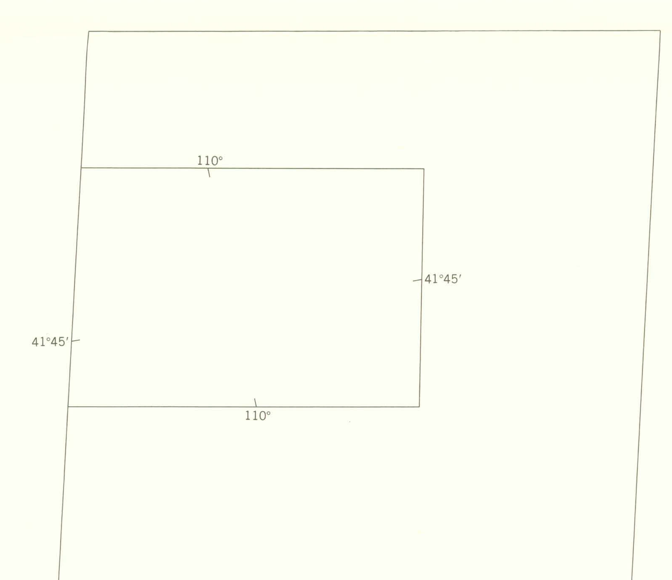


Quaternary not shown on section



Quaternary not shown on section

INTERIOR-GEOLOGICAL SURVEY, RESTON, VA—1990



Outline of SPOT image J266 K266 860427 showing area enlarged to scale 1:50,000 for the geologic map

EXPLANATION OF MAP UNITS

- **Qal** — Alluvium } QUATERNARY
- Unconformity
- **N2** — Undivided sedimentary rocks } TERTIARY
- Unconformity
- Age relations not implied
- **Pd** — Diorite
- **Pgd** — Granodiorite
- **Pgb** — Biotite Granite
- **Pgl** — Leucogranite
- **Pq** — Quartz veins and plugs } PERMIAN
- Intrusive contacts
- Age relations not implied
- **Cv** — Volcaniclastic and epiclastic rocks
- **Cgp** — Granite porphyry
- **Csp** — Serpentine } CARBONIFEROUS
- Unconformity(?)
- **Y18** — White and gray limestone (100 m)
- **Y14–17** — Gray limestone (200 m)
- Unconformity(?)
- **Y9** — Black shale and intercalated carbonate rock (350 m)
- **Y8** — Limestone and dolomite and intercolated quartzite (390 m)
- **Y7** — Sandstone, quartzite, and limestone (115 m)
- **Y6** — Arkosic sandstone and quartzite (135 m)
- **Y5** — Thin-bedded carbonaceous shale (130 m)
- **Y4** — Dark-colored quartzite (165 m)
- **Y3** — Carbonaceous shale (70 m)
- **Y2** — Tan to white quartzite (65 m)
- **Y1** — Coarse sandstone and basal conglomerate (95 m) } Bayan Obo Group } PROTEROZOIC
- Unconformity
- **Awt** — Migmatite (basic dikes and sills occasionally occur) } Wu Tai Group } ARCHEAN
- Hornfels
- Fault melange
- **vms** — Volcanic-associated massive-sulfide deposits } OTHER ROCKS

Information for uncolored labeled areas taken from unpublished Brigade maps of China, scale 1:200,000

EXPLANATION OF MAP SYMBOLS

- **Contact**—Dashed where interpreted from geological structures recognized on SPOT satellite imagery, dotted where concealed
- **Fault**—Dashed where inferred, dotted where concealed
- **Thrust fault**—Dashed where inferred, dotted where concealed. Sawteeth on upper plate
- **Tear fault**—Arrows show relative movement
- **Anticline**—Showing crestline
- **Dome**
- **Syncline**—Showing troughline
- **Basin**
- **Strike and direction of dip of beds**
- **Bedding form lines**
- **Ore body**

DISCUSSION

STRATIGRAPHY

The oldest rocks in the Bayan Obo area are Archean migmatites (**Awt**) which consist of gneisses, leucosomes, melanosomes (interpreted to be restites), and granites. Basic dikes and sills have intruded these migmatites. Sedimentary rocks of the Bayan Obo Group (**Y1 - Y18**), which crop out in the mapped area, include shales, arkosic sandstones, quartzites, limestones, and dolomites. These sedimentary rocks are Middle Proterozoic in age. The metamorphic grade of Bayan Obo Group rocks is low; the matrix of the shales contains muscovite and biotite. Some kaolinite and smectite occur (R. Polastero, written commun.) which may be a result of hydrothermal alteration associated with the emplacement of the granites, or ground water, or a remnant of the original shale matrix. The organic material in these shales is fine grained, highly reflective, and nonfluorescent implying that only organic carbon remains in these shales (R. Stanton, 1989, oral commun.). Other sedimentary rocks include epiclastic volcanic-derived sediments and associated graywackes (**Cv**) which constitute a sequence of volcanic rocks of Carboniferous age. Cemented Tertiary gravels (**N2**) and Quaternary alluvium (**Qal**) also occur.

A variety of intrusive and extrusive igneous rocks, which range in age from Carboniferous to Permian, occur in the Bayan Obo area. Four types of intrusive igneous rocks of Permian age are recognized: diorite (**Pd**), granodiorite (**Pgd**), biotite granite (**Pgb**), and leucogranite (**Pgl**). Quartz veins and plugs (**Pq**) are associated with this suite of rocks. Extrusive igneous rocks (**Cv**) also occur in the region and include rhyolite domes, flows, breccias, and tuffs, and associated epiclastic rocks. A kuroko-type massive sulfide deposit occurs in these volcanic rocks in the upper middle part of the map in unit **Cv**. The rocks associated with this deposit include a rhyolite dome, vent facies, white exhalite with sulfides, epiclastic sediments, graywacke, and purple chert. A large fault truncates this sequence of volcanic rocks above the purple chert. The volcanic rocks which host the massive sulfide deposit have been interpreted from field mapping to be Carboniferous in age, whereas, the larger volume of volcanic rocks along the same trend outside the mapped area to the northwest are mapped as Jurassic. A granite porphyry (**Cgp**), possibly also of Carboniferous age, crops out in the southeastern part of the mapped area.

The large veins and plugs of quartz (up to 100 meters across) associated with the Permian intrusive rocks, occur most frequently in fault zones. Several of these quartz bodies are being mined for gold. Placer gold deposits occur along drainages away from these quartz bodies.

Rocks of the Bayan Obo Group have been variously metamorphosed within the contact aureoles to the granitoid rocks. A dense-black andalusite-bearing rock occurs at the contact of the **Y9** shale and the biotite granite (**Pgb**) at several locations while a variety of less severely altered rocks (hornfels) occur in both the coarse- and fine-grained clastic rocks of the Bayan Obo Group in many locations near contacts with intrusive igneous rocks of Permian age. For example, silicification and iron metasomatism of the **Y9** shale along bedding planes and joints is common near granodiorite (**Pgd**). Skarn bodies also occur, particularly at the contact of the **Y8** and **Y14–17** carbonate rocks with biotite granite (**Pgb**).

STRUCTURAL GEOLOGY

The structural geology in the Bayan Obo area is complex and includes large folds, numerous thrust faults, duplex structures, basement horses, and fault melange. Serpentinite bodies occur within one of the larger thrust-fault zones. Tectonic transport during the Permian was from northwest to southeast and resulted from continent-to-continent collision (Wang Hongzhen, 1985). The complexity of the thrusting in the Bayan Obo area is well illustrated by cross section *A-A′* that shows 18 emergent thrust faults. Also shown are upright and overturned folds, domes, basins, and other fold interference structures, unfolded single and multiple-bed segments, back-limb thrust segments, and basement horses.

Cross section *B-B′* shows a large breached anticline that has a core of migmatite (**Awt**). It also shows a basement horse of migmatite above a zone of fault melange that is approximately one kilometer wide. The large syncline at the surface at the southern end of both cross sections *A-A′* and *B-B′* contains the rocks that host the enormous iron-niobium rare-earth ore bodies at Bayan Obo.

The complex structure of the rocks in the Bayan Obo group, which includes the thrusting of younger rocks over older as shown in the northern half of cross section *A-A′*, can be compared to that of the Morcles nappe in Switzerland (Ramsay and others, 1983). The thrusting and folding in the northern half of this cross section is similar to that in the upper limb of the Morcles nappe where numerous buckle folds and smaller thrusts resulted from the intense simple shear within this nappe. In contrast, the structural deformation of the rocks in the Bayan Obo Group, which crop out in the southeastern part of the mapped area, is less severe as demonstrated by the general pattern of younger and younger rocks toward the southeast. This area contains a series of imbricate thrusts that are interpreted to be late emergent faults that formed as the tectonic stress was taken up by layer-parallel shortening in areas of the foreland, further toward the southeast. The diminishing intensity of thrusting and folding toward the foreland is a common feature in the thrust and fold belts throughout the world (Jones, 1987, fig. 1).

Basin and dome structures in the northwestern part of the mapped area located directly west of the large zone of fault melange, as well as the duplex structure which breaks up the large fold located in the southeastern part, suggest two phases of deformation that were oriented at about right angles to each other. The fishhook termination at the northern end of this large fold probably resulted from coaxial fold interference and provides additional evidence for a very complicated tectonic history for the Bayan Obo area during the Permian continent-to-continent collision. Polydeformation and associated out-of-sequence thrusting explains the younger over older thrusting within the Bayan Obo Group as shown in cross section *A-A′*.

Large scale tectonic processes have controlled emplacement of igneous rocks and deposition of sedimentary rocks in the area. For example, serpentinite bodies in the large thrust fault in the northwestern part of the mapped area clearly result from Permian continent-to-continent collision. These bodies are interpreted to be remnants of oceanic crust. The large volume of granitoid rocks of Permian age also resulted from this collision. The large granite body (**Pgb**) in the middle of the mapped area crops out in an approximately parallel trend to the direction of strike of the thrusting, and the diorite (**Pd**) has intruded into one of the large thrust faults as have several other masses of granitoid rocks. They were, therefore, emplaced after the period of thrusting. The leucogranite (**Pgl**) cuts both the biotite granite (**Pgb**) and the granodiorite (**Pgd**) as well as the older rocks and has a highly evolved mineralogy composed principally of potassic feldspar and quartz. Sparse biotite is the only mafic mineral. In contrast, fluorite commonly occurs in this leucogranite as veins and irregular masses. These masses of fluorite are locally several meters long and wide. The mineralogy and cross cutting relationships of the leucogranite indicate that it is a late-stage granitoid and thus may be host for the occurrence of associated tin, tungsten, and base-metal deposits.

Evidence of repeated rifting of the craton is recorded in the rocks that crop out in the Bayan Obo area. The repeated deposition of very coarse-grained clastic rocks, both in the mapped area as well as the adjacent area to the south, indicates repeated tectonic movements throughout geologic time. The basal conglomerate in the **Y1** sandstone-conglomerate occurs in ancient river channels and alluvial fans. This unit results from the development of the Middle Proterozoic intracontinental rift described by Wang Hongzhen (1985). A large pulse of arkosic sediment resulted in the **Y6** sandstone. This unit is related to movement on a large syndepositional fault near the edge of the craton during the Middle Proterozoic. During spasmodic movements on this fault, coarse-grained clastic sediments were deposited in at least four pulses, as is suggested by units **Y1**, **Y4**, **Y6**, and a wedge of similarly coarse-grained detritus during the Sinian period (approximately 800 million years before present).

Evidence for additional rifting during the Paleozoic is provided by the volcanogenic massive sulfide deposit in unit **Cv**. The rocks in which this deposit occurs (vent facies, exhalites, epiclastic sediments, graywacke, and purple chert) are indicative of deposition in a subaqueous environment in a rift basin.

ECONOMIC GEOLOGY

The enormous iron-niobium rare-earth ore bodies that occur as carbonate replacements of the **Y8** dolomite in the large syncline have a mineralogy that is also indictive of being associated with intracontinental rifting. Bailey's (1960) description of the hydrothermal alteration of sedimentary rocks around the carbonatite bodies in the central African rift is similar to the alteration in the **Y9** shale that serves as a caprock over the ore bodies that were formed by hydrothermal replacement of the **Y8** dolomite. In the Bayan Obo area, however, neither carbonatites nor alkaline rocks are known to crop out. However, large veins (up to three meters wide) and stockworks of smaller veins crosscut the adjacent clastic rocks (**Y1** through **Y9**) and basement migmatites. These veins and stockworks crop out to the north and east of the ore bodies and contain magnetite, barite, apatite, soda-amphiboles, aegirine, monazite, and many other minerals (Drew, Meng, and Sun, 1989). Integration of these data with the tectonic setting of the Bayan Obo area results in a model that suggests that the ore bodies are situated near the top of a hydrothermal system associated with an unexposed alkaline-carbonatite pluton.

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GEOLOGIC MAP OF THE BAYAN OBO AREA, INNER MONGOLIA, CHINA

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1990

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