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The Ajo Mining District, Pima County, Arizona—Evidence for Middle Cenozoic Detachment Faulting, Plutonism, Volcanism, and Hydrothermal Alteration

Professional Paper 1733

U.S. Department of the Interior
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The Ajo porphyry copper deposit and surrounding Upper Cretaceous rocks have been separated from their plutonic source and rotated by detachment faulting. Overlying middle Cenozoic sedimentary and volcanic rocks have been tilted and show evidence for two periods of rotation. Following these rotations, a granitic stock (23.7±0.2 Ma) intruded basement rocks west of the Ajo deposit. This stock was uplifted 2.5 km to expose deep-seated Na-Ca alteration.

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DIRK KEMPTHORNE, Secretary

U.S. Geological Survey
P. Patrick Leahy, Acting Director

U.S. Geological Survey, Reston, Virginia: 2006

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Cataloging-in-publication data are on file with the Library of Congress (http://www.loc.gov/).

Produced in the Western Region, Menlo Park, California
Manuscript approved for publication, August 29, 2006
Text edited by Peter H. Stauffer
Layout and design by Judy Weathers

FRONT COVER
View to the west from the Scenic Loop Drive south of the town of Ajo. The hill at right shows pronounced layering in the Oligocene-Miocene Locomotive Fanglomerate. The sharp peak in the distance is North Ajo Peak, formed by units of the Miocene Ajo Volcanics.

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By Dennis P. Cox[1], Eric R. Force[2], William H. Wilkinson[3], Syver W. More[4], John S, Rivera[4] and Joseph L. Wooden[1]

Abstract

The Ajo mining district, best known for its Laramide porphyry copper deposit, is a collage of different types of ore minerals, altered rocks, and plutons of Precambrian, upper Mesozoic (Laramide), and middle Cenozoic age. Recent work, reported here, identifies a regional detachment system, a plutonic complex, extensive alteration, a volcanic stratigraphy, and a complex tilting history, all of Cenozoic age. A better understanding of middle Cenozoic events is important in the search for fragments of Laramide ore bodies detached by younger faulting.

Precambrian rocks include the 1.7– Ga Cardigan Gneiss and the 1.4–Ga Chico Shunie Quartz Monzonite. Laramide rocks are represented by the andesitic to rhyolitic Concentrator Volcanics of Cretaceous age and by granodiorite and quartz diorite of the Cornelia Pluton, which intrude the volcanics. The Ajo porphyry copper deposit (65-63 Ma) is localized in the porphyry phase of the granodiorite. Cenozoic rotation has overturned the deposit (Hagstrum and others, 1987).

Two units of coarse clastic sedimentary rocks of middle Cenozoic age overlie the Laramide deposit. The older Darby Arroyo Formation is slightly overturned to the south where it unconformably overlies Concentrator Volcanics. The Locomotive Fanglomerate, deposited with angular unconformity on both the Darby and the porphyry deposit, dips 30° to 65° south and contains cobble to boulder size clasts of Precambrian granite, granodiorite porphyry, and other rocks, the rock type depending on location within a complex dispersal pattern. The Locomotive Fanglomerate also contains large masses, as much as 300 m thick, of brecciated rhyolite, granodiorite, and other rocks that are interpreted as landslide megabreccias. The thickness of the Locomotive Fanglomerate is probably greater than 1,500 m.

Flows of andesitic volcanic rocks are present in the upper part of the Locomotive Fanglomerate and are the predominant rock type in the upper part of the middle Cenozoic sequence. These rocks, collectively named the Ajo Volcanics, are here divided into four members. Total thickness varies from 420+ m to 1,145+ m. A dacitic member yielded K–Ar biotite and whole-rock ages of 23.8±0.8 and 25.0±2.7 Ma, respectively. Potassium metasomatism of the Ajo Volcanics occurs in the form of adularia veining and replacement of plagioclase.

The Cardigan Peak Pluton intrudes Cardigan Gneiss west of the Gibson Fault. A uranium-lead zircon age for the pluton is 23.7±0.2 Ma. The pluton is zoned compositionally and texturally from fine-grained quartz diorite in the west to coarse-grained monzodiorite and monzogranite and fine-grained granite in the east. All of these zoned phases are within 0.2 m.y. of being the same age. Sodic-calcic alteration, in which sodic plagioclase replaces K–feldspar, and actinolite and chlorite replace biotite, is pervasive on the north side of the pluton. This alteration resulted in the depletion of K, Fe, Cu, Mn, and other elements. Quartz grains in the pluton contain abundant fluid inclusions with NaCl, KCl, and $FeCl_2$ daughter minerals.

Paleomagnetic studies (Hagstrum and others, 1987) indicate that, while the Cardigan Peak Pluton is unrotated, the Laramide rocks, including the New Cornelia orebody, are overturned to the south by two successive rotations of 68° and 55°. Overturned bedding in the Darby Arroyo Formation was partly tilted during the first rotation, which we infer is related to a buried detachment fault that separates Precambrian rocks from Laramide rocks and Darby Arroyo Formation in the area south of the present Ajo district. The Locomotive Detachment Fault, capturing part of the surface of the Darby detachment, produced the second rotation and resulted in the accumulation and tilting of the Locomotive Fanglomerate and overlying Ajo Volcanics. The headwall of the Locomotive detachment is the South fault, which separates steeply dipping Ajo Volcanics from gently inclined layers to the south. Drilling data define the fault as a curved surface that is more than 1,000 m deep below the New Cornelia Mine.

Eight or more north-dipping normal faults on the north flank of Cardigan Peak have dropped the upper part of the pluton 2,100 m. These faults suggest the possibility that an

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orebody, formed initially at the top of the Cardigan Peak pluton by processes related to sodic-calcic alteration, has been downdropped and lies below Cenozoic cover on the north side of the Little Ajo Mountains Fault.

Nearly flat-lying Miocene Sneed Andesite (~21 Ma), Childs Latite, Batamote Andesite, and Quaternary deposits postdate detachment faulting, as do the Little Ajo Mountains Fault on the north, the Black Mountain Fault on the east, and several other normal faults.

Introduction

The Ajo mining district is best known for its Laramide porphyry copper deposit (described in the classic paper by Gilluly, 1946). The New Cornelia Mine, developed on the Ajo porphyry copper deposit by Phelps Dodge Corporation, is presently inactive. It has produced more than three million metric tons of copper since it was opened in 1917. The mine was put on standby and the smelter closed in 1990. Additional contiguous resources were discovered in 1995 and await development (Wilkinson, 1998).

This paper focuses on the Miocene structures in the Ajo mining district, the plutonic, volcanic, and hydrothermal events associated with these structures, and, to the extent possible, on the timing of these events. The importance of post-Laramide extension and rotation of porphyry copper deposits in Arizona and adjacent states has been reviewed by Wilkins and Heidrick (1995), who conclude that 45 percent of the deposits in this area were extended and rotated by faults during the Miocene. These faults include normal faults rotated to low angles during extension (for example, Yerington district; Proffett, 1977), detachments of low initial dip and large displacement (as in the Mission-Pima district; Cooper, 1962, 1973; Wilkins and Heidrick, 1995), and combinations of the two (San Manuel district; Force and Dickinson, 1994).

The Ajo porphyry copper deposit is situated on the western edge of the southern Arizona Laramide porphyry copper province. Like many porphyry deposits of this province, Ajo is a rootless deposit, underlain by Precambrian rocks (Wilkinson, 1998). This paper will describe evidence for the detachment faulting and rotation of the deposit and examine the possibility that tectonic fragments of the original deposit may still be found. In addition, the Miocene detachment faulting at Ajo is of special interest because it was accompanied by intense plutonic and hydrothermal activity. We intend to show that extension in the Ajo district took place along a listric detachment fault and to show how this interpretation can be used to predict undiscovered resources.

This report and accompanying maps bring together new work by the authors and several gray-literature reports. Extensive new work by the first author (Cox) in the southern part of the district, completed in 1997, was done for BHP Minerals Inc. under the direction of Patrick Fahey. Also incorporated are two U.S. Geological Survey Open File Reports (Cox and Ohta, 1984, and Cox, 1988). The work of the second author (Force) is more restricted to detachment faulting, the Darby unit, and the Copper Canyon Fault, partly reported in a field-trip guidebook (Force, 1997a). Contributions from Wilkinson, More, and Rivera represent many years of work in the New Cornelia mine by Phelps Dodge Corporation. Wooden provided U-Pb data that firmly established the Miocene age of the Cardigan Peak Pluton.

Location and Access

The town of Ajo and the Ajo porphyry copper deposit (fig. 1) are situated in southern Arizona, 211 km west of Tucson via State Highways 86 and 85 and 64 km south of Gila Bend on highway 85 (see regional map on plate 1). The town is 550 m above sea level, and the surrounding mountains attain 884 m in elevation. The region is dry but heavily vegetated by saguaro and organ pipe cactus and other members of the lower Sonoran plant community. The land south of Ajo (see pl.1) is administered by the Bureau of Land Management and accessed by a network of improved gravel roads.

The geologic map with cross sections, at a scale of 1:24,000 (pl. 1), includes parts of the Chico Shunie, Childs Mountain, Ajo North and Ajo South 7.5 Minute Quadrangles. Sources of map information are shown on plate 1. Late Cenozoic basin-range faulting and extensive cover of middle to late Miocene volcanic rocks and Quaternary alluvium have hindered interpretation of older events and sequences.

Previous Work

The geology of the Ajo 15-minute quadrangle (see pl. 1, sources of data) and the New Cornelia Mine was described by Gilluly in 1946 (see also Gilluly, 1937). He described Precambrian gneiss and granite as well as volcanic rocks of possible Mesozoic age, which are intruded by granitic rocks, ranging in composition from quartz diorite to monzogranite, that he called the Cornelia Quartz Monzonite. Those plutonic rocks, termed the Cornelia Pluton by Wadsworth (1968), include the intrusive rocks of Mesozoic age in and around the New Cornelia Mine and also a larger area of intrusives, adjacent to the west across a fault in Gibson Arroyo. Gilluly mapped the fault in Gibson Arroyo and concluded that the copper deposit represented the down-faulted apex of the large pluton, which lies mostly in the Cardigan Peak area west of this fault.

Wadsworth (1968) subdivided intrusive phases in the Cornelia Pluton and described textural features in support of Gilluly's idea that the Ajo deposit was the apex of the pluton. McDowell (1971) published K-Ar ages of 65-63 Ma for mineralized rocks in the New Cornelia Mine and 20 Ma for a sample from intrusive rocks in the Cardigan Peak area west of Gibson Arroyo. He ascribed this difference in ages to a younger episode of hydrothermal alteration. Lukanuski and others (1975) described the Locomotive Fanglomerate and compared it to the Helmet Fanglomerate, between the Mission-Pima deposits and Twin Buttes, and the Cloudburst Formation at San Manuel.

As a part of the Ajo Lukeville 1ºx2º Mineral Resource Assessment, a study of the Ajo mining district was made to determine the relationship between the Ajo deposit and the surrounding plutonic rocks. Cox and others (1981) described fluid inclusions, in igneous quartz from widely separated samples in the pluton west of the Gibson Fault, that contain daughter minerals of Na, K, and Fe chlorides and Cu-Fe sulfide minerals. These indicated that highly saline, metal-rich solutions were circulating within the pluton at the time of crystallization, consistent with the idea that the pluton was the root zone of the deposit (Cox and others, 1981). Cox and Ohta (1984) mapped the pluton at a scale of 1:25,000 (see pl. 1, sources of data) and outlined areas of hydrothermal alteration that are cut by the fault in Gibson Arroyo. This alteration type, in which biotite and K-feldspar are replaced by actinolite and oligoclase, respectively, had been noted by Carten (1986) and Dilles and Einaudi (1992) in the root zone of the Yerington and Ann Mason porphyry copper deposit in Nevada. This similarity further supported Gilluly's root-zone interpretation.

The root-zone theory was not to survive the continuing work of geochronologists. Lee Silver (oral commun., 1985), R.M.Tosdal (written commun., 1987), and J.S.Stacey and J.L.Wooden (written commun., 1986) obtained incomplete U-Pb ages that corroborate McDowell's (1971) Middle Cenozoic age for the plutonic rocks of the Cardigan Peak area. R. J. Miller (Hagstrum and others, 1987) reported K–Ar ages for the pluton ranging from 23.0 to 21.6 and for the Ajo Volcanics, 25.3 to 23.8 Ma. These ages confirm that the pluton is roughly 40 m.y. younger than the porphyry copper deposit and similar in age to the Ajo Volcanics to the south.

Thus the term Cornelia Pluton should be restricted to intrusive rocks of Laramide age exposed in the New Cornelia Mine, in Ajo town, and on Camelback Mountain. Intrusive rocks of Middle Cenozoic age west of the Gibson Fault have been named the Cardigan Peak Pluton (Hagstrum and others, 1987).

Hagstrum and others (1987), with the cooperation of Ron Gibbs of Phelps Dodge Corp., collected oriented samples from the New Cornelia Mine area and from the Cardigan Peak Pluton. Paleomagnetic analysis of these samples revealed that the Ajo deposit was first tilted approximately 68°±20° to the south, and after deposition of the Locomotive Fanglomerate a

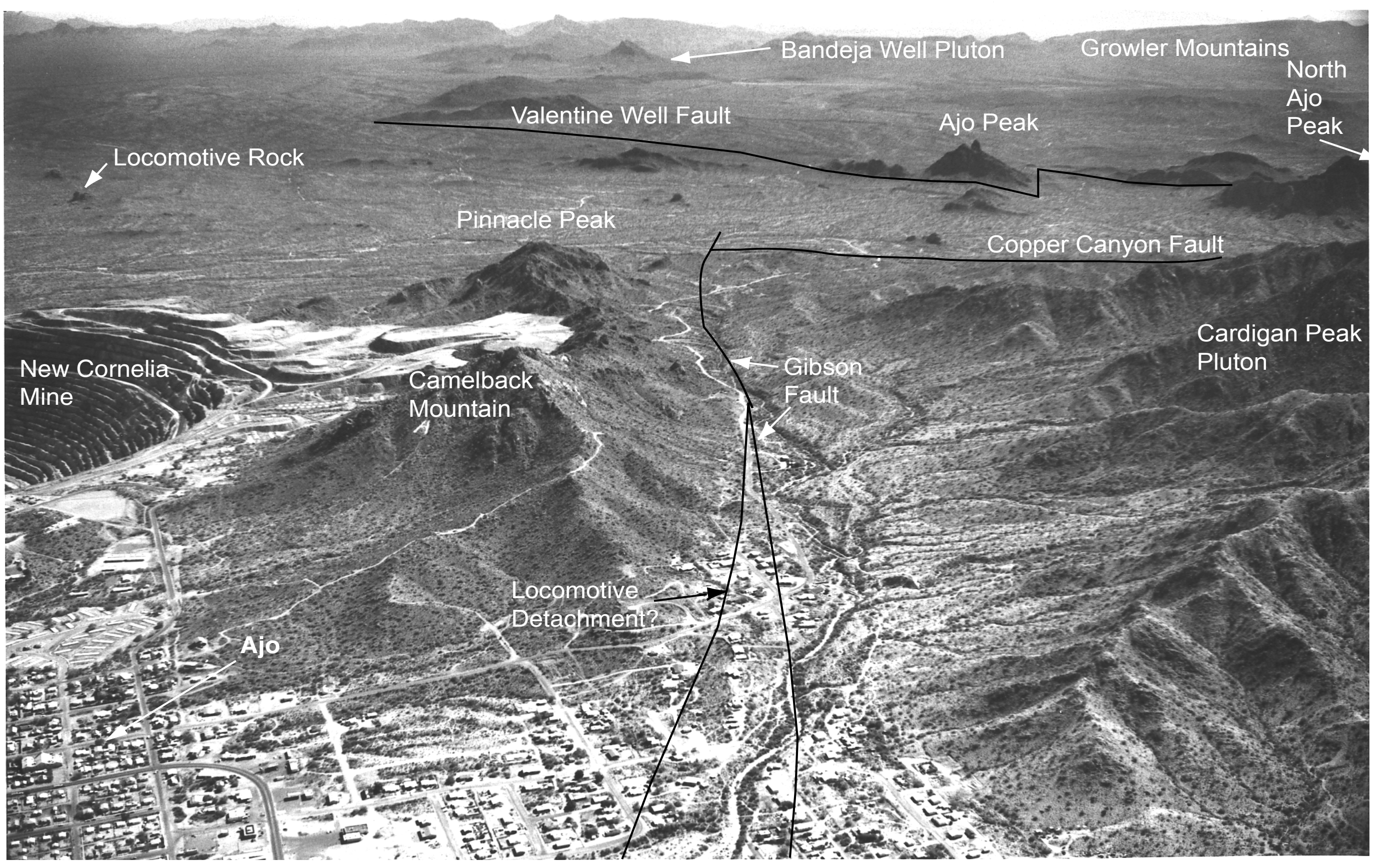

Figure 1. Oblique aerial view looking to the south, showing the west edge of the New Cornelia Mine pit, Camelback Mountain, Pinnacle Peak, Gibson Arroyo, and the Gibson Fault. Altered rocks of the Cardigan Peak Pluton are on the lower right.

further 55° to the south, both rotations around a horizontal axis with an azimuth of 105°. The result of this tilting is that the apex of the deposit plunges 30°±20° to the south and its root zone is exposed north of the pit, near the town of Ajo.

In the Cardigan Peak area, steeply dipping dikes cutting the pluton show consistent middle Cenozoic paleomagnetic poles, indicating that these dikes were not tilted after intrusion. Data from the granitic rocks of the pluton were more complex (Hagstrum and others 1987). J.T. Hagstrum, in a further review of these data (written commun., 1999), concluded that the rocks of the Cardigan Peak Pluton have Cenozoic magnetic directions and probably have not been tilted. The data indicate that the fine-grained granitic rocks were cooling during both normal and reversed polarities of the geomagnetic field. Intermediate directions between the expected normal and reversed Cenozoic directions were likely acquired during a reversal, or could be accounted for by overlapping normal and reversed components within the same sample. The dike rocks, because they cooled rapidly, show only normal or reversed Cenozoic directions.

Cox (see pl.1, sources of data) mapped the lower Cenozoic rocks south of the mine as part of an exploration program begun by Magma Copper, Inc., and continued by BHP Minerals. This program was aimed at evaluating the possibility of finding a detached part of the New Cornelia ore body under cover north of the town of Ajo.

Force (1997a; see pl.1) described steeply overturned beds of conglomerate, lying between the Locomotive Fanglomerate and the Concentrator Volcanics, which he named the Darby Arroyo Formation. He briefly described and named the Locomotive Detachment Fault from exposures near North Ajo Peak.

Phelps Dodge Corp. conducted subsurface exploration south of the New Cornelia Mine (Wilkinson, 1998) that resulted in a contour map of the Locomotive Detachment Fault surface made from the drilling results (fig.2). This map has been critical in understanding the structure of the district. Everywhere beneath the fault is Precambrian gneiss, generally altered and fractured.

Description of Map Units

Correlation of the map units discussed below is shown in plate 1. A summary of the geochronology of these units is given in table 1.

Pre-Extension Units

Cardigan Gneiss

Gilluly (1937) described the Cardigan Gneiss (see pl.1, unit Xcg) as metamorphic rocks composed of quartz, sericitized plagioclase, chlorite, biotite, muscovite, and minor microcline. These rocks have a variety of textures, including well-foliated coarsely crystallized gneiss, fine-grained gneiss, augen gneiss, schist, and weakly foliated tonalite. Gray and others (1985a) considered the Cardigan Gneiss to be equivalent in age to the 1.7–Ga Pinal Schist of Ransome (1923), which is widespread in southern Arizona. The Cardigan Gneiss probably underlies all of the rocks in the Ajo mining district except where it was removed by emplacement of Precambrian and Cenozoic plutons.

Chico Shunie Quartz Monzonite

The Cardigan Gneiss is intruded by a porphyritic monzogranite called the Chico Shunie Quartz Monzonite (Gilluly, 1937) (see pl. 1, unit Ycs). The rock contains 20 to 30 percent quartz plus euhedral or rounded phenocrysts of pink microcline 2 to 3 cm in diameter. Small, square, light gray plagioclase crystals and anhedral biotite and muscovite are less abundant. A K–Ar date of 1.4 Ga was obtained from hornblende in a dike cutting the Chico Shunie by R.M. Tosdal (Gray and others, 1985a) suggesting that the pluton is correlative with the widespread granite intrusions referred to as Oracle or Ruin granite in other parts of southern Arizona (Anderson, 1989).

Paleozoic Rocks

Metasedimentary rocks, believed to be equivalent to the Cambrian Bolsa Quartzite and Cambrian Abrigo Formation, are exposed 16 km south of Ajo (Gray and others, 1985a). The Abrigo Formation is metamorphosed to wollastonite skarn by the nearby Bandeja Wells Pluton.

Mesozoic Rocks

Mesozoic plutonic and volcanic rocks, mainly Cretaceous in age, are present at Pinnacle Peak, Concentrator Hill, New Cornelia Mine, west of Bandeja Wells, and in the Gunsight Hills (Ajo district and surrounding region, see pl. 1). In addition to the Ajo porphyry deposit, these rocks host small gold-quartz veins in the Gunsight Hills (Tosdal and others, 1986). All of the Mesozoic rocks in plate 1 are structurally underlain by Precambrian rocks and have been rotated about 120° to the south and southwest. They may have been tectonically transported from near the volcanic-plutonic complex 16 km south of Ajo at Bandeja Wells (see regional map in pl. 1).

The Concentrator Volcanics of Gilluly (1937) is a sequence of andesitic to rhyolitic flows, tuffs, lahars, and flow breccias that underlie Concentrator Hill and part of Pinnacle Peak (see pl. 1, unit Kc). A small exposure of metaandesite and metarhyolite on the west contact of the Bandeja Wells Pluton is also considered to belong to this unit (see regional map in pl.1) (Gray and others, 1988). The unit is predominantly andesitic and dark gray to greenish gray in color, but the presence of a few layers of light gray tuffs with fiame texture indicate that some dacite or rhyolite is present. This unit has been dated at 71.6 ± 0.6 Ma, by the U-Pb, zircon method

(Wilkinson, 1998). Alteration of the Concentrator Volcanics was not investigated in this study. Propylitic alteration (albite, chlorite, actinolite, and hematite) believed to be related to the Ajo porphyry copper system is widespread. Near Pinnacle Peak white alteration streaks, megascopically determined to be albitic, accompany abundant specular hematite veinlets and disseminations. If this alteration is related to the Cenozoic sodic-calcic alteration of the Cardigan Peak Pluton (see below), some constraints on timing of detachment faulting are implied.

The Cornelia Pluton intrudes the Concentrator Volcanics and comprises a dioritic facies, a main equigranular granodiorite facies, and a porphyry facies that includes the Ajo porphyry copper ore body. K–Ar ages ranging from 65 to 63 Ma have been published for the pluton and its alteration biotite (Hagstrum and others, 1987). Two biotite fractions of a granodiorite sample from Camelback Mountain have K–Ar ages of 42 and 39 Ma. This discrepancy was attributed to argon loss by heating related to intrusion of the Cardigan Peak Pluton to the west (Hagstrum and others, 1987, p. 1351). A more likely explanation discussed below is that argon loss was caused by a reheating event at 20 to 19 Ma related to a deep concealed intrusion within the Cardigan Peak Pluton.

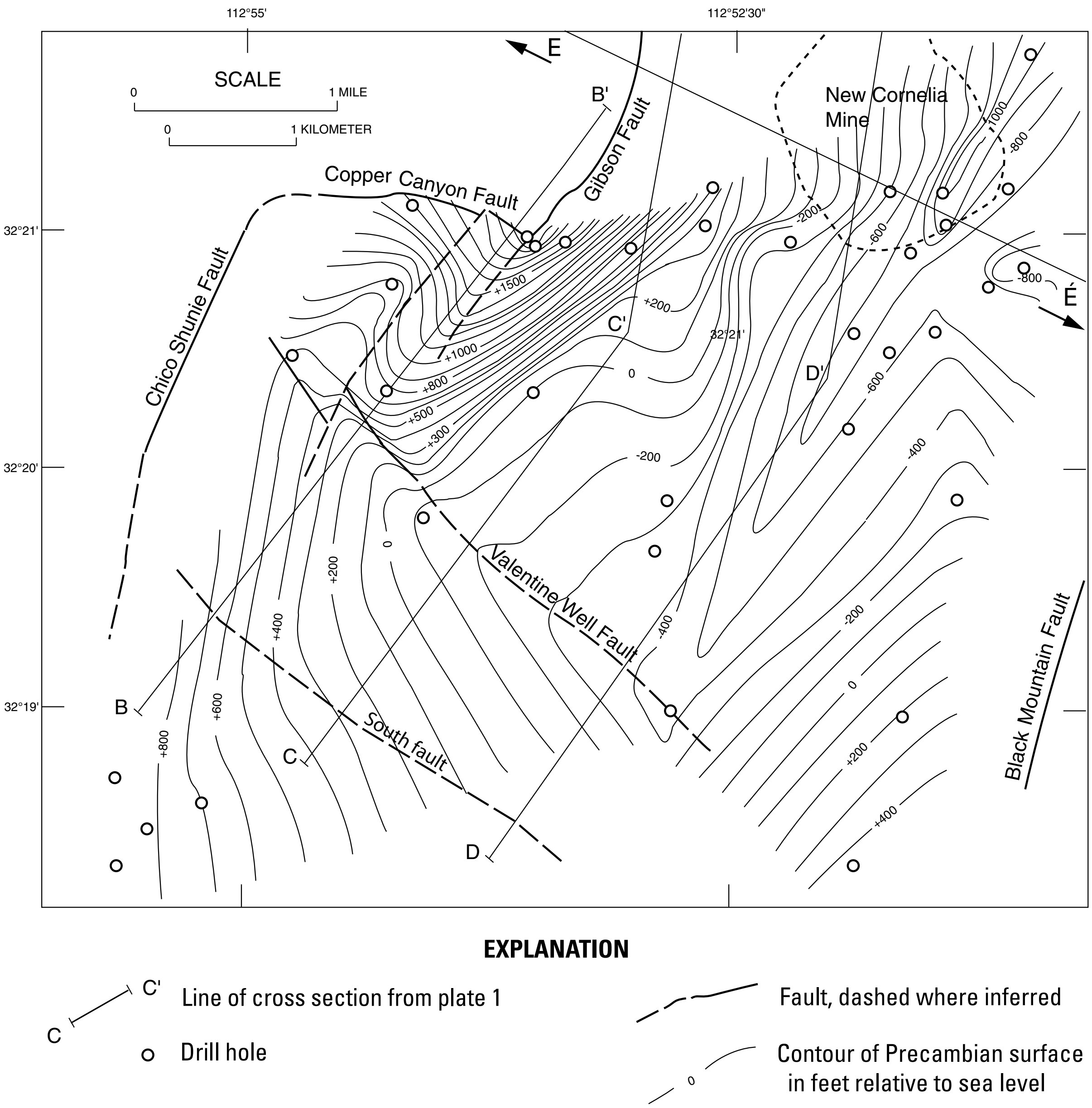

Figure 2. Map of the Ajo mining district showing contours on the surface of Precambrian Cardigan Gneiss underlying the Locomotive Detachment Fault. Contours are in feet relative to sea level. Drill holes are shown as circles. Faults and cross-section lines are from plate 1.

Table 1. Geochronology of metamorphic, intrusive, and extrusive events in the Ajo mining district.

UNIT	EVENT	AGE	REFERENCE
Cardigan Gneiss	Regional metamorphism	1,700-1,650 Ma	Anderson, P., 1989
Chico Shunie Quartz Monzonite	Intrusion	1,440±.03 Ma, U/Pb, zircon	Anderson, J.L., 1989
Concentrator Volcanics	Extrusion	71.6±.06 Ma, U/Pb, zircon	Wilkinson, 1998
Cornelia Pluton	Intrusion	65-63 Ma, K/Ar, biotite	Hagstrum and others, 1987
Darby Conglomerate	Deposition, rotation	35.2±0.9 Ma, from clast, K/Ar, whole rock	Force, 1997a
Locomotive Fanglomerate	Deposition, rotation	Early Miocene	This paper
Valentine Well member, Ajo Volcanics	Extrusion, rotation	23.8±0.8 Ma, K/Ar, biotite 25±2.7 Ma, K/Ar, whole rock	Gray and Miller, 1984
Cardigan Peak Pluton monzodiorite	Intrusion	23±0.7 Ma, K/Ar, biotite	Hagstrum and others 1987
Cardigan Peak Pluton monzogranite	Intrusion	21.6±0.7 Ma, biotite	Hagstrum and others, 1987
Cardigan Peak Pluton, all phases	Intrusion	23.7±0.2 Ma, U/Pb, zircon	Wooden, this paper
Cardigan Peak Pluton monzogranite	Intrusion, reheating?	20.1±3.5 Ma, hornblende 19.6±1.3 Ma, biotite	McDowell, 1971
Sneed Andesite	Extrusion	22.0±0.7 Ma, K/Ar, biotite 21.73±0.1 Ma, Ar/Ar, sanidine	Gray and Miller, 1984; This paper
Childs Latite	Extrusion	18.4±0.9 Ma, K/Ar, plagioclase	Gray and Miller, 1984
Batamote Andesite	Extrusion	14.4±0.7 Ma, K/Ar, whole rock	Gray and Miller, 1984

Fine-grained diorite.—Fine-grained diorite, monzodiorite, and quartz monzodiorite (see pl. 1, unit Kd) is equivalent to the border facies (quartz diorite) of Gilluly (1946). It forms a major part of the Camelback Mountain block and is present as small, irregular bodies in the porphyry phase of the Cornelia Pluton in the New Cornelia Mine (Dixon, 1966). Typical rocks of this unit contain 65 volume percent plagioclase (An_{60}), 11 percent K–feldspar, 10 percent quartz, 10 percent hornblende, and 3 percent biotite. Typical grain size is 1 to 2 mm.

Granodiorite.—Granitic-textured rocks (see pl. 1, unit Kg) ranging in composition from granodiorite to monzogranite make up the north end of Camelback Mountain and underlie most of the town of Ajo, south of the Little Ajo Mountains Fault. Rocks of this unit typically contain plagioclase, K-feldspar, quartz, biotite, and hornblende, with grain size ranging from 1 to 3 mm. Biotite forms euhedral crystals that are extended in the direction of the c-axis. This habit is locally termed stacked biotite and is typical of Laramide age granitoids in southern Arizona (Don Hammer, oral commun. 1981).

Granodiorite Porphyry.—Aplitic granodiorite porphyry (see pl. 1, unit Kp) is characterized by phenocrysts, 2 to 4 mm in size, of plagioclase, quartz, and stacked biotite set in a fine-grained (0.05 to 0.2 mm in diameter) groundmass composed of aplitic textured quartz and K–feldspar that makes up 20 to 50 percent of the rock by volume. The porphyry forms a small body on the east side of Camelback Mountain and is abundant in a belt of exposures along the north rim of the New Cornelia Mine pit. Most ore-bearing rocks in that mine are of this type. Rocks with aplitic texture are illustrated in plate 13 E and F and plate 14 B, C, and D of Gilluly (1946). Small bodies of pegmatite are present in the porphyry. These contain large grains of quartz and hexagonal books of biotite, replaced by chlorite, as large as 2 cm in diameter.

Dikes.—Andesite porphyry dikes (unit Kfa), the feldspathic andesite porphyry of Gilluly (1946), are abundant near Camelback Mountain and toward the south part of Ajo town. They intrude rocks as young as granodiorite porphyry. Quartz veinlets cutting altered granodiorite porphyry were locally observed having been cut off by a feldspar porphyry contact, suggesting that these dikes are younger than copper mineralization.

Paleomagnetic data for samples from the east side of the New Cornelia pit show the two stages of tilting described above

(Hagstrum and others, 1987). Rocks on the west side of the pit and on Camelback Mountain show mainly middle Cenozoic poles, possibly due to remagnetization related to intrusion of the Miocene Cardigan Peak Pluton. One exception is a feldspathic andesite dike from the northeast side of Camelback Mountain, which shows a pole direction similar to samples from the east side of the pit (Hagstrum and others 1987). This allows the interpretation that some of the feldspathic andesite dikes are of Laramide age. However, the steep northerly dip of most of these dikes requires that their Laramide pre-rotation dip must have been less than 20° north. This unlikely conclusion indicates that most of these dikes are probably Cenozoic.

Chemical Composition.—Rocks of the Cornelia Pluton range in silica content from 59.7 to 66.2 weight percent (table 2) and fall within the range of composition typical of igneous rocks of southern Arizona (fig. 3) as defined by Spencer and others (1995). They are calc-alkalic as shown by the alkali-iron-magnesium (AFM) plot (fig. 4). They have a Peacock index of 55 and are metaluminous with Al_2O_3 / (CaO + Na_2O + K_2O) ranging from 0.94 to 1.01. Trace element patterns (fig. 5*A*) are typical of calc-alkalic rocks. Rare-earth elements (fig. 6*A*) are distributed in a smooth concave-upward trend without a europium anomaly (Cox, 1988).

Comparison with the Bandeja Well Pluton.—The Bandeja Well Pluton, 16 km south-southwest of Ajo (pl. 1, regional map) is a possible root of the Cornelia Pluton. The K–Ar age of biotite from the pluton is 66 Ma (Richard M. Tosdal, oral commun. 1986). Geologic mapping of the Bandeja Wells Pluton by Cox in 1996 showed it to be of uniform granodiorite composition and equigranular texture with only one small area of aplite. No evidence of hydrothermal alteration was seen. The pluton is in contact with quartzite and carbonate rocks of presumed Paleozoic age on the east, and with metavolcanic rocks similar to Concentrator Volcanics on the west (Gray and others, 1985a). The surface dimensions of the pluton are about 3 km wide in an east-west direction and 4.26 km long, north-south. These dimensions compare reasonably with the 3 km wide exposure of the Cornelia Pluton at Ajo. The main difference between the Bandeja Wells and Cornelia Plutons is that the former is composed of a single rock type while the latter contains several types ranging from quartz diorite to granodiorite.

Geology of the New Cornelia Mine

Early copper production from the New Cornelia mine through 1930 was derived from a zone of copper carbonate and silicate mineralization, 6 to 45 meters thick, developed parallel to the present erosional surface, that is, along the side of an overturned plutonic slice. Very little chalcocite formed beneath the oxide zone, and mineralization passed into primary sulfides with little change in grade. Mine production from 1930 to 1984 exploited disseminated and veinlet-controlled primary ores of chalcopyrite and bornite. The New Cornelia deposit differs from other southwestern porphyry copper deposits in several ways—the unique bornite component of the primary copper assemblage (high Cu to sulfide ratio), the presence of trace gold in the ore, the low overall total sulfide content of the orebody (averaging 3 volume percent), the presence of magnetite, and the low intensity of stockwork fracturing and vein quartz.

Geology

Whereas plate 1 shows the distribution of rock units based on mapping and interpretation in the early 1980s (Ron Gibbs, Phelps Dodge Corp. written commun., 1983), figure 7 is based on mapping at a deeper mining level in the 1990s. The elongate outline of the inclined Cornelia granodiorite porphyry stock is shown in both maps. The increase in outcrop area of Concentrator Volcanics and fine-grained diorite in figure 7 results from increased proximity to the lower contact of the stock, the south contact in its original configuration. West dipping normal faults Arkansas Mountain, Easy, Fox, and George are probably related to the Gibson Fault and uplift of the Cardigan Peak block to the west. The south-dipping Baker Fault may be related to the Copper Canyon Fault. The Cenozoic Locomotive Fanglomerate unconformably overlies the Cretaceous rocks on a south-dipping contact.

Mineralization

The distribution of copper grade in the New Cornelia Mine lacks the symmetry that is characteristic of copper mineralization in most porphyry deposits. The wide area of low-grade ore on the northeast flank is related to proximity to the lower side of the porphyry column. The highest grades are present on the southwest and southeast sides, and grades fall off abruptly at the edge of the ore body. This abrupt boundary may be caused by erosion of the deposit before deposition of the Locomotive Fanglomerate. A zone of secondary chalcocite has been recognized near the Locomotive contact (fig. 7).

The primary sulfide ores consist of chalcopyrite and bornite, in a volume ratio of 4:1, occurring as fine disseminations in K-feldspar-impregnated granodiorite, often with chalcopyrite replacing chlorite and biotite. Much of the chalcopyrite and bornite is associated with retrograde K-feldspar-chlorite alteration or narrow stockwork stringers of sulfides that cut orthoclase veins. Deposition of bornite diminishes following K-feldspar-chlorite alteration, while chalcopyrite continues into phyllic-stage alteration. Bornite tends to be more prevalent at the southern end of the pit, that is, in the originally higher portions of the Cornelia Pluton. Volume percent of disseminated chalcopyrite tends to exceed that of disseminated pyrite.

Molybdenite is widespread in the pit but has only been intermittently recovered. It is preferentially distributed in a 245-meter-wide northwest-trending zone centered on the Hospital Porphyry dike and in an east-west elongate mass south of the Baker Fault (that is, in transposed Fox Fault slices, trending to the southeast). Molybdenite occurs largely in early

Table 2. Analytical data on rocks of the Laramide Cornelia Pluton, Ajo, Arizona.

[X–ray spectroscopic analyses of major element oxides were made by A. J. Bartel, K. Stewart, and J. E. Taggart in Lakewood Colorado. Determination of FeO, H_2O, CO_2, Cl, and F were made by D. V. Vivit in Menlo Park, California. Be, Co, Cr, Cu, Ga, Ni, Pb, and V were determined by emission spectrograph by Judith Kent and R. Lerner in Menlo Park. Rb, Sn, and Nb were determined by L. F. Espos in Menlo Park and J. S. Kane and M. W. Doughten and R. Somers in Reston, Virginia. Remaining elements in table 2 were determined by radiochemistry by J. Storey, J. R. Budahn, R. J. Knight, S. Danehey, and R. B. Vaughn in Lakewood.]

Analysis no.[1]----	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Field no.[1]---------	**214, Kd**	**806, Kg**	**805, Kp**	**540, Kp**	**503, KTfa**	**Kd**	**Kp**
Major elements (weight percent)							
SiO_2	59.7	65.7	64.5	64.4	64.3	60.59	66.23
TiO_2	0.87	0.57	0.54	0.57	0.51	0.61	0.67
Al_2O_3	16.8	15.4	15.6	16.3	16	17.39	15.71
Fe_2O_3	3	2.29	2.1	2.09	2.06	1.60	2.20
FeO	2.43	1.57	1.68	1.71	1.63	1.98	1.98
FeO*	5.13	3.63	3.57	3.59	3.48	2.94	2.02
MnO	0.09	0.06	0.03	0.05	0.03	0.08	0.08
MgO	3.05	1.79	1.6	1.69	1.81	2.38	1.58
CaO	4.8	3.43	3.27	3.96	3.45	5.06	3.78
Na_2O	4.31	3.98	4.00	4.31	4.06	4.09	3.89
K_2O	2.42	3.1	3.42	2.98	3.52	1.63	3.22
P_2O_5	0.28	0.21	0.2	0.23	0.23	0.36	0.24
H_2O+	1.1	0.67	1.11	0.59	0.88	3.29	0.67
H_2O-	0.12	0.16	0.16	0.12	0.22	0.78	0.03
CO_2	0.1	0.03	0.64	0.07	0.08	—	—
Cl	0.02	0.019	0.012	0.02	0.034	—	—
F	0.03	0.04	0.04	0.02	0.05	—	—
TOTAL	99.12	98.979	98.86	99.11	98.864	99.84	100.08
Trace elements (parts per million)						[Samples 6 and 7 not analyzed for trace elements]	
Be	1.9	1.7	1.8	2	2.2		
Co	19	12	9	13	12		
Cr	31	14	17	19	30		
Cu	32	7.8	60	17	15		
Ga	26	18	20	25	19		
Ni	18	9.2	9	10	18		
Pb	18	<10	20	18	18		
V	140	81	83	100	64		
Y	16	13	14	16	19		
Zr	150	93	120	99	220		
Sn	1.5	2.8	1.6	1.2	1.9		
Nb	1	13	12	12	15		
U	1.19	3.28	3.49	3.72	2.21		
Ba	836	846	973	927	1260		
Co	16.5	9.53	7.45	8.95	8.97		
Cr	28.3	12.3	12.6	13.6	24.8		
Cs	1.83	1.47	2.59	1.43	2.3		

Table 2. Analytical data on rocks of the Laramide Cornelia Pluton, Ajo, Arizona.—Continued

[X–ray spectroscopic analyses of major element oxides were made by A. J. Bartel, K. Stewart, and J. E. Taggart in Lakewood Colorado. Determination of FeO, H_2O, CO_2, Cl, and F were made by D. V. Vivit in Menlo Park, California. Be, Co, Cr, Cu, Ga, Ni, Pb, and V were determined by emission spectrograph by Judith Kent and R. Lerner in Menlo Park. Rb, Sn, and Nb were determined by L. F. Espos in Menlo Park and J. S. Kane and M. W. Doughten and R. Somers in Reston, Virginia. Remaining elements in table 2 were determined by radiochemistry by J. Storey, J. R. Budahn, R. J. Knight, S. Danehey, and R. B. Vaughn in Lakewood.]

Analysis no.[1]----	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Field no.[1]---------	**214, Kd**	**806, Kg**	**805, Kp**	**540, Kp**	**503, KTfa**	**Kd**	**Kp**
	Trace elements (parts per million)					[Samples 6 and 7 not analyzed for trace elements]	
Hf	4.06	3.64	3.65	3.96	5.03		
Rb	58.8	73.8	94.7	77.9	88.5		
Sb	0.302	0.23	1.66	0.108	0.72		
Sr	790	620	560	680	710		
Ta	0.426	0.82	0.826	0.751	0.73		
Th	3.68	8.43	7.99	7.2	10		
Zn	59.1	26.8	28.5	27.2	<50		
Zr	139	124	124	136	198		
Sc	10.7	6.49	6.29	6.67	6.67		
La	28.6	29.5	27.7	30.9	44.9		
Ce	57.4	59.3	56.2	61.6	81.6		
Nd	24.1	24.7	22.7	23.7	32.1		
Sm	4.52	4.24	4.14	4.62	4.66		
Eu	1.36	1.12	1.05	1.2	1.24		
Gd	3.51	2.98	2.98	3.24	3.75		
Tb	0.492	0.45	0.401	0.445	0.51		
Dy	—	—	—	—	<0.1		
Tm	0.197	0.2	0.19	0.188	0.24		
Yb	1.06	1.15	1.09	1.17	1.44		
Lu	0.158	0.18	0.167	0.179	0.21		

[1]Description of samples analyzed:

1. Fine-grained hornblende granodiorite, Gibson Road at UTM Zone 12, 3582100N, 322795E.
2. Biotite granodiorite at 3582680N, 323200E.
3. Granodiorite porphyry with aplitic groundmass, Indian Village Road at 3582320N, 323960E.
4. Granodiorite porphyry dike with aplitic groundmass at 3582400N, 323570E.
5. Feldspathic andesite dike at 3582870N, 323280E.
6. Biotite quartz diorite at 3582670N, 324910E (Gilluly, 1946, analysis 1).
7. Hornblende biotite quartz monzonite porphyry at 3582210N, 323390E. (Gilluly, 1946, analysis 4).

quartz-sulfide veinlets in phyllically altered volcanic rocks adjacent to the potassic core zone and more sparsely in potassic veinlets associated with main-stage copper mineralization, in younger quartz-sericite-pyrite veins, and as paint on faults and fractures.

Pyrite is the chief gangue mineral and rarely exceeds several volume percent of the rock. It is most prevalent in the silicified and sericitized Concentrator Volcanics on the eastern edge of the pit, as noted by the strong jarositic staining of the upper benches. Pyrite occurs as fine disseminations and small veinlets in quartz-K-feldspar and quartz-sericite assemblage rocks. The low total pyrite content of the New Cornelia deposit accounts for the relatively sparse secondary sulfide enrichment blanket.

Silver (average 0.035 ppm) and gold (average 0.003 ppm) are distributed in a prominent northwest-trending zone on the west and south ends of the deposit. Both metals show a positive correlation with increased copper grades. Gold occurs as micron-size inclusions in bornite and to a lesser degree in chalcopyrite. Gold has also been observed as blebs in magnetite.

Magnetite occurs as a primary component of the pluton and as a hydrothermal gangue product associated with potassic assemblages, where it is paragenetically older than pyrite, and younger than secondary orthoclase. It also occurs as sparse complex veinlets associated with pegmatite and in deep potassic assemblages.

Alteration

In spite of the intense structural dislocation and jumbling of lithologic units, basic alteration assemblages common to most porphyry copper deposits can be recognized at the New Cornelia deposit. A large portion of the Concentrator Volcanics, both proximal and distal to the Cornelia Pluton, and the diorite and quartz diorite units of the Cornelia Pluton show an early albitization overprint that consists of albite rimming of original andesine cores. The process involves depletion of the calcium component from andesine and is related to regional propylitic alteration.

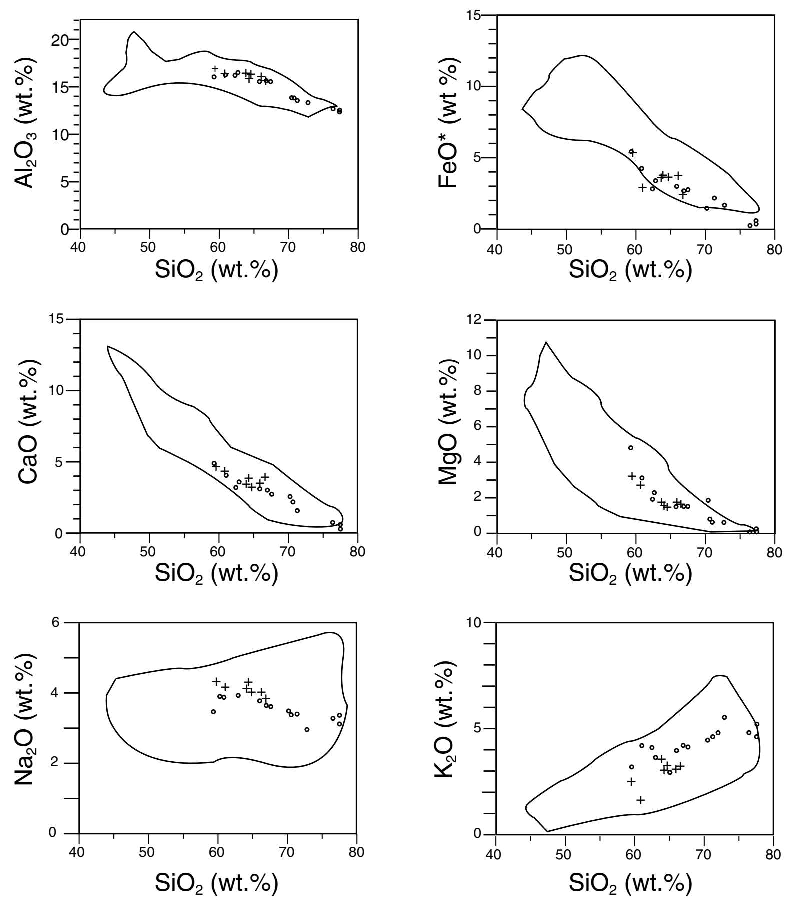

Figure 3. Plots of major-element oxides against weight percent silica for Laramide Cornelia Pluton (crosses) and Miocene Cardigan Peak Pluton (circles). FeO* is total iron expressed as FeO. Polygon in each plot represents compositions of Middle Cenozoic volcanic and shallow intrusive rocks in southern Arizona (Spencer and others, 1995).

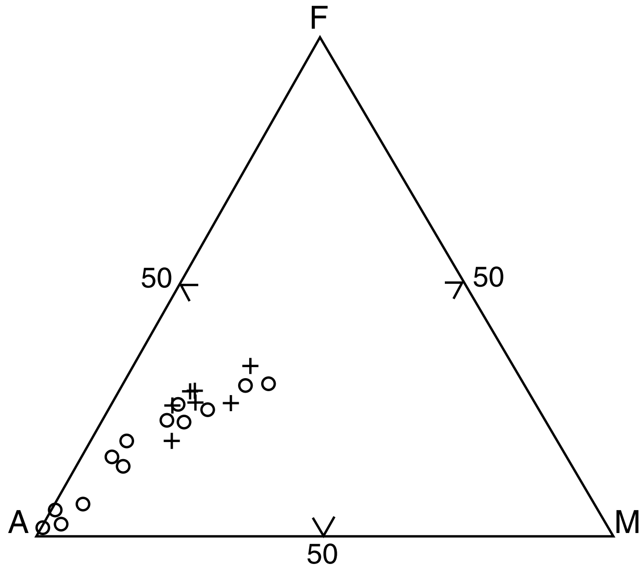

Figure 4. Alkali-iron-magnesium plot in weight percent (A=Na2O+K2O, F=total Fe expressed as FeO, M= MgO) illustrating the calc-alkalic trend of compositions of the Laramide Cornelia Pluton (crosses) and Miocene Cardigan Peak Pluton (circles).

The dominant alteration seen in the New Cornelia deposit is pervasive potassic alteration that forms a core about the axis of the gently plunging Cornelia Pluton. This is characterized by pervasive flooding of the central plutonic core zone with secondary orthoclase. Orthoclase replaces plagioclase, is intergrown with quartz, and to a lesser degree forms veins and veinlets with variable amounts of quartz and sulfides. Secondary orthoclase is most prevalent in the Cornelia granodiorite, with a lesser degree of replacement in the diorite, quartz diorite, and Concentrator Volcanics. Anhydrite veinlets are common in the potassic zone. Most of the potassic core zone is overprinted with a retrograde chlorite alteration resulting in conversion of mafic minerals to chlorite and formation of minor chlorite veinlets and fracture coatings.

Within the volcanic rocks, alteration is more vein controlled. Secondary biotite replacement of preexisting ferromagnesian minerals is relatively minor overall in the New Cornelia deposit; where found, secondary biotite tends to be affiliated with the more mafic portions of Concentrator Volcanics and is usually chloritized.

An interesting central breccia or "pegmatitic" zone, aligned N45°W, formed early in the fracturing history of the pluton. The "pegmatite" consisted of massive bornite with lesser chalcopyrite, enmeshed in a vuggy gangue of pink microcline intergrown with comb quartz, coarse biotite altered to chlorite, and apatite. The two parallel "pegmatite" bodies, long since mined out, were 213 by 305 meters and 31 by 122 meters in plan and more than a hundred meters thick.

Early potassic assemblages are estimated to have formed at 580°C to 470°C, and less commonly as low as 280°C at 650 bars (UyTana, 1983). Main-stage copper mineralization is affiliated with the early potassic alteration, overlapping into K-feldspar-chlorite retrograde alteration.

Drill holes in the deeper parts of the pit (305 to 610 m) pass into K-feldspar-chlorite rock with decreasing sulfide content and more calcite, epidote, sphene, magnetite, saussurite, and anhydrite-gypsum. This transition overlaps with the diminution in copper grade.

Flanking the K-feldspar-chlorite zone is a broad transition zone of potassic alteration overprinted with a phyllic assemblage. The K-feldspar-phyllic overlap assemblages are best developed in Concentrator Volcanics, where veinlet-dominated K-feldspar alteration is overprinted by both pervasive and veinlet-phyllic alteration (quartz + sericite +/- pyrite).

True stockwork phyllic vein development, in the sense of quartz-pyrite veining with prominent sericite selvages, is restricted to a zone a few tens of meters wide in the Concentrator Volcanics at its contact with the Cornelia Pluton. The

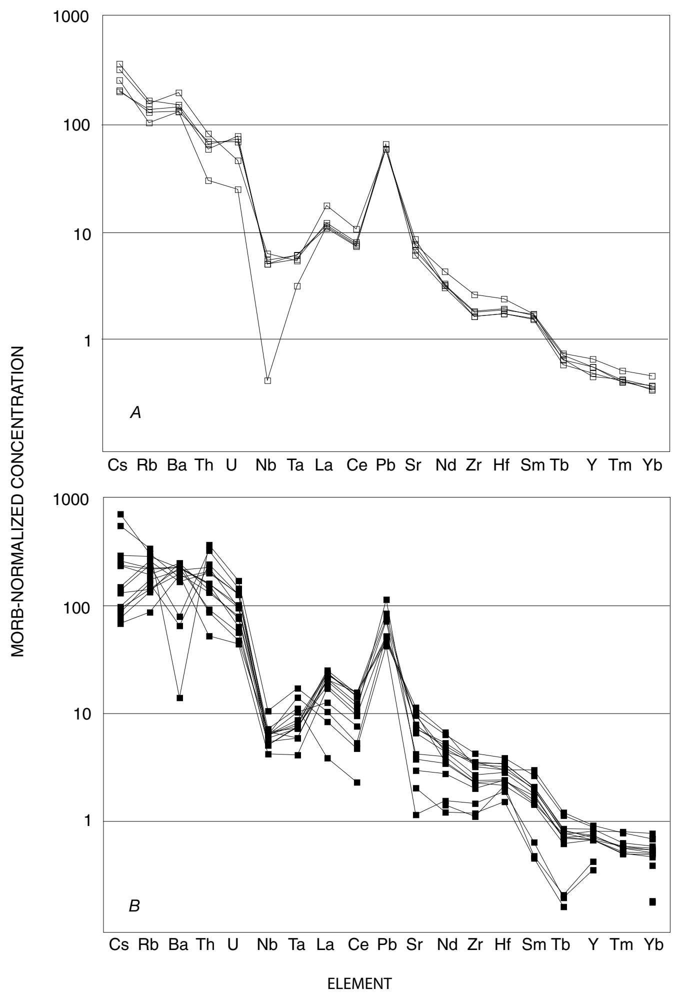

Figure 5. Spider diagrams showing MORB-normalized trace-element values for the Laramide Cornelia Pluton (*A*) and the Miocene Cardigan Peak Pluton (*B*). The low Th, U, and Nb values in A are from the quartz diorite unit, Kd. MORB values from Sun and McDonough (1989).

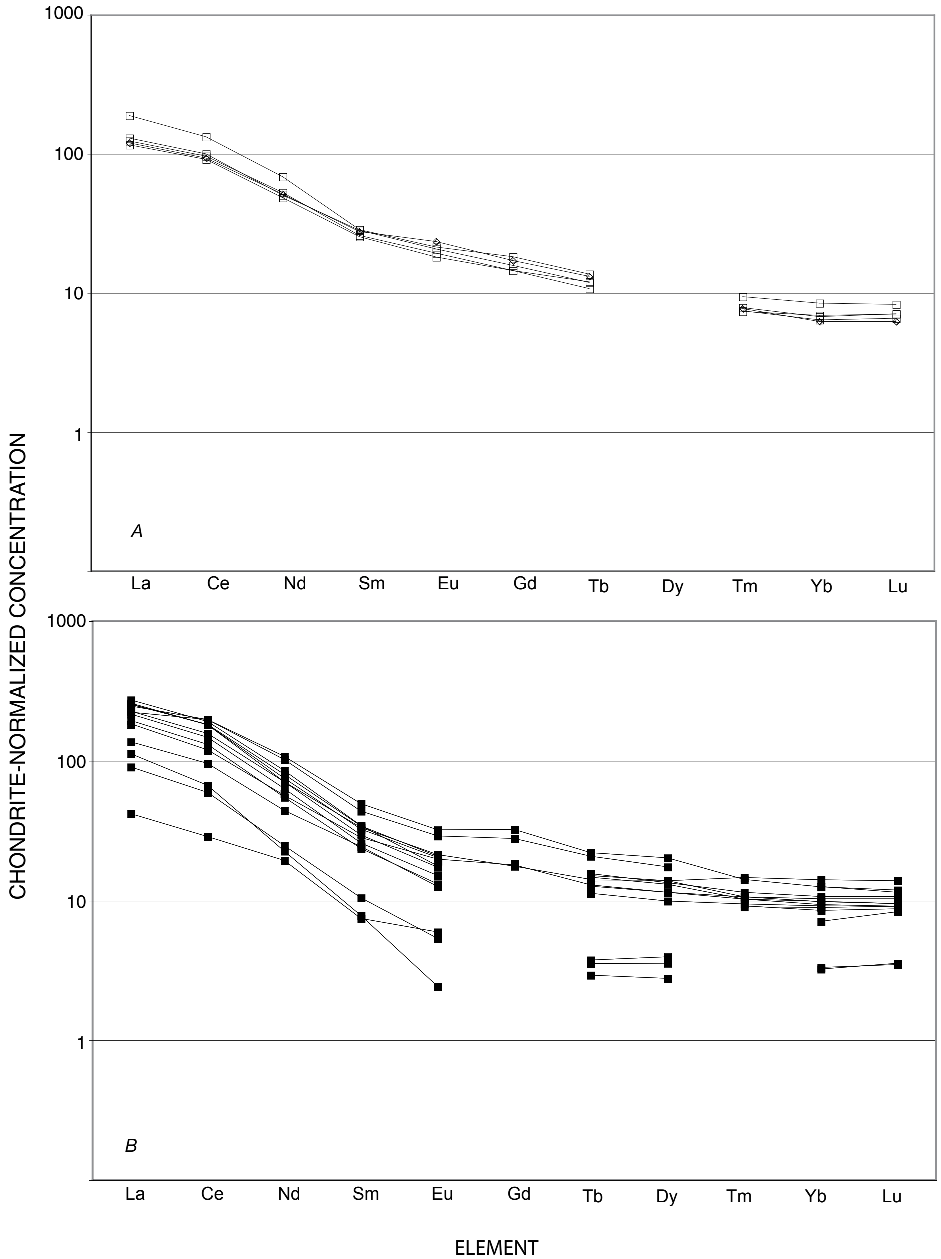

Figure 6. Spider diagrams of chondrite-normalized rare-earth values for the Laramide Cornelia Pluton (*A*) and the Miocene Cardigan Peak Pluton (*B*). Gadolinium was undetected at the 2-ppm level. Chondrite values from Sun and McDonough (1989).

greater proportion of phyllic alteration involves pervasive sericitization of the volcanic groundmass.

Instances in which phyllic stockwork veins cut earlier potassic veins show that minerals engulfed by the sericitic envelope are further altered to sericite or sericite-chlorite. Phyllic assemblages are more common on the eastern and southwestern edges of the system. Most of the Concentrator Volcanics show mild to intense sericitic alteration, with two to three volume percent pyrite content. Restoration of phyllically altered volcanic rocks along a high-angle fault places the eastern phyllic alteration at a position that suggests it was coextensive with a phyllic zone that may have existed above the present pit.

Intense silicification is restricted to narrow intervals in K-feldspar and phyllic assemblage zones. Tuffaceous sections show mild to strong sericitization and devitrification of glassy fragments.

Late-stage oxidized hypogene sulfate and carbonate minerals cut all assemblages. Veins and fracture fillings of anhydrite-gypsum-calcite +/- quartz are common in the potassic core zone. Carbonate veining (dolomite to calcite) is ubiquitous on a microscopic scale in all zones.

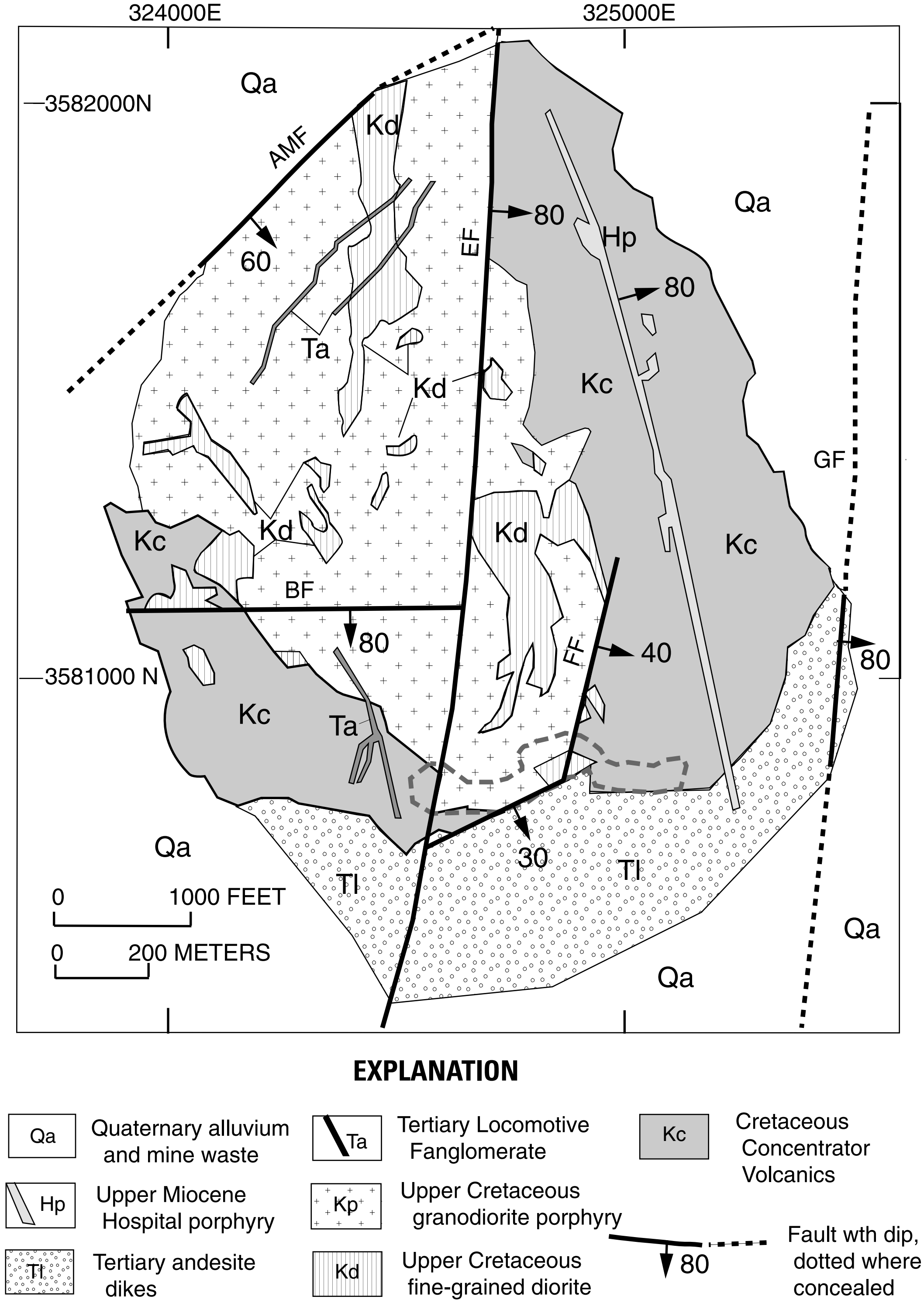

Figure 7. Geology of the New Cornelia Mine. Faults are labeled as follows: AMF, Arkansas Mountain; BF, Baker; EF, Easy; FF, Fox; GF, George. Secondary chalcocite mineralization related to the pre-Locomotive erosion surface is shown by the gray dashed outline. Coordinates are UTM.

Specular hematite, as coarse flakes and fracture fillings, is abundant in the volcanic rocks on the east side of the pit. It is not clear if the hematite is a product of early albitization, late-stage cooling and oxidizing of the Cornelia intrusive or a superimposed mid-Cenozoic event related to the Cardigan Peak intrusion.

At least two stages of supergene alteration and enrichment are documented in the New Cornelia deposit. Remnants of an older chalcocite blanket, formed on the apex of the pluton before tilting and transport, are preserved at the south end of the pit beneath the disconformity at the base of the fanglomerate (fig. 7). Massive chalcocite is developed in the K-feldspar-rich portion of the apex and was derived from supergene destruction of chalcopyrite and bornite.

The second supergene event affected the rocks within several hundred feet of the original ground surface in the pit area. Altered rocks have been converted to masses of clay, sericite, hematite, saussurite, and copper oxides. The copper oxides formed the main ore mined in the initial phases of development. Dating by Cook (1995) on New Cornelia alunite veins demonstrates relatively young ages of 11 and 2.2 Ma for this second stage of supergene development. Two rare copper aluminum hydrous silicates, ajoite and papagoite, were discovered in this ore. Blue-green ajoite contains K and Na (Schaller and Vlisidis, 1958), and blue papagoite contains calcium (Hutton and Vlisidis, 1960).

Mid-Cenozoic Alteration

Andesite dikes associated with the Ajo Volcanics intrude both low- and high-angle structures in the mine-sequence rocks and the Locomotive Fanglomerate. Dikes are altered to sericite and calcite and are associated with open-space fillings and veins of chrysocolla, barite, specularite, and calcite. This assemblage of andesitic rocks and copper oxide mineralization is found in the district at prospects in the Sneed Ranch and Copper Canyon areas affiliated with low-angle faulting related to Cardigan Peak magmatism.

Cenozoic Sedimentary and Igneous Rocks Formed During Extension

Darby Arroyo Formation

The Darby Arroyo Formation (pl. 1) was identified and mapped by Force (1997a). It consists of a gray to maroon volcanic-cobble conglomerate in which both the clasts and the matrix are weakly chloritized. The presence of rounded, pebble- to cobble-size clasts of light-gray rhyolite and dark-gray, aphanitic andesite is characteristic of the Darby. These clasts and the dark-gray, rather than red, matrix are the most useful features in distinguishing the Darby from the overlying Locomotive Fanglomerate. The Darby is distinguished from the Concentrator by the contained cobbles, but, because of the similar gray color, it can be confused with flow breccias belonging to the Concentrator. Gilluly (1946) mapped as Concentrator a large area south of Pinnacle Peak that we think most probably belongs to the Darby.

The Darby Arroyo Formation is underlain by altered Concentrator Volcanics on an overturned unconformable contact dipping steeply north (Force, 1997a). It is overlain by Locomotive Fanglomerate dipping 50° to 60° south, but locally two normal faults drop Locomotive Fanglomerate against it. Because the base of the unit is steeply dipping and the top is an erosion surface inclined parallel to the dip of the overlying Locomotive, the thickness of the Darby increases downward and southward. The interpretative cross section D-D’ (pl. 1) suggests that it was at least 700 m thick before erosion.

According to Force (1997a), the age of the unit is bracketed by the 35.2±0.9 Ma age of a sanidine-phyric rhyolite clast (by whole rock K-Ar) and the 25±2.7 Ma age of volcanic rocks of the overlying Ajo Volcanics. No other rock units of 35-Ma age are known in southern Arizona, and it is possible that this age may represent loss of argon due to heating from the 23 to 21 Ma Cardigan Peak Pluton. However this age may be interpreted, the Darby records a phase of extension and tilting prior to that represented by the Locomotive Fanglomerate. The proposed 35–25 Ma period of deposition and rotation is consistent with the two stages of tilting of the Cornelia Pluton proposed by Hagstrum and others (1987), that is, the 120° tilting recorded in the porphyry body, and with ages of early tilting in other districts in southern Arizona (Dickinson, 1991).

Locomotive Fanglomerate

Gilluly (1937) named the Locomotive Fanglomerate for exposures at Locomotive Rock (fig. 1). It is a red boulder conglomerate, presumably deposited on an alluvial fan in a steep-sided desert basin. Sorting is extremely poor, with boulders as large as 1.5 m in diameter intermixed with cobbles and sand-size particles (fig. 8). Locally thin beds of grit and sandstone provide opportunity to measure bedding attitudes. Well-bedded red sandstone and minor siltstone (see pl. 1, unit Tlfs) predominate in the Locomotive Fanglomerate southeast of Valentine Well. A drill hole north of Ajo (UTM E326300, N3588500) revealed beds of friable brown mudstone within the fanglomerate (Patrick Fahey, BHP Billiton, oral commun., 1996). No outcrops of this mudstone were observed in the district.

The proportions of clasts making up the fanglomerate were estimated at each major outcrop. Clasts of Concentrator Volcanics are common on the east side, but are rarely abundant. Fanglomerate with abundant clasts of Chico Shunie Quartz Monzonite (unit Tlfc) underlies the western two-thirds of the outcrop area and the area north of Ajo town. Fanglomerate with abundant granodiorite clasts (unit Tlfg) occupies the eastern part of the area, separated from the Tlfc unit by a gradational boundary. Fanglomerate with clasts of granodiorite porphyry is found close to the mine area (unit Tlfp). The clasts in Tlfg and Tlfp units are similar to corresponding phases in the Cornelia Pluton. Clasts of Cardigan Gneiss, quartzite, fine-grained gray limestone, and chloritic microbreccia are rare throughout the unit.

The Locomotive Fanglomerate is inclined 30° to 65° to the south, varying somewhat with the attitude of the underlying Locomotive Detachment Fault. It unconformably overlies the Cornelia Pluton porphyry phase in the south end of the New Cornelia Mine and unconformably overlies the Darby Arroyo Formation nearby. East of the mine area it unconformably overlies the Concentrator Volcanics.

Over most of the map area the Locomotive Fanglomerate is bounded by the Locomotive Detachment Fault below and by overlying flows and tuffs. The Locomotive Fanglomerate and Ajo Volcanics together form a sequence that records a late stage of detachment-related rotation of the porphyry ore body. The links among accumulation, faulting, and rotation are discussed along with the structures involved.

The thickness of the Locomotive Fanglomerate in the western part of the map area is at least 1,070 m, probably greater than 1,500 m, the uncertainty being due to questions about the amount of the section that was removed by detachment faulting. The thickness farther east is even less clear; measurement depends on how many layers of andesitic volcanic rocks are present within the Locomotive and how many faults offset these. However, the thickness in the mine-dump area could be as great as 4,500 m. Outcrops of fanglomerate similar to the Locomotive have been mapped in the northern Growler Mountains and 40 km to the north-northeast of Ajo in the Hat mountains Quadrangle (Gray and others, 1985a,b), suggesting that faulting produced other basins in the area similar to the Locomotive basin.

No fossils have been found in the Locomotive Fanglomerate. It is older than the 25–Ma Ajo Volcanics and younger than the 35–Ma clasts in the Darby Arroyo Formation. Its age is probably upper Oligocene to lower Miocene.

Mapping in the northeast part of the Locomotive outcrop area revealed a previously undescribed series of rhyolite breccia beds as much as 300 m thick within the fanglomerate (unit Tmr). These are composed chiefly of light gray, aphyric, devitrified glassy rhyolite in the form of crackle breccia, clast-supported breccia, and minor matrix-supported breccia (fig. 9). These rocks resemble landslide megabreccias described by

Figure 8. Oligocene-Miocene Locomotive Fanglomerate showing subangular clasts of Chico Shunie Quartz Monzonite. Location: UTM 321,500E, 3,580,400N.

Cooper (1962) in the Helmet Conglomerate near Mission and Pima Mines and by Krieger (1977) in Miocene fan deposits near the Ray and Christmas Mines. Such megabreccias have been described and modeled on a regional basis by Yarnold and Lombard (1989). Other landslide megabreccias at Ajo were found, some composed of quartzite (unit Tmq) similar to quartzite near Bandeja Wells, others made up of granodiorite, aplite, and pegmatite (unit Tmg). Most interesting are those composed mainly of hypabyssal felsic porphyry containing phenocrysts of feldspar, quartz, and biotite (unit Tmp). They are distinguished from porphyry of the Cornelia Pluton by the flaky rather than columnar book habit of biotite. Megabreccia beds occur in all parts of the Locomotive Fanglomerate. They are most abundant toward the base of the formation (pl. 1).

Ajo Volcanics

The Ajo Volcanics were named by Gilluly (1937), and four informal members of this unit, with a total thickness of more than 1,300 m, were recognized during the present investigation. The map pattern they form (pl. 1) is made complex by faults of several types.

Lower andesite member

This member (see pl. 1, unit Taa) forms a series of flows 75 to 150 m thick within the Locomotive Fanglomerate, about 300 m below its upper contact. Other outcrops, 1.5 to 2 km to the north, are assumed to be extensions of the same unit, divided into two flows and dropped down on normal faults. The member also crops out in an area 900 m wide north of the town of Ajo. The width of this exposure suggests that a normal fault has repeated part of the section (pl. 1). The lower andesite member is a dark gray, brown-weathering andesite with small phenocrysts of plagioclase, hornblende, and augite. It commonly contains altered small lapilli and millimeter-size drab-white rock fragments. Typical specimens contain 65 volume percent fine crystalline groundmass, 25 volume percent plagioclase (An_{47} to An_{67}) as phenocrysts 1 to 2 mm long, and 8 percent clinopyroxene. Locally, the lower andesite member is a matrix-supported breccia with 2-mm to 5-mm clasts of feldspar porphyry in a fine, nearly isotropic groundmass.

Valentine Well Member

This member (unit Tavw), named for exposures southeast and southwest of Valentine Well, is a plagioclase-biotite dacite

Figure 9. Outcrop of clast-supported rhyolite megabreccia in the Locomotive Fanglomerate. Location: UTM 326,000E, 3,579,500N.

containing large subangular porphyritic clasts in a light gray, tan-weathering, groundmass (fig. 10). The upper 100 m of this member is more friable than the lower part and erodes to form a vertical cliff on the north face of Ajo Peak (fig. 11). Typical samples of clasts contain 60 to 70 volume percent groundmass, rich in fine crystalline plagioclase, 20 to 39 volume percent of plagioclase (An_{50} to An_{65}) as phenocrysts 2 to 5 mm long, 7 percent biotite, and 7 percent hornblende. The hornblende and biotite have thick rims darkened by fine opaque oxide minerals. Small quartz phenocrysts are rare. The texture of the matrix has been largely destroyed by adularia and calcite replacement. The overall fragmental texture of this part of the unit suggests a volcanic mudflow origin.

A bed of Locomotive-type conglomerate lies between this unit and the overlying Ajo Peak member in two widely separated localities: one near North Ajo Peak, and the other at the Copper Giant Mine in the southeast corner of the Ajo Volcanics outcrop area. The Valentine Well member has a maximum thickness of 370 m near South Ajo Peak and thins to the northwest and southeast to about 75 m on North Ajo Peak and near the Copper Giant Mine.

Samples from this unit collected near South Ajo Peak have K–Ar biotite and whole rock ages of 23.8±0.8 and 25.0±2.7 Ma, respectively (Gray and Miller, 1984). These ages may partly reflect the addition of potassium during the adularia veining event. The age of the Valentine Well member is probably early Miocene.

Ajo Peak Member

This member (unit Taap) is named for outcrops on the sharp summit of South Ajo Peak (fig. 11). The unit also forms the summit of North Ajo Peak. It is andesite lava and minor welded tuff composed of prominent phenocrysts of plagioclase, small grains of hornblende and clinopyroxene, and rare quartz phenocrysts in a dark gray groundmass. Locally, layers with fiame structures and small lithic clasts are present. This rock contains 60 to 70 volume percent fine crystalline groundmass, 20 to 25 volume percent plagioclase (An_{50} to An_{76}), 7 to 13 percent hornblende, and as much as 4 percent pyroxene. Phenocrysts are 1 to 2 mm in length and are unbroken. The groundmass is composed of fine needles of plagioclase and

Figure 10. Exposure of lahar breccia of the Miocene Valentine Well member of the Ajo Volcanics showing poorly sorted angular clasts of dacite. Location: UTM 321,000E, 3,578,100N

irresolvable, nearly isotropic material. Near North Ajo Peak small phenocrysts of biotite indicate that the member is dacitic near its contact with the Valentine Well member. The Ajo Peak member is about 200 to 300 m thick near South Ajo Peak, but thins to about 120 m at North Ajo Peak.

South Ajo Member

This andesite lava (unit Tasa) is distinguished from the Ajo Peak member by the scarcity of phenocrysts. It contains small (0.2 to 1.0 mm), widely spaced unbroken phenocrysts of plagioclase (An_{50} to An_{70}), pyroxene, and hornblende in a dark gray crystalline groundmass that makes up 40 to 50 volume percent of the rock. Locally small lithic clasts are present. The top of this unit is not exposed; its maximum observed thickness is about 400 m.

Chemical Composition and Alteration

On the basis of silica content (table 3), eight samples of Ajo Volcanics range from basaltic andesite (analysis 7, lower andesite member) to dacite (analysis 5, Valentine Well member). This classification is suspect however, because of the variable content of introduced K–feldspar in six of these rocks. The K–feldspar forms along cleavage planes in plagioclase and in irregular veinlets and is accompanied locally by calcite. Its crystal habit in veinlets is similar to that of adularia.

Cardigan Peak Pluton

The Cardigan Peak Pluton, lying west of Gibson Arroyo, was originally considered a part of the Cornelia Pluton (Gilluly, 1946, Wadsworth, 1968). It was renamed (Hagstrum and others, 1987) because of its younger age. The pluton intrudes Precambrian gneiss west of the Gibson Fault (pl. 1) and exhibits a zonal distribution of rocks ranging from diorite to granite, in which the eastern granitic portion may represent the central core. Because of downdropping by the Gibson and Little Ajo Mountains Faults on the east and north and subsequent burial by more recent deposits on the north, it is possible that only the southwest portion is exposed of what may have been a large plutonic complex.

Fine-Grained Diorite

The fine-grained diorite, quartz diorite, monzodiorite, and quartz monzodiorite (see pl. 1, unit Tfd) is equivalent to the quartz diorite of Wadsworth (1968). This unit is present along the western contact of the Cardigan Peak Pluton. Rocks of this

Figure 11. View of Ajo Peak from the west, showing the Valentine Well member of the Ajo Volcanics. The notch at the summit was formed by erosion of the friable upper part of the unit. The overlying Ajo Peak member forms the spire and the dark rim rock descending to the right.

Table 3. Analytical data for member units of the Ajo Volcanics, Ajo, Arizona. Major elements by X-ray fluorescence in weight percent.

[X–ray fluorescence analysis by M. Miller, ICP analysis by F. Mereshensky, both of XRAL Laboratories, Don Mills, Ontario, Canada. Looked for but not found (parts per million detection levels in parentheses): Mo (1), Cd (1), Sb (5), W (10), Bi (5). Detection limits (parts per million) for samples with missing data: Be (0.5), Sc (0.5), As (3).]

Analysis no.[1]---	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Sample no.[1]----	**646 Taa**	**709 Taa**	**647 Tavw**	**712 Tavw**	**656 Taap**	**661 Taap**	**400 Tasa**	**710 Tasa**
SiO2	60.1	55.7	60.9	64.6	59.7	58.8	61.6	59.2
Al2O3	15.9	16.2	15.9	15.9	16.9	15.9	15.9	16.1
Fe2O3	4.46	5.67	4.26	4.13	4.96	5.5	4.8	5.65
MgO	1.91	3.65	1.1	1.29	2.15	3.66	3.03	2.64
CaO	3.66	6.37	2.87	1.55	3.53	6.21	5.15	5.01
Na2O	5.09	3.44	4.02	5.28	3.65	3.43	4.26	3.69
K2O	4.49	3.46	6.66	4.17	5.35	1.83	1.95	3.56
TiO2	0.592	0.809	0.577	0.574	0.697	0.694	0.658	0.714
P2O5	0.23	0.36	0.25	0.2	0.24	0.34	0.31	0.4
MnO	0.06	0.07	0.06	0.08	0.06	0.1	0.07	0.04
LOI	3.55	3.75	2.95	1.7	2.15	3	2.25	1.75
TOTAL	100.3	99.8	99.9	99.8	99.7	99.9	100.2	99.1
X-ray fluorescence analysis (parts per million)								
Rb	196	99	332	144	214	50	173	100
Zr	196	803	204	188	226	250	285	354
Nb	8	11	7	11	9	10	12	12
Inductively coupled plasma-atomic emission spectrography (parts per million)								
Be		0.7		0.9	0.6			
Sc	3.3	5.8	3.2	3.2	1.0	4.6		2.9
V	65	70	68	46	77	43	43	42
Cr	23	52	13	16	15	7	17	18
Co	10	16	7	5	12	3	3	8
Ni	27	60	14	16	22	8	12	28
Cu	14.5	8.4	9.0	29.0	5.7	15.6	33.9	14.9
Zn	55.9	55.4	36.7	33.7	56.9	17.3	15.3	47.1
As	12	4	8	14				
Sr	468	775	656	640	724	1320	915	816
Y	14	18	14	14	14	18	18	22
Ba	1010	1400	1540	1480	1380	1860	1370	1540
La	27.3	35.6	32.4	25.4	24.1	24.6	15.8	37.2
Pb	11	11	16	13	13	6	3	7

[1]Description of samples analyzed:

1. South Ajo member, unaltered at UTM Zone 12, 3577330N, 320290E.
2. South Ajo member, traces of K–feldspar along plagioclase phenocryst edges and in groundmass at 357789N, 319100E.
3. Ajo Peak member, Plagioclase phenocrysts 20 to 50 percent replaced by K–feldspar, hornblende replaced by white mica at 3578740N, 319340E.
4. Ajo Peak member, unaltered at 3578340N, 319040E
5. Valentine Well member, Plagioclase phenocrysts 10 to 25 percent replaced by K–feldspar, hornblende replaced by white mica at 3579960N, 319670E.
6. Valentine Well member, Plagioclase phenocrysts 60 to 75 percent replaced by K–feldspar, hornblende replaced by white mica at 3576320N, 321940E.
7. Lower andesite member, Plagioclase phenocrysts 0-10 percent replaced by K–feldspar, clinopyroxene unaltered at 3578200N, 325100E.
8. South Ajo member, Plagioclase phenocrysts 0-50 percent replaced by K–feldspar, abundant K–feldspar in groundmass, hornblende replaced by white mica at 3578880N, 321398E.

unit contain 60 volume percent plagioclase (An_{44} to An_{48}), 13 percent K–feldspar, 7 percent quartz, 9 percent hornblende with cores of clinopyroxene, and 6 percent biotite. This rock bears a close resemblance to the Laramide fine-grained diorite (unit Kd) on the east side of Gibson Arroyo; however, K–feldspar is more abundant than in exposures of Laramide diorite. Zircon U-Pb dating (see below) establishes a clear Miocene age and paleomagnetic data for the western fine grained diorite indicate that it has not been tilted (Hagstrum and others, 1987, fig. 6).

Quartz Monzodiorite

The coarse-grained quartz monzodiorite, monzodiorite, and quartz monzonite (unit Tmd) is approximately equivalent to the granodiorite of Wadsworth (1968). This unit is exposed in a broad zone inboard of the fine-grained diorite in the Cardigan Peak Pluton. Rocks of this unit contain 47 to 57 volume percent plagioclase (An_{50} to An_{70}), 25 to 30 percent K–feldspar, 12 to 24 percent quartz, 10 percent hornblende with cores of unreplaced pyroxene, and 3 percent biotite.

Monzogranite

The equigranular monzogranite (unit Tm) matches Wadsworth's description of equigranular quartz monzonite (1968). This rock forms the central part of the Cardigan Peak Pluton and is lighter colored than the previously mentioned units. It is composed of 36 volume percent plagioclase (An_{30} to An_{40}), 30 to 34 percent K–feldspar, 20 to 24 percent quartz, 5 percent biotite, and 3 percent hornblende with a trace of pyroxene.

Oikocrystic Monzogranite

The monzogranite with oikocrystic quartz K–feldspar (unit Tmo) is probably equivalent to the porphyritic quartz monzonite of Wadsworth (1968, p. 1083). It has roughly the same mineral composition as the equigranular monzogranite but differs in the presence of large (2 mm) rounded quartz grains, several adjacent grains of which may be oriented in optical continuity (fig. 12; see also plate 13*D* in Gilluly, 1946). These grains enclose abundant subhedral plagioclase crystals 0.1 to 0.5 mm in diameter. K–feldspar locally has the same habit, enclosing grains of quartz and plagioclase. Wadsworth (1968) ascribed this distinctive texture to crystallization during boiling of contained aqueous fluids. The oikocrystic monzogranite is distributed in a zone within the monzogranite and surrounding the central core of fine-grained granite (unit Tfg). Its mapped distribution pattern strongly suggests that its origin is closely related to intrusion or crystallization of the fine-grained granite.

Fine-Grained Granite

The fine-grained granite and monzogranite (unit Tfg) is equivalent to porphyritic micro-quartz monzonite of Wadsworth (1968). This unit is recognized by its uniformly fine, allotriomorphic-granular texture and scarcity of phenocrysts (fig. 13). It forms one large body and five or six small east-west trending fault slices within the monzogranite of the Cardigan Peak Pluton. Rocks of this unit are composed of 25 to 30 volume percent quartz, 30 to 40 percent K–feldspar, 20 to 35 percent plagioclase (An_6), and 3 to 7 percent biotite. This rock typically has sharp but intricately anastomosing contacts into the coarser monzogranite. Pegmatites 10-20 cm in width, containing quartz and K–feldspar, are found in the fine-grained granite within meters of its contact with coarser monzogranite.

Monzogranite Porphyry

The monzogranite porphyry (unit Tap) forms two small bodies intimately associated with fine-grained granite in the north-central part of the pluton and is found in small dikes with chilled margins that are distributed along the southern contact of monzogranite with the Precambrian Cardigan Gneiss. Rocks of this unit contain phenocrysts of plagioclase, quartz, and K-feldspar in a microaplitic groundmass.

Dikes

Porphyry dikes are of two types: a light colored feldspar porphyry with prominent plagioclase phenocrysts and subordinate chloritized amphiboles (unit Tfp,); and a dark colored hornblende andesite porphyry with small phenocrysts and glomerocrysts of hornblende (unit Tha), equivalent to the nonporphyritic andesite of Gilluly (1946). Abundant feldspar porphyry dikes intrude fine-grained diorite and coarse-grained monzodiorite on the west side of the Cardigan Peak Pluton. Some dikes extend from the monzodiorite a few tens of meters and, rarely, hundreds of meters into the monzogranite, but otherwise these dikes are absent from the core of the pluton. This suggests that the monzogranite and other rocks in the core were not sufficiently crystallized to provide fractures for dike intrusion. The hornblende andesite is confined to the eastern part of the Cardigan Gneiss outcrop area. Its Cenozoic age can only be inferred.

Chemical Composition

Rocks of the Cardigan Peak Pluton are more compositionally expanded than are those of the Cornelia Pluton (silica content ranges from 61 to 77.5 weight percent, table 4) but still fall within the compositional field of southern Arizona igneous rocks (Spencer and others, 1995) (fig. 3). They follow the same calc-alkalic trend as the Cornelia Pluton samples (fig. 4). They are metaluminous, with Al_2O_3 / ($CaO + Na_2O + K_2O$) ratios ranging from 0.84 to 0.99.

Cox (1988) showed that the trace element chemistry of the Cardigan Peak and Cornelia Plutons are indistinguishable (fig. 5). The fine-grained quartz diorite of the Cornelia Pluton has lower Th, U, and Nb than the comparable Tfd unit of the

Cardigan Peak Pluton. Levels of compatible trace elements are lower in the high-silica samples.

Rare-earth-element curves for the two plutons are typical for calc-alkalic rocks (fig. 6). Cardigan Peak samples that have silica content greater than 70 weight percent have distinctly lower rare earth values. There is no europium anomaly in the Cornelia Pluton curve. For the Cardigan Peak rocks, gadolinium was not detected at the 2-ppm level, so here also, no europium anomaly is likely.

Alteration

Figure 14 shows the distribution of sodic-calcic alteration (see Carten, 1986; Battles and Barton, 1989; Dilles and Einaudi, 1992) in the Cardigan Peak Pluton determined from field observation and aerial photographs. Gilluly (1946) referred to this alteration briefly as albitization. Sodic-calcic alteration results in the replacement of biotite by pale-green fibrous amphibole or chlorite and of K–feldspar by coarse-grained twinned sodic oligoclase that is rich in dusty, unidentified inclusions. This replacement produces chalky white, hard rocks that are resistant to weathering and erosion (fig. 15). Altered rocks may appear to have had a different primary igneous composition than their unaltered equivalents because of their lighter color due to conversion of biotite to pale colored amphibole. This alteration is strongly fracture controlled, forming whitish envelopes around veinlets of epidote, hematite, actinolite, or, more rarely, tourmaline. Where these veinlets are abundant the alteration becomes pervasive.

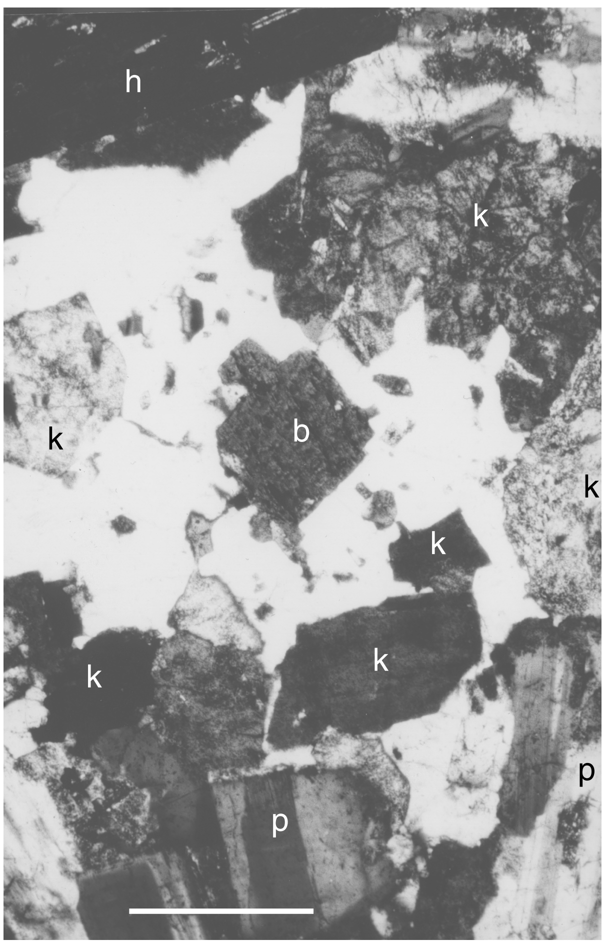

Figure 12. Photomicrograph showing texture of oikocrystic monzogranite (unit Tmo) of the Miocene Cardigan Peak Pluton. White area is a single grain of quartz that has many small inclusions of K–feldspar and plagioclase. K–feldspar, k; plagioclase, p; biotite, b; and hornblende, h. Scale bar is 0.5 mm.

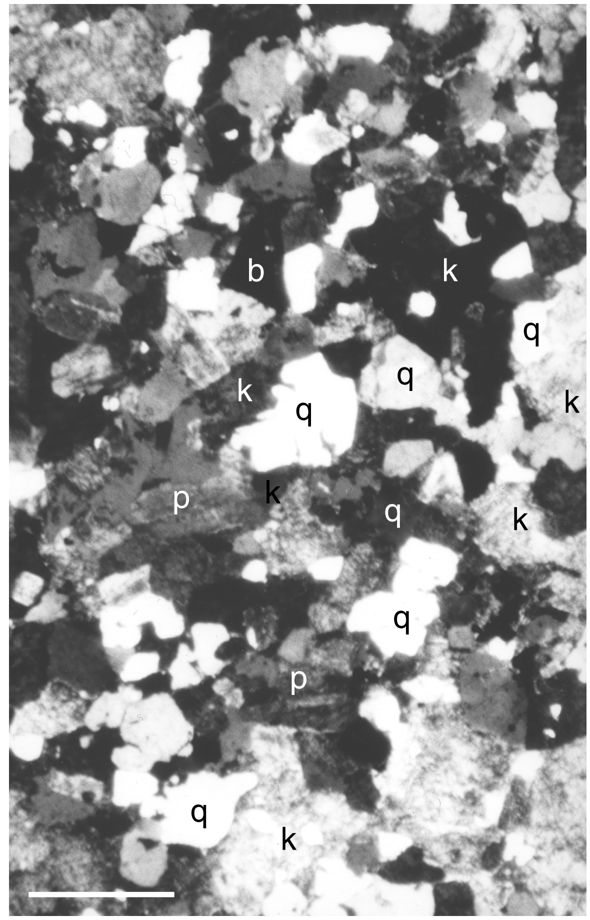

Figure 13. Photomicrograph showing allotriomorphic granular texture of fine-grained granite (unit Tfg) from the Cardigan Peak Pluton. Quartz, q; K–feldspar, k; plagioclase, p. Scale bar is 1 mm.

Along the north and southeast contacts of the main body of fine-grained granite (unit Tfg), fracture-controlled replacement of K–feldspar and biotite was preceded by an early alteration affecting only biotite. The biotite was replaced by well-crystallized, pale-green amphibole and locally by diopside in the presence of stable igneous K–feldspar.

Table 5 compares the chemical composition of fresh and altered rocks and shows the elements added and depleted as a result of alteration. Note that the twofold increase in sodium content was accompanied by depletion of the elements potassium,

Table 4. Analytical data for granitic rocks of the Cardigan Peak Pluton, Ajo, Arizona.

[For analysts see table 1.]

Analysis number[1]---	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Sample number[1]---	516 Tfd	436 Tmd	434T Tmd	264 Tmo	44 Tmo	24 Tm	289 Tmo	252 Tmo	270 Tmo	278 Tmo	101 Tfg	315 Tfg	311 Tfg	517 Tfp
X-ray fluorescence analysis (weight percent)														
SiO_2	61.1	59.6	63.2	66	67.4	77.5	67.1	76.7	70.4	70.1	71.5	73	77.5	63.1
TiO_2	0.57	0.79	0.67	0.43	0.44	0.1	0.44	0.12	0.28	0.34	0.23	0.21	0.1	0.59
Al_2O_3	16.1	16	16.4	15.9	15.4	12.1	15.5	12.6	14.8	14.8	14.4	14.1	12.2	16.2
Fe_2O_2	2.43	2.48	2.02	1.96	1.52	0.49	1.66	0.15	1.28	1.18	1.42	0.3	0.36	2.54
FeO	2.03	3.19	1.5	1.23	1.46	0.07	1.25	0.05	0.89	0.38	0.44	0.32	0.05	1.36
FeO*	4.22	5.42	3.32	2.99	2.83	0.51	2.74	0.18	2.04	1.44	1.72	0.59	0.37	2.88
MnO	0.04	0.09	0.03	0.04	0.05	<0.02	0.03	<0.02	0.03	<0.02	0.04	<0.02	<0.02	0.02
MgO	3.06	3.85	2.31	1.53	1.47	0.17	1.45	0.14	0.79	0.95	0.63	0.57	0.14	1.93
CaO	4.94	5.63	4.65	3.03	2.89	0.36	3	0.75	2.07	2.58	1.73	1.45	0.53	4.05
Na_2O	3.88	3.47	3.91	3.78	3.62	3.11	3.63	3.28	3.37	3.57	3.35	2.95	3.38	3.88
K_2O	2.92	3.18	3.68	3.97	4.14	5.23	4.17	4.8	4.65	4.46	4.85	5.54	4.74	4.03
P_2O5	0.22	0.38	0.29	0.19	0.18	<0.05	0.18	<0.05	0.1	0.14	0.09	0.07	<0.05	0.24
H_2O+	0.93	0.5	0.38	0.46	0.31	0.08	0.39	0.19	0.08	0.32	0.35	0.25	0.44	0.61
H_2O-	0.27	0.09	0.14	0.2	0.17	0.14	0.16	0.08	0.16	0.17	0.18	0.22	0.03	0.18
CO_2	0.18	0.03	0.08	0.07	0.04	0.03	0.15	0.03	0.11	0.05	0.03	0.07	0.11	0.1
Cl	0.033	0.07	0.05	0.03	0.03	0.02	0.02	0.04	0.02	0.03	0.03	0.02	<0.02	0.033
F	0.08	0.07	0.09	0.06	0.06	<0.02	0.07	<0.02	0.05	0.05	0.05	0.04	<0.02	0.23
TOTAL	98.783	99.4	99.4	98.8	99.2	99.4	99.2	98.93	99.08	99.07	99.3	99.11	99.58	99.09
Inductively coupled plasma-atomic emission spectrography (parts per million)														
Be	2	2.4	3.1	3	3.3	3.6	2.8	2.4	2.1	3.9	2.8	2.5	7.1	2.4
Co	14	16	12	9.3	9.7	4.3	7	5.4	4.3	1.8	3.8	2.9	3.2	9.9
Cr	110	89	49	22	23	11	15	10	<10	<10	<10	<10	<10	39
Cu	7.1	50	71	12	14	1.6	18	6.3	21	2.3	7.9	130	1.5	6.2
Ga	21	21	24	21	22	21	19	20	19	17	19	18	21	20
Ni	46	44	30	17	17	10	13	8.5	6.3	2.5	4.8	5.7	3.2	19
Pb	16	14	15	16	23	<10	26	22	35	<10	13	<10	16	<10
V	84	120	110	66	71	48	48	45	31	19	33	29	29	68
Y	19	26	25	21	24	19	20	21	19	<10	10	23	12	19
Zr	240	210	200	160	190	160	140	180	150	53	86	130	65	280
Sn	1.2	1.3	1.9	1.8	2	1.2	1.6	2.3	2.6	1.1	2.1	1.4	2	1.3
Nb	10	13	16	14	15	15	15	12	12	17	15	15	25	16
U	2.12	2.71	3.81	3.66	4.6	4.57	4.89	3.07	6.12	6.08	6.94	6.17	8.19	2.29
Ba	1240	1450	1270	1600	1460	1380	1450	1440	1180	420	512	1080	90	1610
Co	11	18.9	8.73	7.14	7.27	2.2	6.82	4.03	3.05	0.278	0.826	1.6	0.5	7.21

Table 4. Analytical data for granitic rocks of the Cardigan Peak Pluton, Ajo, Arizona.—Continued

[For analysts see table 1.]

Analysis number[1]---	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Sample number[1]---	516 Tfd	436 Tmd	434T Tmd	264 Tmo	44 Tmo	24 Tm	289 Tmo	252 Tmo	270 Tmo	278 Tmo	101 Tfg	315 Tfg	311 Tfg	517 Tfp
Inductively coupled plasma-atomic emission spectrography (parts per million)														
Cr	111	97.3	41	20.5	19.4	8.5	17	8	4.61	0.69	0.25	2.79	0.5	34.2
Cs	0.491	0.94	0.67	1.69	1.87	0.7	1.7	2.1	5.11	0.621	0.994	1.07	3.97	0.548
Hf	4.9	6.24	8.07	6.69	7.16	5.92	7.09	5.04	4.47	3.15	3.93	5	4.44	6.23
Rb	49.9	81	81.3	111	128	99.3	125	164	174	92.9	136	149	195	76.8
Sb	0.151	0.13	0.11	0.184	0.16	0.1	0.1	0.11	0.1	0.181	0.318	0.083	0.8	0.211
Sr	920	1040	903	723	669	603	660	385	344	186	105	270	<75	880
Ta	0.553	0.79	0.98	0.977	1.09	1.17	1.04	1	1.02	1.5	1.89	1.38	2.31	0.797
Th	6.42	11.3	16.3	17.1	19.8	27.8	19.7	19.3	25.4	29.9	40	24.8	45.4	10.7
Zn	17.7	54	56	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50	<50
Zr	172	241	321	252	259	202	265	180	170	89	110	151	83.2	267
Sc	9.79	13.9	8.54	5.99	5.56	3.5	5.55	3.36	2.32	0.547	0.423	2.89	0.74	7.29
La	43.4	58.2	52.6	60	59.5	60.9	64.2	50.8	45.8	9.85	21.3	32.2	26.4	53.4
Ce	73	120	120	110	111	110	116	89.4	79.5	17.5	36.2	58.2	40.7	95.5
Nd	26.3	49.9	47.3	34.9	37.2	32.8	39.5	29.4	25.5	8.98	11.5	20.5	10.5	32.9
Sm	4.58	8.01	7.07	5.25	5.53	4.78	5.58	4.19	3.83	1.21	1.7	3.94	1.27	5.39
Eu	1.14	1.85	1.67	1.17	1.2	1	1.02	0.87	0.76	0.344	0.31	0.726	0.14	1.23
Gd	3.67	6.6	5.69	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	3.59
Tb	0.482	0.82	0.77	0.547	0.58	0.47	0.561	0.48	0.42	0.109	0.132	0.512	0.14	0.528
Dy	<0.1	5.1	4.4	3.3	3.4	2.9	3.5	2.9	2.5	0.7	0.9	3.5	1	<0.1
Tm	0.232	0.36	<0.5	0.26	0.29	0.27	0.27	0.26	0.24	<0.5	<0.5	0.37	<0.5	0.229
Yb	1.44	2.12	2.13	1.67	1.81	1.66	1.74	1.58	1.55	0.546	0.561	2.38	1.2	1.51
Lu	0.221	0.3	0.29	0.24	0.27	0.24	0.26	0.23	0.23	0.09	0.088	0.35	0.21	0.23

[1]Description of samples analyzed:

1. Fine grained quartz diorite at UTM Zone 12, 3582620N, 318810E.
2. Coarse grained quartz monzodiorite at 3583460N, 319460E.
3. Coarse grained quartz monzodiorite at 3583610N, 319790E.
4. Oikocrystic monzogranite at 3583920N, 323410E.
5. Oikocrystic monzogranite at 3582650N, 321940E.
6. Monzogranite at 3582440N, 321000E.
7. Oikocrystic monzogranite at 3583600N, 321910E.
8. Oikocrystic monzogranite at 3582950N, 322900E.
9. Oikocrystic monzogranite at 3582800N, 321700E.
10. Oikocrystic monzogranite at 3583560N, 321990E.
11. Fine grained granite at 3583950N, 322970E.
12. Fine grained granite at 3583140N, 321580E.
13. Fine grained granite at 3582750N, 322610E.
14. Feldspar porphyry dike at 3582490N, 318860E.

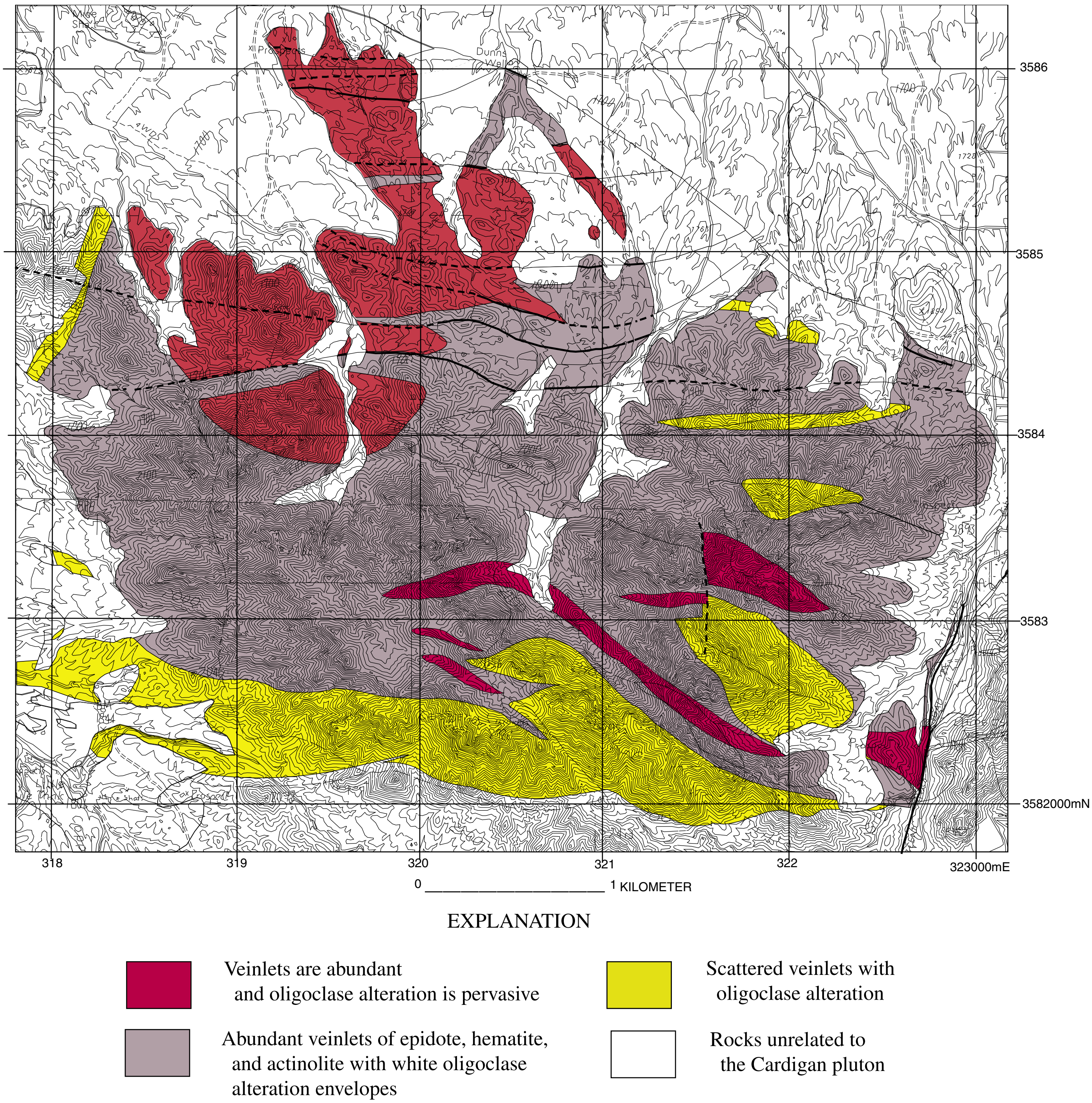

Figure 14. Map showing three levels of Na-Ca alteration in the Miocene Cardigan Peak Pluton. Faults and contacts from plate 1. Coordinates are UTM. Surface contours in feet; contour interval 20 ft.

iron, manganese, cobalt, copper, chlorine, barium, lead, rubidium and zinc. The elements depleted include many of those that are characteristic of porphyry copper and other magmatic hydrothermal mineral deposits. These elements may have been redeposited in a body higher in the pluton and either removed by erosion, displaced northward by the Locomotive Detachment, or displaced downward by breakaway faults discussed below.

Fluid Inclusions

Fluid inclusions are abundant in all coarse-grained phases of the Cardigan Peak Pluton including the small pegmatite pockets in fine-grained granite. The fluid inclusions are trapped in igneous quartz and are aligned along small, healed fractures or randomly distributed in the quartz grains. The several kinds of fluid inclusions present are shown diagrammatically in figure 16 and are described as follows:

Mineral-rich fluid inclusions contain one or more solid phases in addition to a vapor bubble. Some inclusions contain such large or abundant mineral grains that the vapor bubble is distorted and the liquid phase is difficult to see. Scanning electron microscope studies were made of open inclusions on broken surfaces of quartz. Daughter minerals were identified by morphology and metal content using a scanning electron microscope. The studies revealed cubic Na and K chloride minerals, planar Na, K, Fe chloride minerals, a prismatic hexagonal Fe chloride mineral, Ca sulfate (?), hematite, and, rarely, sulfides of iron, copper-iron, zinc, and lead. Mineral-rich fluid inclusions homogenize mainly by dissolution of daughter minerals (fig. 17) between 300°C and 400°C and between 500°C to 550°C (Cox and Ohta, 1984).

Vapor-rich fluid inclusions contain a large vapor bubble and a small amount of liquid that is commonly difficult to see. Rarely, a small cubic-transparent or triangular-opaque daughter mineral is present in the liquid phase. Vapor-rich fluid inclusions homogenize as vapor from 300°C to above 600°C.

Liquid-rich inclusions contain a small vapor bubble and no solid phases. They are smaller than the other two types and most homogenize between 100°C and 300°C. A small number of liquid-rich inclusions homogenize at temperatures between 300°C and 500°C.

Figure 15. Typical Na-Ca alteration in the Cardigan Peak Pluton. Biotite in the monzogranite is converted to pale actinolite or chlorite, and K-feldspar is partly altered to sodic oligoclase. The veinlets contain fine chlorite, epidote, and hematite. The prominent ribs along the vein walls are composed mainly of sodic oligoclase. Location: UTM 321250 E, 35842000N.

Table 5. Analytical data showing effect of hydrothermal alteration on monzogranite of the Cardigan Peak Pluton, Ajo, Arizona.

[X-ray spectroscopic analyses of major element oxides were made by A. J. Bartel, K. Stewart, and J. E. Taggart in Lakewood, Colorado. Determination of FeO, H_20, CO_2, Cl, and F were made by N. Elsheimer in Menlo Park California. Be, Co, Cr, Cu, Ga, Ni, Pb, and V were determined by emission spectrograph by Judith Kent and R. Lerner in Menlo Park. Rb, Sn, and Nb were determined by L. F. Espos in Menlo Park and J. S. Kane and M. W. Doughten in Reston, Virginia, respectively. Remaining elements in table 4 were determined by radiochemistry by J. Storey, J.R. Budahn, R. J. Knight, S. Danehey, and R. B. Vaughn in Lakewood.]

Analysis no.[1]--	1	2	3	4	5	
Field no.[1]------	585	588	586	587	598	
	Unaltered rocks			Altered rocks		Effect of alteration relative to fresh rock
			X-ray spectroscopy (weight percent)			
SiO_2	67.8	66.5	68.8	68.2	67.9	no change
TiO_2	0.42	0.44	0.46	0.47	0.45	no change
Al_2O_3	15.4	15.6	16.1	15.9	16.1	no change
Fe_2O_3	1.50	1.68	0.28	0.33	0.62	depleted
FeO	1.37	1.47	0.46	0.57	0.42	depleted
MnO	0.04	0.04	0.02	0.03	—	depleted
MgO	1.37	1.52	1.4	1.5	1.1	no change
CaO	2.86	2.99	3.01	3.21	2.92	no change
Na_2O	3.71	3.72	6.41	6.42	7.25	added
K_2O	4.09	3.89	0.54	0.6	0.51	depleted
P_2O5	0.17	0.18	0.19	0.19	0.2	no change
LOI	0.75	1.34	1.34	1.7	1.76	added
Cl	0.04	0.045	0.018	0.016	0.017	depleted
F	0.04	0.04	0.03	0.04	0.03	no change
Total	99.56	99.455	99.058	99.176	99.277	
			Emission spectrographic and colorimetric analysis (parts per million)			
Be	2.6	2.5	2.6	2.9	2.6	
Co	8.8	7.8	3.8	4.2	3.1	depleted
Cr	26	26	29	28	28	no change
Cu	20	13	4	3	2	depleted
Ga	21	17	21	16	19	no change
						no change
Ni	16	16	13	16	11	no change
Pb	21	13	<10	<10	<10	depleted
V	50	47	46	46	52	no change
Y	20	20	20	19	16	no change
Zr	300	320	300	248	236	no change
Nb	15	15	17	18	17	no change
Ba	1250	1450	200	215	173	depleted
Rb	100	106	25	33	22	depleted
Sr	630	670	700	690	455	no change

Table 5. Analytical data showing effect of hydrothermal alteration on monzogranite of the Cardigan Peak Pluton, Ajo, Arizona.—Continued

[X-ray spectroscopic analyses of major element oxides were made by A. J. Bartel, K. Stewart, and J. E. Taggart in Lakewood, Colorado. Determination of FeO, H_20, CO_2, Cl, and F were made by N. Elsheimer in Menlo Park California. Be, Co, Cr, Cu, Ga, Ni, Pb, and V were determined by emission spectrograph by Judith Kent and R. Lerner in Menlo Park. Rb, Sn, and Nb were determined by L. F. Espos in Menlo Park and J. S. Kane and M. W. Doughten in Reston, Virginia, respectively. Remaining elements in table 4 were determined by radiochemistry by J. Storey, J.R. Budahn, R. J. Knight, S. Danehey, and R. B. Vaughn in Lakewood.]

Analysis no.[1]--	**1**	**2**	**3**	**4**	**5**	
Field no.[1]------	**585**	**588**	**586**	**587**	**598**	
	Unaltered rocks		**Altered rocks**			**Effect of alteration relative to fresh rock**
Emission spectrographic and colorimetric analysis (parts per million)						
Zn	54	38	27	27	19	no change
La	64	60	100	130	68	added
Ce	110	110	125	174	113	no change
B	<10	<10	26	26	16	added

[1]Description of samples analyzed:

1. Monzogranite at UTM Zone 12,3583410N, 320700E. Equivalent to altered samples 3 and 4.
2. Monzogranite epidote at 3583325N, 320660E.. Equivalent to altered sample 5.
3. Monzogranite, pervasive sodic-calcic alteration. Biotite replaced by actinolite at 3583410N, 320700E.
4. Monzogranite, pervasive sodic-calcic alteration. Biotite replaced by chlorite at 3583410N, 320700E.
5. Monzogranite, pervasive sodic-calcic alteration. Biotite replaced by chlorite and epidote at 3583325N, 320660E.

Close association of mineral-rich and vapor-rich inclusions suggest that brine-vapor immiscibility in an aqueous fluid occurred in an irregular zone extending around the east, south, and west contacts of the fine-grained granite (fig. 16). The western extent of these inclusions is undetermined because of the paucity of quartz grains in fine-grained diorite. Mineral-rich and vapor-rich fluid inclusions are rare in the fine-grained granite except in pegmatite pockets near the contact, where they may be large and abundant. Although there is a lack of correlation between hydrothermal alteration and presence of mineral rich inclusions, both phenomena are believed to be related to an influx of saline fluids from the Locomotive Fanglomerate.

Age of Intrusion

K–Ar ages for the Cardigan Peak Pluton, ranging from 23 to 19 Ma, were reviewed in Hagstrum and others (1987). The oldest age, 23.0±0.7 Ma, was from biotite in monzodiorite in the western part of the pluton. Hornblende from the same rock gave an age of 21.6±1.8, possibly a result of argon loss from secondary chlorite. Biotite from monzogranite near Cardigan Peak gave an age of 21.6±0.7. This age, 1.4 m.y. younger than the monzodiorite, is consistent with the observation that feldspar porphyry dikes intrude the monzodiorite but not the monzogranite. The monzogranite age and ages of 19.6±1.3 Ma for biotite and 20.1±3.5 Ma for hornblende reported by McDowell (1971) are younger than the flat lying Sneed Andesite (22.0±0.7 Ma, Gray and Miller, 1984) exposed north of the pluton. All of the K–Ar ages from the Cardigan Peak Pluton are more than 1 m.y. younger than the 25 to 24 Ma ages given for the Ajo Volcanics. These differences are too large to be accounted for by argon loss during postcrystallization cooling. Argon loss caused by reheating by an unexposed younger phase of the pluton is the most likely explanation for these differences.

In 2006 Cox collected four samples representing the four units of the Cardigan Peak Pluton (table 6). Sample numbers, rock type, and UTM locations are as follows: Ajo 61, monzogranite, 3585404 N, 322256; Ajo 62, fine-grained granite, 3584904 N, 320641 E; Ajo 63, fine-grained hornblende diorite, 3582562 N, 318805 E; and Ajo 64, quartz monzodiorite, 3582584 N, 319064 E. Field relations indicate that sample Ajo 63 is the oldest of the group and that Ajo 62 is the youngest.

From these samples, 34 grains were analyzed for U-Th-Pb isotopic data and Pb-U ages with the SHRIMP-RG ion microprobe in the USGS-Stanford ion microprobe facility at Stanford University (table 6). Zircons were separated by standard mineral separation techniques at the USGS in Menlo Park. Analytical techniques follow the detailed description given in Williams (1998). The age standard used was R33, with an age of 419 Ma (Black and others, 2004), and a gem-quality zircon with 550 ppm U (CZ3) was used as the concentration standard. Data were reduced with the SQUID program (Ludwig, 2001) and ages and plots derived with ISOPLOT

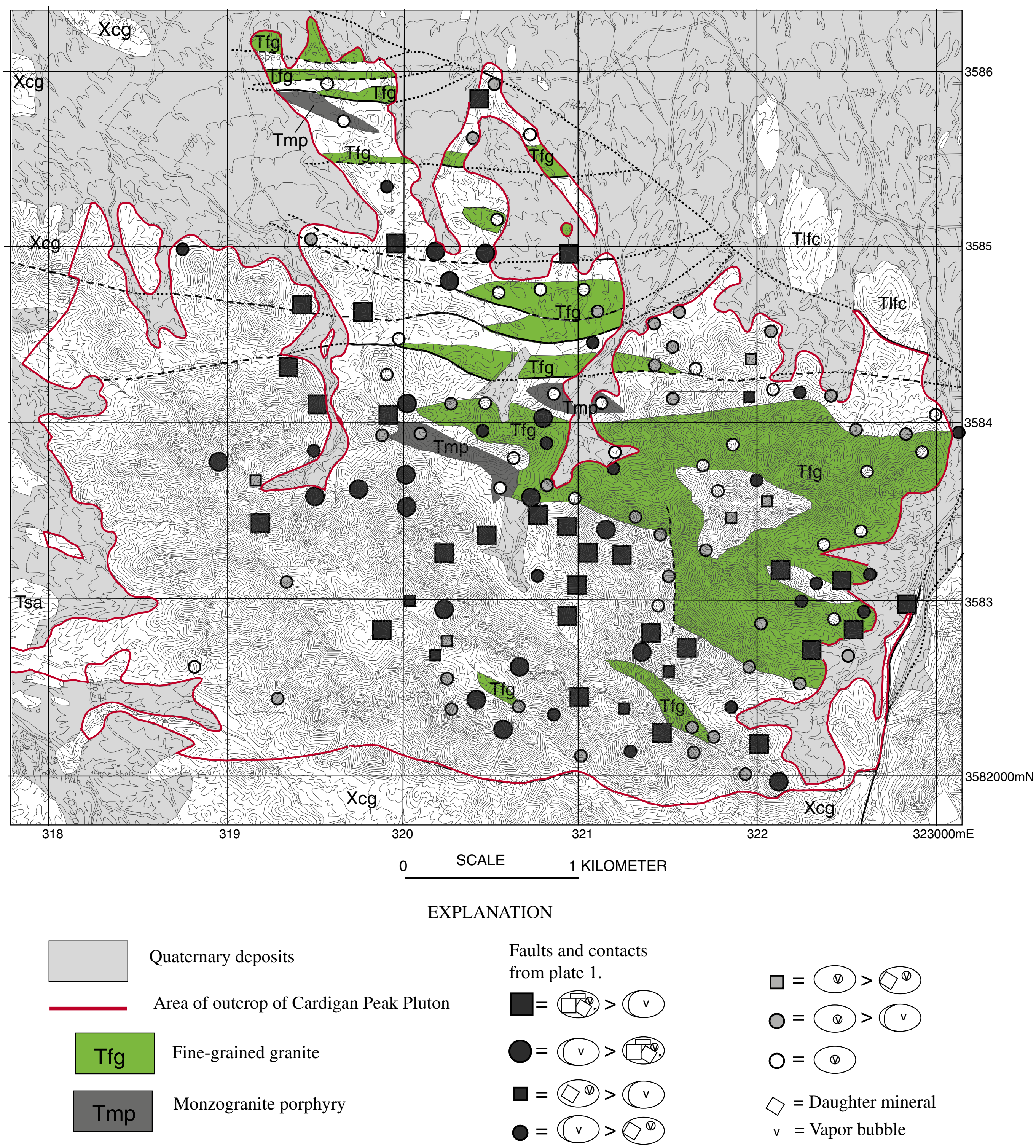

Figure 16. Map showing the distribution and relative abundance of different types of fluid inclusions in the Miocene Cardigan Peak Pluton. Types shown are mineral-rich with multiple daughter minerals (shown by rectangles), mineral-bearing with one daughter mineral, vapor-rich (marked by the letter v), and liquid-rich. Note the close relation between liquid-rich inclusions and the contacts of fine-grained granite and monzogranite porphyry bodies. Other unit symbols from plate 1.

Table 6. Lead, uranium, and thorium isotopic compositions and ages of zircons in four samples of the Cardigan Peak Pluton.

[Sample Ajo 61, monzogranite; Ajo 62, fine-grained granite; Ajo 63, fine-grained hornblende diorite; Ajo 64, quartz monzodiorite; see text for locations. Negative values of calculated common ^{206}Pb are an artifact of the calculation when values of ^{204}Pb are less than the uncertainty in ^{204}Pb background. r, radiogenic. Ratios of $^{238}U/^{206}Pb$ and $^{207}Pb/^{206}Pb$ are uncorrected for common Pb. All errors are 1σ. "Error corr." is the calculated error correlation between the $^{207}Pb/^{235}U$ and $^{206}Pb/^{238}U$ ratios. Analyses done using sensitive high resolution ion microprobe (SHRIMP) instrument at Stanford University; analyst, J.L. Wooden, U.S. Geological Survey, Menlo Park, California.]

Sample	Spot	Common ^{206}Pb %	U (ppm)	Th (ppm)	$^{232}Th/^{238}U$ ratio	^{207}Pb corrected $^{206}Pb/^{238}U$ age (Ma)	1σ error (Ma)	^{204}Pb corrected $^{207}Pb/^{206}Pb$ age (Ma)	1σ error (Ma)	$^{238}U/^{206}Pb$ ratio	Error (%)	$^{207}Pb/^{206}Pb$ ratio	Error (%)	$^{207}Pb(r)/^{235}U$ ratio	Error (%)	$^{206}Pb(r)/^{238}U$ ratio	Error (%)	Error corr.
AJ061	1.1	0.75	217	178	0.85	24.2	0.6			263.64	2.4	0.0524	9.1					
	2.1	0.62	280	210	0.78	24.4	0.5			262.24	2.1	0.0514	9.8					
	3.1	2.75	74	83	1.17	22.5	1.0			278.07	4.1	0.0683	13.9					
	4.1	0.39	306	268	0.91	23.1	0.5			277.47	1.9	0.0496	7.4					
	5.1	0.30	178	227	1.32	23.9	0.6			268.36	2.5	0.0489	10.3					
	6.1	-0.08	357	362	1.05	23.9	0.4			269.27	1.8	0.0459	7.1					
	7.1	0.16	154	170	1.14	24.5	0.7			261.83	2.6	0.0478	10.5					
	8.1	-0.30	280	305	1.13	23.6	0.5			273.76	2.0	0.0441	8.1					
	9.1	0.32	470	472	1.04	23.5	0.4			273.05	1.5	0.0490	5.9					
	10.1	-0.34	278	349	1.30	23.2	0.5			278.01	2.0	0.0438	8.1					
AJ062	1.1	0.66	282	84	0.31	1,252	6	1,375	15	4.63	0.5	0.0879	0.8	2.61	0.9	0.2157	0.5	0.518
	2.1	-0.31	102	55	0.56	1,652	12	1,598	20	3.43	0.8	0.0989	1.0	3.96	1.3	0.2912	0.8	0.589
	3.1	0.54	108	135	1.29	22.8	0.7			280.30	3.1	0.0507	12.0					
	4.1	2.33	64	90	1.45	23.1	1.0			272.25	4.0	0.0649	14.3					
	5.1	4.78	170	307	1.87	23.0	0.6			266.30	2.6	0.0843	7.8					
	6.1	-0.15	204	372	1.89	24.6	0.6			261.71	2.2	0.0453	9.2					
	7.1	-0.47	98	140	1.48	24.2	0.8			267.56	3.2	0.0428	13.5					
	8.1	0.02	177	146	0.85	24.6	0.6			260.99	2.3	0.0467	9.6					
AJ063	1.1	-0.51	96	146	1.57	24.2	0.8			267.42	3.2	0.0425	13.0					
	2.1	-0.56	119	154	1.33	1,493	12	1,392	28	3.86	0.8	0.0884	1.5	3.16	1.7	0.2592	0.8	0.479
	3.1	-0.11	824	588	0.74	1,200	3	1,178	9	4.89	0.3	0.0792	0.5	2.23	0.5	0.2044	0.3	0.499
	4.1	1.87	80	88	1.14	23.0	0.8			274.24	3.5	0.0613	12.3					
	5.1	0.12	136	230	1.75	24.5	0.7			262.53	2.7	0.0475	10.6					
	6.1	-0.20	247	146	0.61	1,430	7	1,395	14	4.03	0.5	0.0886	0.7	3.03	0.9	0.2480	0.5	0.551
	7.1	-0.58	182	101	0.57	1,682	14	1,581	34	3.37	0.8	0.0981	1.8	3.99	2.0	0.2962	0.8	0.406
	8.1	1.05	80	127	1.63	23.2	0.9			274.88	3.4	0.0548	19.0					
	9.1	-0.18	148	238	1.66	24.1	0.6			266.96	2.5	0.0451	10.6					
	10.1	1.05	116	188	1.68	23.4	0.7			272.64	2.9	0.0548	10.7					
AJ064	1.1	-0.14	235	275	1.21	23.1	0.5			278.49	2.0	0.0453	8.9					
	2.1	0.25	202	397	2.03	22.4	0.5			287.08	2.2	0.0485	10.1					
	3.1	0.10	233	334	1.48	23.2	0.5			276.79	2.0	0.0473	8.1					
	4.1	0.65	157	260	1.72	23.7	0.6			269.62	2.4	0.0516	9.4					
	5.1	1.18	259	548	2.19	22.4	0.5			283.98	2.0	0.0558	7.3					
	6.1	-0.69	91	128	1.46	22.0	0.8			295.16	3.4	0.0410	16.5					

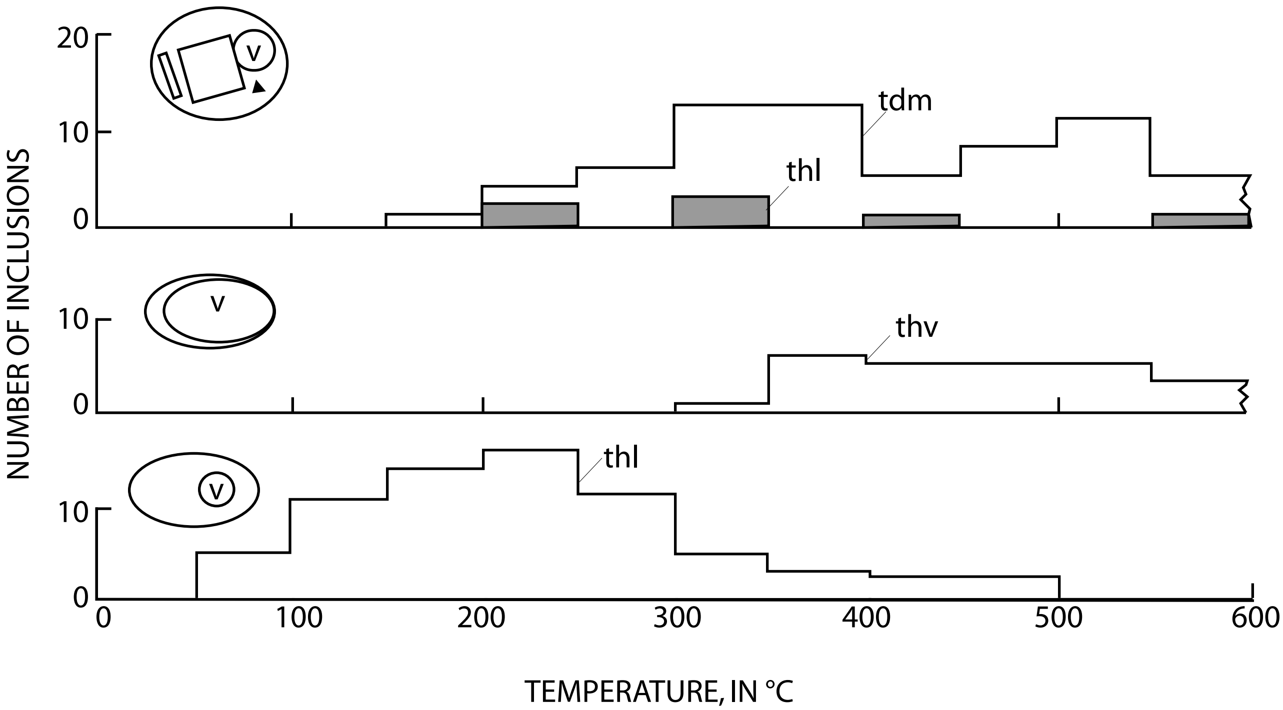

Figure 17. Temperatures of homogenization of (from top to bottom) mineral-rich, vapor-rich, and liquid-rich fluid inclusions in the Cardigan Peak Pluton in degrees Celsius. Daughter minerals shown by polygons, vapor bubbles indicated by the letter v. Abbreviations: tdm, homogenization by final dissolution of a daughter mineral; thl, by final disappearance of the vapor bubble; thv, by disappearance of the liquid phase.

(Ludwig, 2003). All sample age uncertainties are reported at the 95-percent confidence level. Data not corrected for common Pb are plotted on a Tera-Wasserburg diagram (fig. 18), which is best suited for samples with Phanerozoic ages and allows any contribution from common Pb to be directly evaluated. Reported ages will be derived from the ^{207}Pb-corrected ^{206}Pb/^{238}U ratios except for the Proterozoic ones, which are better presented as ^{204}Pb-corrected ^{206}Pb/^{238}U and ^{207}Pb/^{206}Pb ages.

Of the 34 analyzed grains, 6 yielded Proterozoic ages. Ajo 63, the fine-grained hornblende diorite, appears to have a significant fraction of Proterozoic grains that are interpreted to be inherited from the basement of this complex. Ajo 62 appears to have a smaller fraction of inherited grains, and no inherited grains were found in Ajo 61 and 64. However, the number of grains analyzed is too limited for all four samples to provide reliable statistical information about the percentage of inherited grains present. No attempt was made to fully characterize the range of inherited ages because the emphasis was on the crystallization age of the intrusive rocks. Ages (^{207}Pb/^{206}Pb) for the six inherited grains range from 1,581 to 1,178 Ma. The ages at 1,395-1,378 Ma and 1,598-1,581 Ma are consistent with known basement ages. The single concordant age at 1,178 Ma is unexpected.

The other 28 grains give ages from 24.5 to 22.0 Ma. Only Ajo 61 with 10 analyses provides a statistically reliable age for a single sample at 23.7+/-0.4 Ma (9 of 10 analyses used for a weighted average ^{206}Pb/^{238}U age). Data from the other three samples are consistent with this age, as shown on figure 18, but there are too few analyses for each individual sample to calculate a reliable age. All 28 analyses from the four samples give a weighted average of 23.5+/-0.3 Ma, with a mean square of weighted deviates (MSWD) of 1.5. Four of the analyses have slightly elevated ^{207}Pb/^{206}Pb ratios, indicating a small contribution from common Pb, and three of the analyses that give the youngest ages may have experienced some Pb loss. Omitting these seven analyses gives a weighted average of 23.7+/-0.2 Ma and improves the MSWD to 1.0. The weighted average age for these 21 analyses should provide the best age for the intrusive complex. These data cannot be interpreted to show whether or not there is any measurable difference in age among the four samples—a much larger set of data is needed to answer that question. The apparent common inheritance in Ajo 63 implies a distinct history for that intrusion. This is consistent with field evidence, which indicates it is the oldest member of the group. Zircons from all four samples have Th/U ratios from 0.77 to 2.18. This is higher than the typical value of about 0.5-0.7 for most zircons. Ajo 61 is distinctive from the other three samples in having the Th/U ratio restricted to the low end of the range (0.77-1.32) for all samples.

Younger Cenozoic Rocks

In and around the study area are extensive areas of volcanic and lesser sedimentary rocks with no appreciable dip. These rocks apparently postdate the Cenozoic events of main interest in this study.

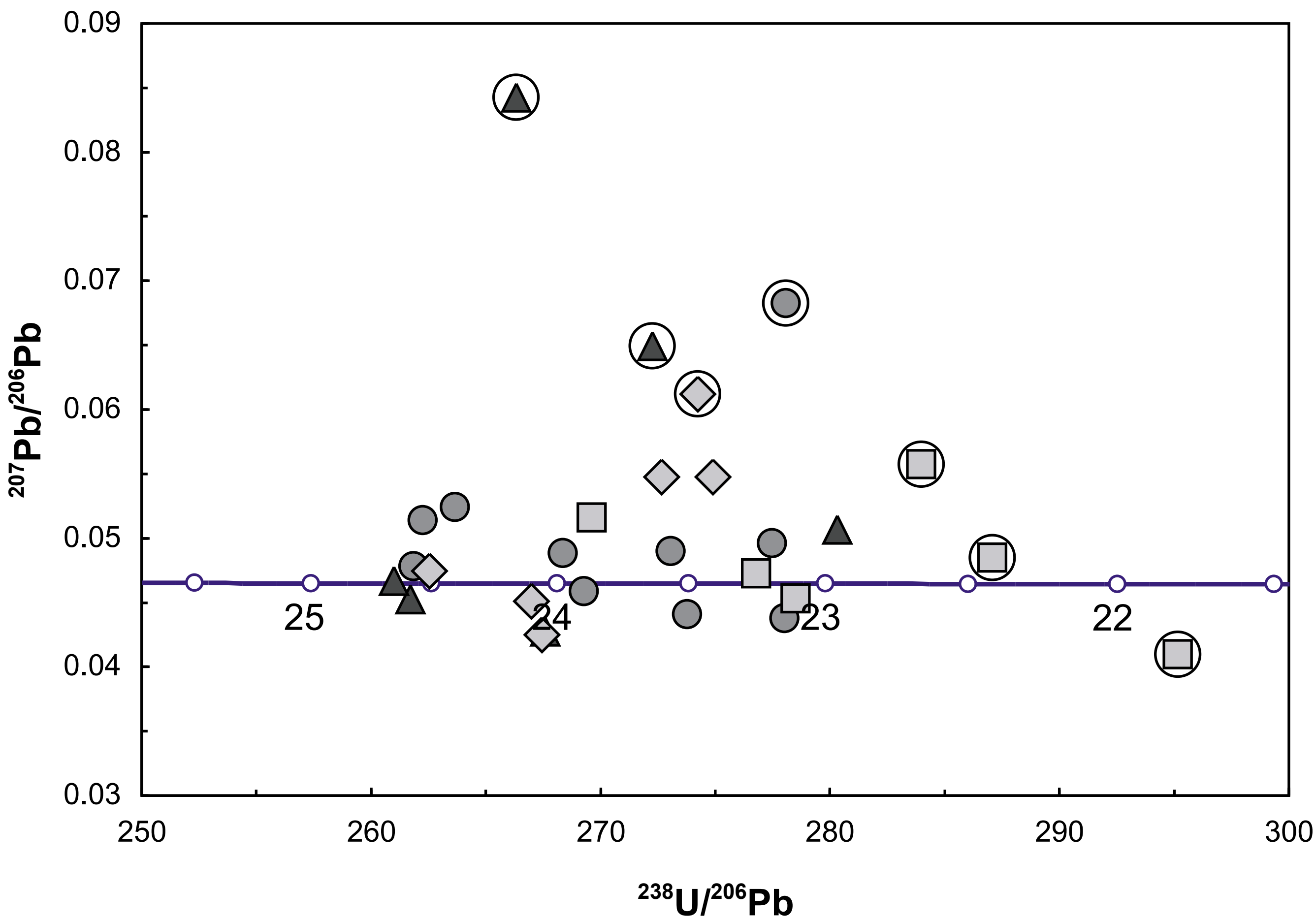

Figure 18. Tera-Wasserburg diagram showing lead and uranium isotopic ratios for zircon grains from four samples of the Cardigan Peak Pluton. Data are uncorrected for common lead. Sample Ajo 61, circles; Ajo 62, triangles; Ajo 63, diamonds; Ajo 64, squares. Circled symbols designate the seven grains omitted from the best-case weighted average, as discussed in the text. Numbers on horizontal line indicate ages in millions of years.

Sneed Andesite

Gilluly (1937) named the Sneed Andesite for exposures near Sneed Ranch, 3.5 miles (5.6 km) northwest of Ajo (unit Tsa, pl. 1). Where it is exposed at the south end of Childs Mountain and west of the Cardigan Peak Pluton, the Sneed is a light-tan, massive flow with phenocrysts of plagioclase, hornblende, and biotite set in a light tan aphanitic groundmass.

The Sneed underlies the Batamote Andesite in the northern part of the Growler Mountains (R.J. Miller, oral commun., 2001), where biotite from the Sneed gave a K–Ar age of 22.0±0.7 Ma (Gray and Miller, 1984). In this area a glassy ignimbrite lies between the Sneed Andesite and the Batamote.

The rock exposed on the 1,785-ft hill south of Sneed Ranch is a well-layered ignimbrite with prominent phenocrysts of quartz and sanidine in a glassy matrix. This may be correlative with the ignimbrite observed by Gray and Miller. An 40Ar/ 39Ar date obtained from sanidine in this rock is 21.37±0.1 Ma (W.C. MacIntosh, New Mexico Geochronology Research Laboratory, written commun., 1997).

Gilluly (1937) noted an angular unconformity between Sneed Andesite and Locomotive Fanglomerate one mile SSW of Salt Well near the northwest corner of plate 1. This outcrop was not found during the present study. The Sneed is generally flat lying with 35° dips measured on the ignimbrite layers in local areas. The absence of major inclination indicates that the Sneed Andesite postdates the extensional tilting in the Ajo mining district.

Childs Latite and Hospital Porphyry

Gilluly (1937) named the Childs Latite for exposures on Childs Mountain northwest of Ajo. The Childs Latite (unit Tcl) also is exposed on a hill in the southeastern part of the area of plate 1 and in a small isolated stream outcrop in the southwestern part. The unit is composed of coarsely porphyritic gray aphanitic to holocrystalline lava with large (1 to 3 cm) plagioclase phenocrysts (Gray and others, 1985a). A K–Ar date obtained from plagioclase is 18.4±0.9 Ma (Gray and Miller, 1984). The Hospital Porphyry (unit Thp) forms prominent vertical dikes extending from Ajo into the New

Cornelia mine pit and intermittently from Concentrator Hill to a point east of Darby Well. Its content of coarse plagioclase phenocrysts suggests a genetic association with the Childs Latite eruptive event.

Batamote Andesite

The Batamote Andesite (unit Tba; Gilluly, 1937) forms thick flows on Childs Mountain on the north, Black Mountain on the east, and an isolated hill on the south side of the area of plate 1. The Batamote Andesite is a dark-gray, vesicular, finely porphyritic basaltic andesite with small phenocrysts of olivine replaced by iddingsite (Gilluly, 1946). A whole rock K–Ar date of 14.4±0.7 Ma has been reported from this unit (Gray and Miller, 1984).

Neogene Cover

Most late Cenozoic to Quaternary sediment cover in the map area is poorly indurated gravel broadly distributed in sheetlike deposits. This gravel is poorly sorted and contains cobbles as large as 15 cm. Gravel composition is extremely variable, and lithic content of the gravel is an unreliable indicator of the composition of the underlying bedrock. Sediment in active streams is finer grained and, as pointed out by Gilluly (1946), represents products of erosion by streams with lower gradients than those that produced the older gravels.

Structures

Structural Context

Beginning with the pioneering work of Anderson (1971) and Wright and Troxel (1973), the importance of Tertiary extensional faults with shallow dip has been recognized in the southwestern United States. Where the full fault geometries can be deciphered, they are listric (that is, concave-upward), so that they intersect the surface at 50° or more but flatten at depth. The surface manifestation may thus be that of a half-graben, but if erosion exposes the gently dipping portion, it may be called a detachment fault, and the steeply dipping part is then commonly called the headwall fault (these features are defined by Davis, 1984). The strongest evidence of this geometry is from seismic reflection data, though some areas expose the fault curvature. In many areas, the curvature is implied by the considerable dips into the fault of synextensional coarse clastic sediments, which had accumulated in the area of negative structural relief and then were rotated by movement along the curved fault (Dickinson, 1991).

Where the listric faulting has reached sufficient depth that some minerals in the footwall become ductile, mylonitic fabrics are observed where the footwall has rebounded sufficiently to expose basement rocks. Such exposures are then called metamorphic core complexes (Spencer and Reynolds, 1989a). If the fault changes locus over time, multiple detachments may be exposed (Lister and Davis, 1989). Further extension basinward of uplift may initiate secondary faults called breakaways. Steep faults that bound different extensional domains are called transfer faults or accommodation zones (Davis, 1984; Faulds and Varga, 1998).

Western and southern Arizona show substantial extension in many places, and our interpretation is guided by the features of extensional domains along the Colorado River extensional corridor (Spencer and Reynolds, 1989b), and the Catalina-Rincon complexes to the east (Force, 1997b). As described above, Tertiary extensional history has become an essential component of the description and exploration for Laramide porphyry copper deposits throughout this terrane.

The Relation of Miocene Structures in Ajo to Those of Southern Arizona

Regional tilt-domain maps produced by averaging the strike and dip of lower to middle Cenozoic layered rocks over wide areas have been important in understanding the structural evolution of southern Arizona (Richard, 1994, Wilkins and Heidrick, 1995). Figure 19 is a slightly modified version of Richard's (1994) domain map. It shows the Gila-Ajo domain extending 300 km from near the Colorado River to its east boundary 75 km east of Ajo. The northwest strike and 35° dip are the approximate average of all lower to middle Cenozoic layered rocks in the domain.

The 48° dip at Ajo (fig. 19) is the average of bedding attitudes in the Locomotive Fanglomerate. The arrow shows the direction of extension assuming that the Bandeja Wells Pluton and Cornelia Pluton were originally one body. The symbols 40 km northeast of Ajo represent an outcrop, 2,000 m in diameter, of Locomotive-like fanglomerate and overlying volcanic rocks in the Hat Mountain Quadrangle (Grey and others, 1985b). The arrow indicates the extension direction assuming that tilting of Locomotive-type rocks is related to detachment faulting.

In the Sells Domain to the east-northeast, extension is indicated by northwest-striking normal faults as much as 10 km in length that displace Cenozoic conglomerate against Mesozoic rocks in the Comobabi Mountains (Haxel and others 1978). Farther to the east, tilt domains are interrupted by uplift of crystalline rocks that are believed to be the exhumed footwall of detachment structures in the Baboquivari Domain (Richard, 1994).

The San Xavier Domain is of particular interest in this study because of the similarity of its structures to those at Ajo. In a classic paper, Cooper (1962) mapped a low-angle fault (the San Xavier) overlain by the Helmet Fanglomerate. He concluded that the Pima-Mission porphyry copper deposits were transported northward 10 km along this fault from their original position above the Twin Buttes deposit. In figure 19,

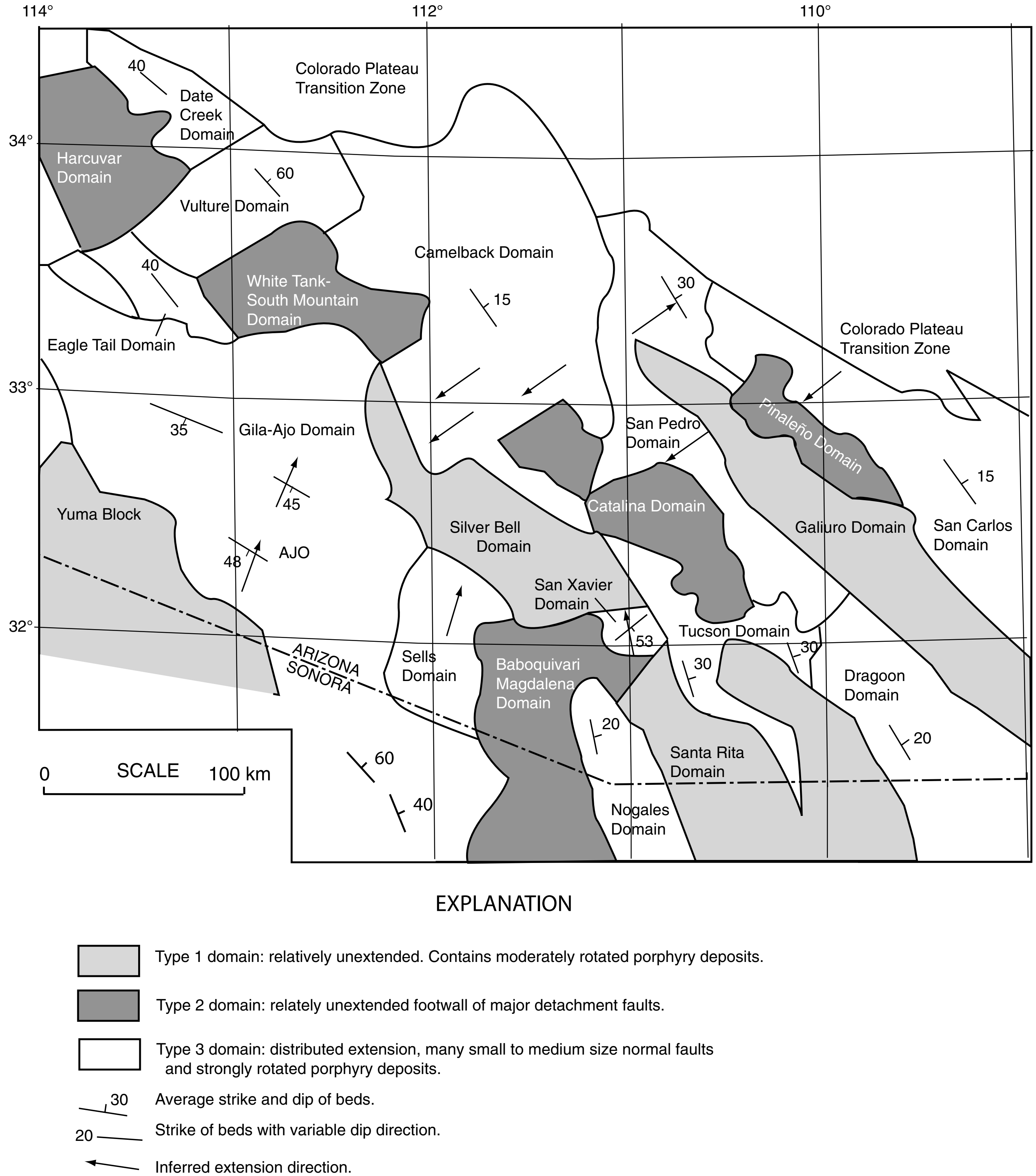

Figure 19. Map showing structural domains in southern Arizona based on dips of middle Cenozoic volcanic and sedimentary rocks. Domains modified from Richard (1994). Extension directions modified from Wilkins and Heidrick (1995). Dips in Sonora, Mexico, from Stewart and Roldán-Quintana (1994) suggest an additional domain south of Gila-Ajo.

the strike and dip is an average attitude of the Helmet (Cooper, 1973) and the extension arrow is the line between Twin Buttes and Pima-Mission deposits.

Structures in the Ajo District

We believe that detachment faults at Ajo can best be visualized by analogy to those described in the Whipple Mountains of southeastern California (Davis and others, 1982, 1986). In both areas sets of parallel normal faults terminate at an underlying master fault and layered rocks between the normal faults are strongly rotated. Structures at Ajo are poorly exposed compared to those in the Whipple Mountains, and it is only through drilling that the shape and depth of the structure can be understood (fig. 2). There is no exposure of an obvious metamorphic core complex near Ajo. Structures at Ajo probably formed at a higher level than those in the Whipple Mountains and there is no evidence of ductile shear or chloritic breccias in the footwalls of the detachment faults.

One important similarity with the Whipple Detachment is that cross sections through the fault cannot be reconstructed using presently visible faults. Miocene sedimentary and volcanic rocks at Ajo can be successfully reconstructed, but structures in the upper plate are abruptly truncated by the detachment fault so that it is not possible to include the Precambrian rocks of the lower plate in the reconstruction. Lister and Davis (1989) describe the same phenomenon in the Whipple Mountains (see their figure 13, p. 81). They explain the missing segments as having been excised by earlier detachment faults and state (p. 81) that “it is impossible to balance the cross sections without further information about the number of detachments that have cut through the section and where the excised material now resides.”

We believe that the inability to balance the cross sections is consistent with the idea that Ajo is the site of numerous episodes of detachment faulting, for which we have rotational evidence for only three or possibly four. The main difficulty in drawing cross sections at Ajo is that we have knowledge about only 7 km of a detachment system that may extend many times that length. To begin a reconstruction of the cross sections, we would move the Cornelia Pluton south 16 km to lie above its purported root zone, the Bandeja Wells Pluton. We could then suspect that the missing pieces of Locomotive Fanglomerate and Ajo Volcanics are buried beneath Batamote andesite and other upper Miocene volcanics that extend 13 km south of Bandeja Wells (Gray and others, 1988).

A great number and variety of faults are present in the study area; they relate systematically to stratigraphic, plutonic, rotation, and alteration features already described, so that it is possible to categorize faults and place them within an areal evolution that includes all the features. The structures will be described from oldest to youngest.

Fault(s?) Coeval with Darby Arroyo Formation

One important fault that seems required by structural-stratigraphic relations is not exposed in the study area. This is a detachment coeval with the earlier stage of rotation of the porphyry ore body and with the Darby Arroyo Formation. We can predict that it is gently dipping and occupies an area south of Locomotive Fanglomerate (fig. 20); it may have originally extended to the Bandeja Wells area.

Faults Coeval with Locomotive Detachment Fault

The structures that seem to form a roughly coeval assemblage of Locomotive-related extensional features include the main Locomotive Detachment Fault itself and its head-wall, several north-dipping normal faults, transfer structures, secondary breakaway faults, and a possible detachment in the upper plate of the main detachment fault.

Main Locomotive Detachment

The Locomotive Detachment Fault underlies all of the tilted middle Cenozoic and Laramide sedimentary and volcanic rocks in the Ajo mining district (pl. 1). It is a gently dipping structure that separates this assemblage of rocks on its upper plate from Precambrian Cardigan Gneiss and Chico Shunie Quartz Monzonite on its lower plate. Phelps-Dodge drilling has constrained its position where it is in the subsurface (fig. 2).

A cross section through features of the Locomotive detachment system is exposed as an outlier on the west flank of North Ajo Peak, west of the Chico Shunie Fault (fig. 21). It was depicted by Gilluly (1946, fig. 5), who interpreted the detachment as a depositional surface that was steeply inclined to the south when the Locomotive and Ajo Volcanics were laid down. He believed that the structure was then rotated 40° to the north. His cross section closely follows our sections in plate 1, in which the contacts between Locomotive Fanglomerate and the Ajo Volcanics dip steeply into the detachment surface. In the outlier both these rock units are unsheared and little altered. The detachment itself consists of 1-3 m of clayey gouge-breccia with weak iron oxide staining. Local chloritic shear surfaces are evident. The breccia grades downward into shattered and sodic-calcic altered Cardigan Gneiss. About 1 km to the south, where sodic-calcic altered Chico Shunie Granite is the lower-plate rock, steep east-west veins or joints filled with dark red gouge-breccia form dense sets over a wide area. No offset is apparent where these veins intersect, indicating that they are the result of tensional stress rather than lateral shear. These features suggest that the western detachment outlier was present over a wide area and less than 100 m (330 feet) above the present land surface (compare Force, 2002).

Another apparent exposure of the detachment is southwest of Gibson, where Cardigan Peak monzogranite contacts Laramide quartz diorite on a surface, presumed to be the Locomotive Detachment, dipping 30° east. Section E-E’ on plate1 shows that the detachment lies less than 50 m (165 feet) below the surface along this part of the section line, so it is not unlikely that it is exposed a short distance to the north. To the north are faulted blocks of Cardigan Gneiss

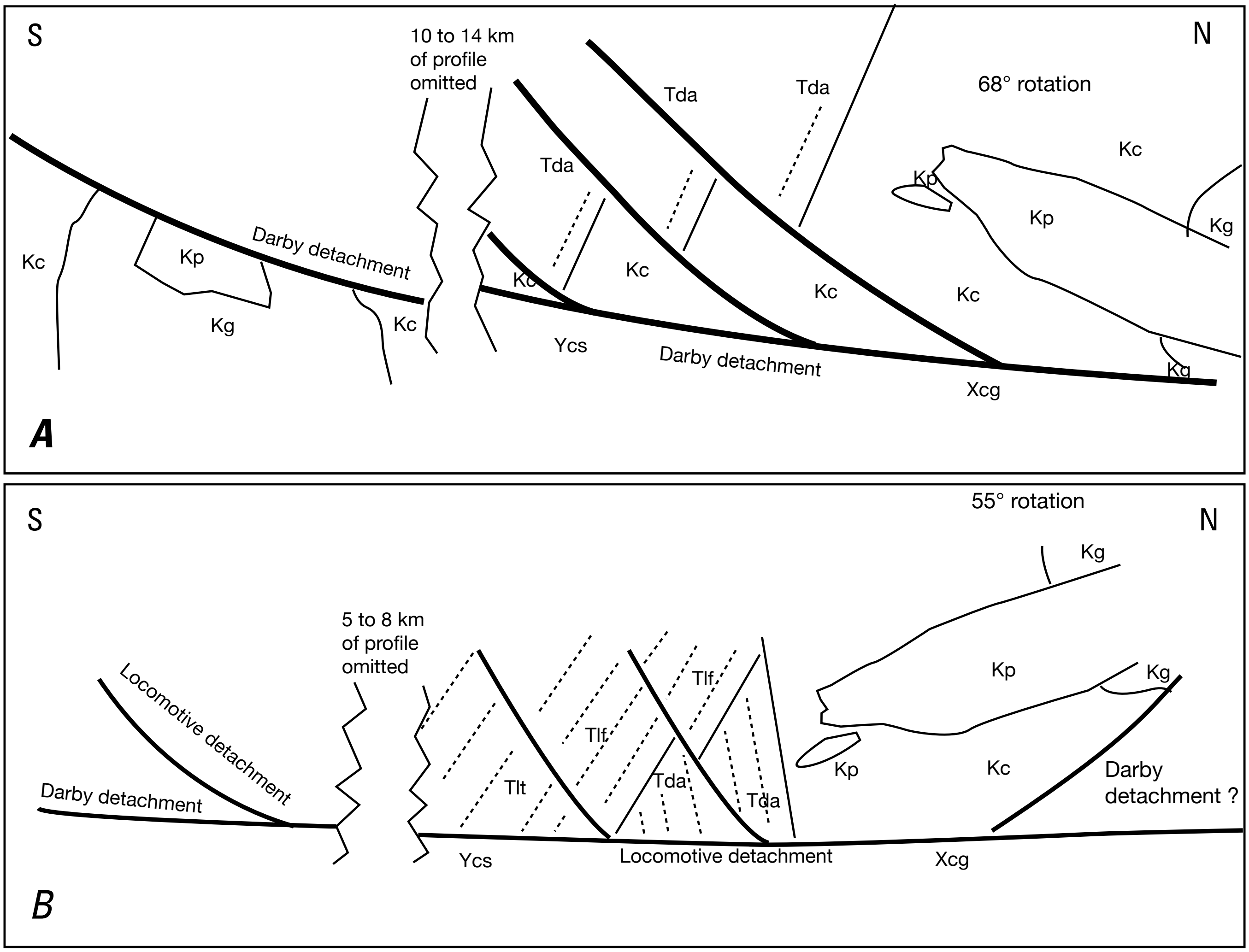

Figure 20. Profiles showing two possible stages in the development of the Darby (*A*) and Locomotive (*B*) detachment structures and their effects on Laramide and Cenozoic rocks. Rotation angles are modified from Hagstrum and others (1987) to accommodate dip angles measured in the field. The Laramide granodiorite porphyry and the New Cornelia ore body are shown plunging 20° to the south, well within the error limits of Hagstrum's 1987 estimate. It is unlikely that all of the rotation and movement shown in profile *B* was caused by the Locomotive detachment. Evidence for one or more detachment episodes that probably occurred between *A* and *B* is concealed. Xcg, Precambrian Cardigan Gneiss; Ycs, Precambrian Chico Shunie Quartz Monzonite; Kc, Laramide Concentrator Volcanics; Kg, Laramide Cornelia Pluton, including possible root zone near Bandeja Wells; Kp, Laramide granodiorite porphyry including New Cornelia ore body; Tda, Lower Cenozoic Darby Arroyo Conglomerate; Tlf, Lower Cenozoic Locomotive Fanglomerate.

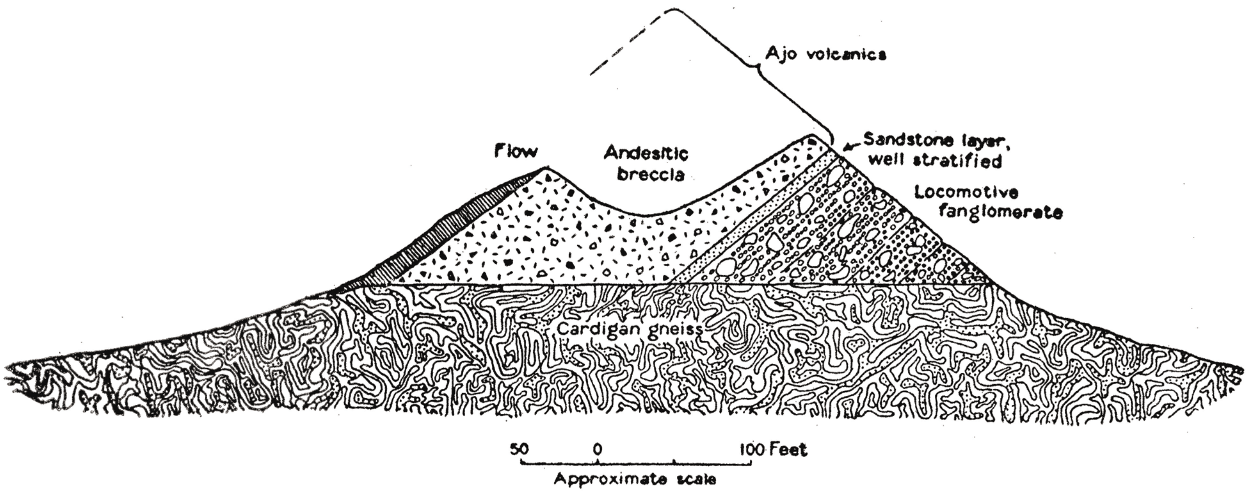

Figure 21. Cross section of the western outlier of the Locomotive Detachment (from Gilluly, 1946, fig. 5). Note the similarity with our cross sections on plate 1.

that may be part of the footwall of the detachment. However, complex cross-faulting, dike intrusion, abundant talus cover, and recent residential construction make it difficult to relate these outcrops to the detachment.

The Locomotive Fanglomerate seems to be the sedimentary consequence of movement on the Locomotive Detachment (Hagstrum and others, 1987; Wilkins and Heidrick, 1995), its accumulation being a response to the crustal hole that the detachment produced and its dip being the result of overall listric shape of the detachment surface (fig. 20). If so, the distribution of Locomotive Fanglomerate is a guide to the extent of the detachment in the subsurface. The detachment must have extended at least into the northern parts of the study area over the Cardigan Peak block, but need not have extended south of the South fault of plate 1, past which Locomotive Fanglomerate is not exposed and Ajo Volcanics become nearly horizontal. The east and west sides of the detached block are not well constrained, but extend at least to Black Mountain and the Growler Mountains, respectively (fig. 1).

Detachments intersect bedding of their coeval synextensional deposits at a regular angle of 45º-60º (Dickinson, 1991). This angle opens in the direction of tectonic transport of the upper plate. Transport along the Locomotive detachment was thus toward N15°E. The N30°E trend of the deep trough in the detachment surface near the New Cornelia Mine probably is a result of this transport direction coupled with uplift of the Cardigan block, which also produced the shallowing of the detachment toward the north. Dips in the Locomotive Fanglomerate are in accordance with such uplift, being locally steeper adjacent to the Cardigan Peak block.

Down-to-North Normal Faults

At least ten down-to the-north normal faults strike west-northwest across the map area (pl. 1, cross sections A through D), apparently confined to the upper plate of the Locomotive detachment system. Some of these faults are required mostly to repeat the Ajo Andesite member. These faults are shown on the cross sections as merging with the Locomotive Detachment Fault at depth. Probably they outline roughly planar panels of upper-plate rock rotated in the "domino" style of Dickinson (1991).

A critical outcrop in the footwall of the south fault, at UTM 3,577,600 N and 327,318,700 E, provides evidence for the classification of this structure. The Valentine Well–Ajo Peak contact is exposed on the east bank of a southwest-trending gully for a distance of 40 m. The contact at the south end of this outcrop is about 2 m below that at the north end, indicating a dip of only 10° to the south in the foot wall of the south fault. This suggests that the fault marks the head wall on the south edge of the zone of tilting and accounts for most of the tilt of the Locomotive-Ajo Volcanics package; it thus must be the headwall fault for the Locomotive detachment system. Subsurface contours on the top of the Precambrian surface show little discontinuity across the south fault. Probably this means that the Locomotive Detachment captured the plane of the older Darby-generation detachment that extended to the south.

Down-to- South Normal Faults

The Copper Canyon Fault, a steep fault in Copper Canyon (Force, 1997a) is poorly exposed, marked mostly by brecciation and iron staining. This fault is required to bring the Locomotive Detachment on its south side from an elevation of about 1,450 ft upward to clear the Cardigan Gneiss at about 1,800 ft on its north side. Considering the local southward dip of the detachment (fig. 2), about 200 ft of down-to-south offset is required. Offset toward the east end of the Copper Canyon Fault may be minor, however, making its trace there essentially the trace of the Locomotive Detachment.

The northwest-striking Valentine Well Fault juxtaposes Locomotive Fanglomerate and the Valentine Well member of the Ajo Volcanics south of North Ajo Peak. The volcanic rocks on the downdropped south side of this fault form a prominent fault-line scarp. Near Ajo Peak this fault cuts the Locomotive Detachment Fault, based on the northwest-trending set of contours in figure 2. Several other down-to-the-south faults with smaller displacement are inferred. The Valentine Well Fault is probably cut off by the Chico Shuni Fault because there is no evidence for it to the west.

The Darby Arroyo Fault has only minor south-side-down displacement (see sections C-C" and D-D" on pl.1). It repeats the Darby Arroyo Formation in the area south of New Cornelia Mine.

Transfer Structures

Several faults separate areas of unequal northeast extension in the Locomotive detachment system. They fit the definition of transfer faults.

The Chico Shunie Fault forms the contact between Precambrian rocks on the west and Locomotive Fanglomerate and Ajo Volcanics on the east. It can be considered as the west boundary of the main Locomotive depocenter, and would be classified as a sinistral, rift-margin transfer fault. The Chico Shunie Fault bounds the east side of the outlier of the Locomotive Detachment west of North Ajo Peak.

The east fault is a dextral transfer fault on the east side of the Locomotive detachment. It is not exposed. Its presence is indicated by the small exposure of Precambrian Cardigan Gneiss 1,000 m (3,300 ft) east of exposures of Ajo Volcanics northeast of the Copper Giant prospect (pl. 1). It is cut off by the younger Black Mountain Fault 2 km to the north.

Other Detachment Faults

The North Ajo Peak Detachment is a minor detachment fault that underlies North Ajo Peak (cross section A-A', pl. 1). Evidence for this fault is the fact that the curved transfer fault that bounds the North Ajo Peak block on the east does not offset the Locomotive Detachment to the north. It is shown as bending west and merging with the proposed North Ajo Peak detachment fault. This detachment is younger than and overrides the Valentine Well Fault. The strongest case can be made for a dextral synthetic transfer fault along the eastern margin on North Ajo Peak (pl. 1), where it juxtaposes Ajo Volcanics to the northwest and Locomotive Fanglomerate to the southeast. The fault shows a 60° westerly dip and slickensides plunging gently to the north-northwest. This fault as exposed is entirely in the upper plate of the Locomotive detachment system.

The Pinnacle Peak Fault crops out on the west summit of Pinnacle Peak. It may be part of a detachment fault, now largely removed by erosion, that lies above the Locomotive Detachment in the Camelback-New Cornelia block (pl. 1). This fault is marked by a 50-cm breccia zone dipping 22° north and slickenside grooves trending N 20°E. The fault is located about 20 m (65 ft) below the summit. Rocks above the fault are dacitic and contain angular clasts with prominent phenocrysts of plagioclase, biotite, hornblende, and minor quartz. They correlate with the Valentine Well member of the Miocene Ajo Volcanics, which crops out 3 km to the south. A second fault, striking N 25°W and dipping 50° north is exposed near the east summit of Pinnacle Peak. This fault cuts the low-angle fault and places a finely porphyritic andesite over Concentrator Volcanics. That andesite resembles the Ajo Peak Member of the Ajo Volcanics. These faults strongly suggest the presence of a high-level detachment bringing Miocene rocks over the Laramide block. If this detachment is preserved and buried on the north side of the Little Ajo Mountains Fault, it would account for the occurrence of the Lower Andesite Member of the Ajo Volcanics overlying Locomotive Fanglomerate in and north of the town of Ajo. This would correspond to a displacement of 6 km to the northeast of the main Lower Andesite outcrop area.

Faults within the Cardigan Peak Pluton

At least eight east-striking normal faults cut the Cardigan Peak Pluton on the north side of its exposure. These faults are well exposed and exhibit zones of brecciation as much as 2 m thick dipping 30° to 70° north (fig. 22). Seven east-west slices of fine-grained granite have been cut off from the central body and dropped down to the north. Fault reconstruction indicates that the combined dip-slip displacement was more than 2,000 m (6,500 ft); horizontal extension was probably of about the same magnitude. The conclusion that the north side of the outcrop area represents a higher level in the pluton is consistent with the appearance of stable biotite in monzodiorite and granite, south and west of Dunns Well. This indicates that these blocks originated from levels in the pluton above the zone of sodic-calcic alteration. The normal faults are cut off by the Little Ajo Mountains Fault, and it can be expected that parts of the pluton representing still higher levels are concealed on the north side of the fault. The north-dipping extensional faults in the Cardigan Peak Pluton could be part of the same Pinnacle Peak structural assemblage, and if so perhaps all of these faults are secondary breakaways (compare Spencer and Reynolds, 1989a) that postdate movement of the Locomotive Detachment Fault south of Cardigan and Pinnacle Peaks.

Younger Faults

Faults that cut the Locomotive generation of structures are here described together. Broadly speaking, some are basin-and-range structures. They are sufficiently numerous and disruptive to have made interpretation of older structures difficult.

The Gibson Fault (pl. 1; fig. 23) was originally regarded as a transfer structure in the Locomotive detachment system, but it is more gently dipping than would be expected for a transfer fault. In addition, local development of downdip striations indicates that it acted as a normal fault. The Gibson Fault cuts the Locomotive Detachment, as indicated by the abrupt change in spacing of contours southeast of the Gibson-Copper Canyon Fault intersection (fig. 2).

The fault is well exposed for long distances in Gibson Arroyo (fig. 1). Its average dip is 45° east, but the dip ranges from 35° to 60° east. A gouge zone, 1 to 3 m thick, locally contains clasts of Cardigan Peak Pluton. Grooves on the fault plane indicate dip-slip movement.

The Gibson Fault juxtaposes Cardigan Peak Pluton rocks with deep-seated Na-Ca alteration against shallow propylitically altered rocks of the Concentrator Volcanics and Cornelia Pluton. According to Carten (1986, fig. 3), Na-Ca alteration occurred at Yerington Nevada at depths between 2 and 3 km (6,500-9,800 ft.). This is consistent with his estimate of 800 bars lithostatic and 300 bars hydrostatic pressure of formation (Carten, 1986, p. 1514), roughly equivalent to 2.5 km (8,200 ft) depth. Thus the minimum throw on the Gibson fault is probably 2 km). This estimate corresponds well with the 2-km combined displacement that was estimated for the normal faults on the north side of the Cardigan Peak Pluton (see above).

Gilluly (1946) described the Little Ajo Mountains Fault as a great fault, responsible for uplift and exposure of the Little Ajo Mountains, which contain all rocks that are the subject of this paper. In the town of Ajo the fault juxtaposes granitic rocks of the Laramide and Miocene plutons with Locomotive Fanglomerate and Ajo Volcanics. The fault is exposed northwest of Gibson, where its dip can be estimated at about 50°N. In the northwest corner of the area of plate 1, Quaternary sediments conceal the fault, but it apparently brings Precambrian rocks against Sneed Andesite. Its southeast extension is not exposed, but aeromagnetic data (Klein, 1982) suggest that it terminates or deflects the large magnetic anomaly produced by the Batamote Andesite of Black Mountain. If this is correct, then the Little Ajo Mountains Fault also

Figure 22. Photograph of a normal fault believed to be a breakaway structure in the Cardigan Peak Pluton. The hanging wall on the left is composed of Na-Ca altered and brecciated fine-grained granite (Tfg). The footwall is weakly altered monzogranite. Person standing beyond dead tree at right indicates scale. Location: UTM 321000 E, 35842070 N.

cuts the Black Mountain Fault and may be the youngest fault in the Ajo mining district.

On the north side of the Cardigan Peak block, the Locomotive Detachment Fault is downdropped by the Little Ajo Mountains Fault and buried by younger rocks and sediments. It extends in the subsurface an unknown distance to the northeast. Patrick Fahey (oral commun., 1998) described results of subsurface exploration north of Ajo, where BHP Minerals drilled three reversed circulation holes in a search for a possible faulted extension of the Ajo ore body. The holes encountered several hundred feet of gravel underlain by as much as 300 m of Locomotive Fanglomerate. One hole (UTM E326300, N 3588500) encountered a metavolcanic rock with fine-grained biotite at 350 m (1,150 ft) depth. This rock is similar to Concentrator Volcanics. Another hole drilled by The Anaconda Company (UTM E 329215, N 3585772) encountered 120 m of gravel underlain by an equal thickness of Locomotive Fanglomerate. The bottom 200 m was in biotite-bearing dacite similar in description to the Valentine Well member of the Ajo Volcanics. These holes establish that rocks in the detachment package north of the Little Ajo Mountains Fault are similar to those south of the mine.

The Black Mountain Fault extends S30°W from a point under the New Cornelia Mine waste dump and follows the west side of Black Mountain, separating Locomotive Fanglomerate from Batamote Andesite. The fault surface, which dips 85° east, is well exposed on the slopes of Black Mountain, where it locally forms an overhanging cliff. A fault breccia, as much as 120 m wide, is exposed for 1 km along the fault. It is composed of clast-supported blocks, decimeters to meters in size, of Batamote Andesite cemented by dark-red ferric oxide. Other late north-striking faults are present in the New Cornelia Mine area, the Copper Giant prospect, and the western flanks of Ajo Peak. The last may have been a continuation of the Gibson Fault at some stage. No consistent throw direction is apparent in this fault set.

Figure 23. The smooth surface of the Gibson Fault in Gibson Arroyo dipping 50° toward the viewer. The footwall is sodic-calcic-altered monzogranite of the Cardigan Peak Pluton. Grooves on the surface are in the downdip direction. Location: UTM 332800 E, 3582000 N.

Timing of Faulting Relative to Cardigan Peak Pluton

General correlation of igneous activity versus faultiing (as in table 1) is not sufficiently finely detailed to resolve the timing of tectonic events at the time of Cardigan Peak plutonism. It seems likely that Ar resetting, remagnetization, and Na-Ca alteration of rocks near Camelback Mountain were caused by heat and fluids from the Cardigan Peak Pluton (compare Hagstrum and others, 1987), directly across the Gibson Fault. If so, large-scale movement of the Locomotive Detachment must have been largely completed at that time. The contrasting alteration styles on the east and west sides of the Gibson Fault could have been formed at the same time, their juxtaposition being due to more than 2,000 m (6,500 ft) of uplift of the Cardigan Peak block. The postdetachment timing is consistent with younger ages for Cardigan Peak Pluton than for Ajo Volcanics. The Cardigan Peak Pluton being cut by north-dipping normal faults is consistent with these faults as secondary breakaways postdating uplift of the Cardigan Peak block.

Structural-Stratigraphic Reconstruction

The diagram in plate 1 showing correlation of units and tectonic events gives a general correlation of structural, stratigraphic, and plutonic events in the study area. Figure 24 is a series of map cartoons that represent our ideas about the history of the district envisioned from youngest event to oldest.

Reconstruction that erases late faulting of the basin-and-range type is simple but illuminating. Figure 24*A* is a paleogeologic map for this situation at 22 Ma, the time of extrusion of Sneed andesite. The Locomotive Detachment Fault was then more continuous than at present north of its headwall at the south fault, but divided into panels by transfer structures, and was overlain by an extensive upper plate of synfaulting supracrustal rocks that dip southward into it. This Cenozoic sequence unconformably overlies a rotated Camelback-New Cornelia block of Laramide rocks in the upper plate. The detachment is arched upward to clear the Cardigan Peak block; that is, uplift of the Cardigan Peak block of lower-plate rocks had already occurred at this time west of the Gibson Fault. Volcanic rocks derived from the Cardigan Peak Plutonic activity have been stripped off by erosion. Removal of basin-range faults thus makes the Cardigan Peak block very similar to typical metamorphic core complexes of the southwestern United States (noted by Force, 1997a) as described by Davis (1983), Spencer and Reynolds (1989a, 1991), Lister and Davis (1989), Force (1997b), and many others. Among the similarities is a set of secondary breakaway structures that elsewhere correlates with block uplift (Spencer and Reynolds, 1989b). The plane of this secondary breakaway is in the lower plate of the primary Locomotive Detachment in the Cardigan Peak block, but at upper-plate levels in the Camelback-New Cornelia block, and it translates the synextensional package 6 km to the north. Intrusion of most of the feldspathic andesite dikes (KTfa) north of the mine pit may have occurred at the same time as the breakaway structures.

Reconstruction of the Locomotive generation of features can best be described in stages from youngest to oldest. Removal of the secondary breakaway and any other high-level detachment comes first, as shown in figure 24A, translating the Locomotive Fanglomerate-Ajo Volcanics contact back into continuity to the south. Figure 24B shows the allochthon at 24–23 Ma before the uplift of the Cardigan Peak block. Intrusion of Cardigan Peak magma has caused flows and lahars of andesite and dacite to cover the allochthon and form the rock unit mapped as Ajo Volcanics. Undoing the uplift of the Cardigan Peak block leaves the Locomotive Detachment plane a uniform but gentle northward dip, present over the entire area, though stepped across the Chico Shunie Fault and east fault transfer zones. Northeast extension results in a 55°–60° rotation of the Ajo Volcanics and underlying Locomotive Fanglomerate. This additional rotation results in a 20° southwest plunge of the new Cornelia orebody

In figure 24*C,* removal of the Cardigan Peak Pluton leaves the Cardigan Peak area entirely composed of Precambrian rocks. The Darby allochthon is cut by the south fault and deposition of Locomotive Fanglomerate has begun. Figure 24*D* shows removal of the Locomotive and earlier detachment faults and their synextensional supracrustal deposits, leaving the area with a porphyry copper deposit in Laramide rocks overlain by Darby Arroyo Formation. As extension proceeds, these rocks are rotated 60° south. At this point a cross section of the area resembles the upper panel of figure 20. The Laramide terranes of the Camelback-New Cornelia block and Bandeja Wells block may have been approximately contiguous.

Mineral Occurrences Related to Extension

Table 7 describes small copper occurrences and mineral prospects that are abundant in the area surrounding the Cardigan Peak Pluton. The regional map on plate 1 shows the location of only the largest of these occurrences; more than one hundred smaller ones were noted in the area of plate 1 during the course of this study. Many are in the Cardigan Camp area, where the Gibson and Copper Canyon Faults intersect. Mineral occurrences vary from malachite coatings on shears to copper-rich specular hematite veins as much as 50 cm in thickness. Veins commonly follow andesitic dikes that are altered to chlorite. The veins occur in both the footwall and hanging wall of the Locomotive Detachment Fault and are found chiefly in Cardigan Gneiss, Concentrator Volcanics, and in Locomotive Fanglomerate and its included rhyolite megabreccia bodies. The Copper Giant prospect is hosted in a bed of fanglomerate between the Valentine Well and Ajo Peak members of the Ajo

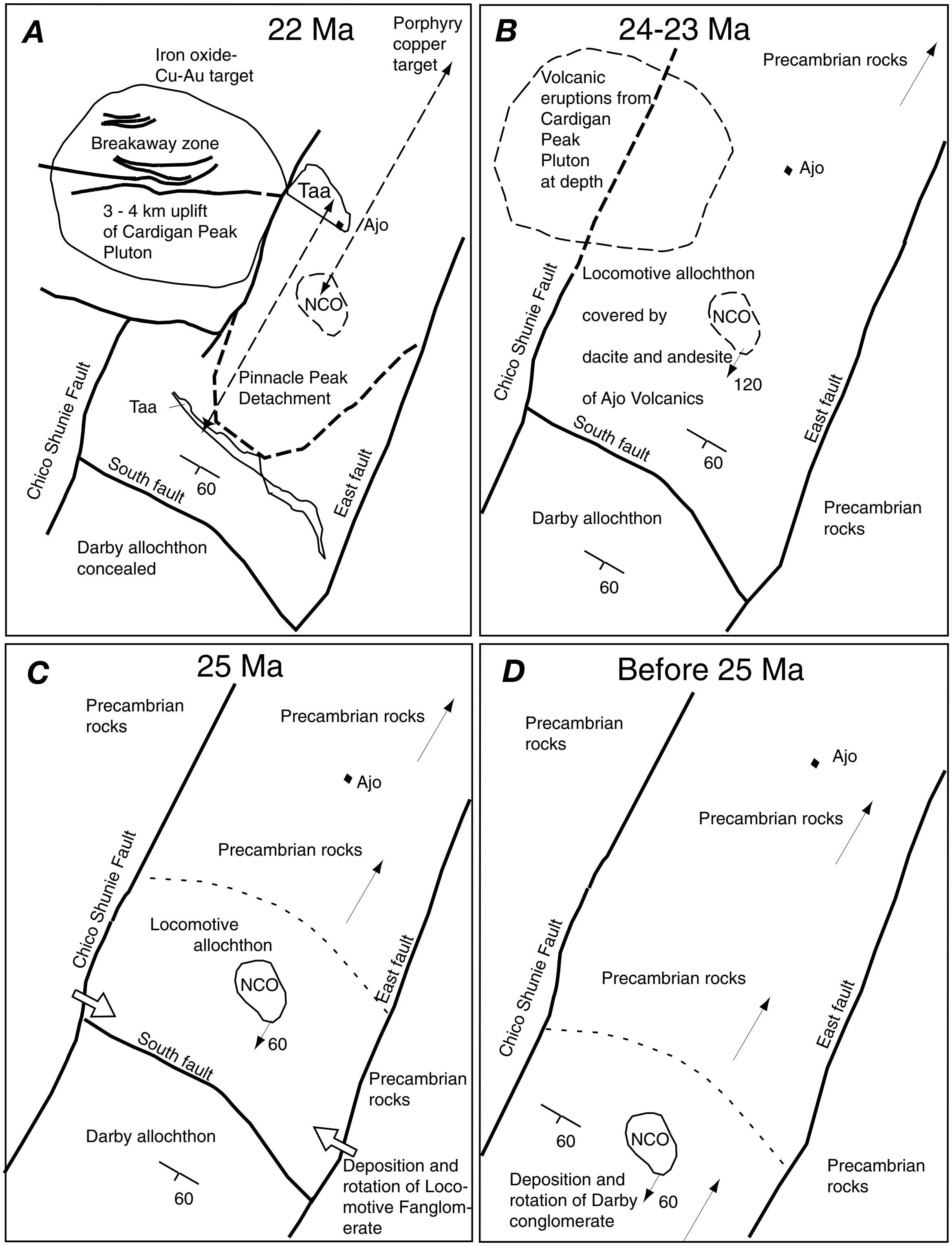

Figure 24. Maps showing four postulated stages of reconstruction of the Ajo district, *A* to *D*, from youngest to oldest. The black box at Ajo marks the present location of the Ajo town plaza. The new Cornelia orebody is labeled NCO. The lower andesite member of the Ajo Volcanics is labeled Taa. Arrows indicate direction of detachment. See text for description of each map.

Table 7 Mineral deposits and occurrences in the Ajo mining district and surrounding region, Arizona. Modified from Peterson and Tosdal (1986). Map numbers are shown on plate 1.

Map number	Latitude (N)	Longitude (W)	Mine name	Description	Host rock
1	32°21'54"	112°51'40"	New Cornelia Mine	Porphyry copper	Laramide porphyry
2	32°21'03"	112°54'50"	West Cardigan, Eighty-five Group	Hematite breccia	Cardigan Gneiss cut by veins and breccia below the Locomotive Detachment
3	32°20'55"	112°54'00"	Ajo Peak	Quartz-specularite veins with copper oxides	Locomotive Fanglomerate
4	32°20'50"	112°53'25"	Cardigan Camp	Veins of specular hematite with copper oxide. Na-Ca alteration along vein wall	Concentrator Volcanics cut by strand of Gibson Fault
5	32°20'35"	112°51'10"	Ajo Cornelia	Specularite veins with chrysocolla	Locomotive Fanglomerate
6	32°21'10"	112°50'35"	Copper Ledge	Chrysocolla, malachite and specularite on shears	Rhyolite megabreccia in Locomotive Fanglomerate
7	32°17'55"	112°52'10"	Copper Giant	Malachite on north-trending fractures cutting fanglomerate	Locomotive type Fanglomerate between Valentine Well and Ajo Peak members of Ajo Volcanics
8	32°12'10"	112°39'50"	Surprise, Morning Star, Gunsight Mines	Barite-fluorite veins with galena, gold, copper oxide	Miocene fine-grained granite
9	33°08'20"	112°38'35"	Copper Mountain	Hematite veins with copper oxides	Laramide pluton

Volcanics. Two drill holes in the prospect failed to find significant mineralization (Romslo and Robinson, 1952). These veins are typical of copper-rich hematite deposits associated with detachment faults in southwestern Arizona and southern California (Wilkins and Heidrick, 1982; Bouley, 1986; Spencer and Welty, 1986).

In the Gunsight Hills, 25 km southeast of Ajo, veins of copper-oxide minerals, barite, fluorite, and galena cut Miocene fine-grained granite. This granite closely resembles the fine-grained granite of the Cardigan Peak Pluton.

Conclusions

Geologic History

The Ajo district is of special interest because of the wide variety of geologic events that have occurred there. Regional metamorphism of Precambrian rocks was followed by intrusion of the 1.4–Ga Chico Shunie Quartz Monzonite. A long period of stability, erosion, and deposition of Paleozoic sedimentary rocks followed. Rocks in the Bandeja Wells area record volcanism, intrusion of the 66–Ma granodiorite pluton, and contact metamorphism of Paleozoic rocks. The Cornelia Pluton and associated Ajo porphyry copper deposit are interpreted to have formed in the upper part of this pluton.

At some time in the early Cenozoic the region was uplifted and a package of Mesozoic rocks became detached from the Precambrian basement and moved northward. The resulting depression was filled with Darby Arroyo Formation. The detachment fault presumed to be responsible for this tilting is not exposed. Its listric form caused the rocks in the upper plate (including the Cornelia Pluton) to be tilted 68°±20° south around an axis striking 101° (Hagstrum and others, 1987).

A second period of tilting in the middle Miocene resulted in slip on the Locomotive Detachment Fault and a second 55° to 60° tilting of the Mesozoic rocks and the overlying Darby. A second basin opened and was filled by the Locomotive Fanglomerate and younger Ajo Volcanics. Major landslides occurred along the steep walls of this basin, and large masses of Mesozoic and Precambrian rocks moved into the fanglomerate deposits. The chief source area for the fanglomerate was a highland area on the west side of the basin that provided abundant clasts of Chico Shunie Quartz Monzonite. The east side of the basin received clasts of Laramide granodiorite and porphyry that must have originated from highlands within the upper plate of the detachment.

Rise of the Cardigan Peak Pluton and its Precambrian country rock along the Gibson and Copper Canyon Faults impeded the northeast movement on the Locomotive Detachment, and movement was transferred upward to the North Ajo Peak Detachment. Continued rise of the Cardigan Peak block resulted in a second upward transfer of motion to the Pinnacle Peak Detachment. At the same time, continued northeast movement of the rocks north of Ajo removed support from the north side of the Cardigan Peak block, and a series of eight east-west-striking breakaway faults were formed.

In what could be considered a chance coincidence, the Miocene Cardigan Peak Pluton intruded the Precambrian rocks exactly adjacent to the final resting place of the Laramide Cornelia Pluton. This coincidence has been a source of confusion for many geologists who worked in the district.

In its final configuration, the Locomotive Detachment surface formed a complex surface showing transfer structures and an arch over the Cardigan Peak Pluton. Secondary breakaway structures carried parts of the Locomotive Fanglomerate and Ajo Volcanics northward from this uplift. The gently dipping 21.7 Ma Sneed Andesite marks the end of the period of extension-related rotation and the beginning of upper Miocene volcanism over a broad region. The Little Ajo Mountains and Black Mountain Faults caused downward displacement and burial of the north and east sides of the district, respectively.

Potential for Undiscovered Mineral Deposits

The possibility of discovery of detached fragments of Laramide porphyry copper ore in this extended terrane has intrigued geologists for many years. The geometry of tilting of the Ajo orebody requires that the lower contact of the porphyry with Concentrator Volcanics in the New Cornelia Mine represents the south side of the original porphyry column near Bandeja Wells. Thus the entire economic part of the porphyry column was shifted north, and hence it is unlikely that a large fragment of ore could exist between Bandeja Wells and the mine area. However, movement was in two stages, much of it being on the inferred Darby generation of detachment, and in this sense it is quite possible that part of the Laramide sequence, including plutonic-volcanic contacts, can be found in the intermediate area in the upper plate of the Darby detachment. The possibility that a second fault, similar to the Gibson Fault, could have cut off the upper part of the ore body and dropped it down to the east of the mine was also examined, but geologic mapping did not reveal such a fault. The large area north of the Little Ajo Mountains Fault, covered by Quaternary deposits, is probably the most attractive area for exploration. This is based on the possibility that the Pinnacle Peak detachment structure cut off the originally lower side of the Ajo porphyry copper column and transported it to the north of Ajo town (fig. 24*A*). Evaluation of this theory by BHP Minerals in 1997 was unsuccessful, but, since only a small part of the covered area has been explored, the possibility of a discovery still exists. A third possibility is based on the supposition that the Bandeja Wells Pluton is not the root zone of the Cornelia Pluton. This would imply that a decapitated deposit exists beneath Batamote Andesite and other Cenozoic rocks 10 to 12 km S15°W of the New Cornelia Mine.

The abundance of mineral-rich fluid inclusions in rock quartz of the Cardigan Peak Pluton indicates that high-salinity fluids carrying dissolved metals passed upward through the pluton before its final stages of crystallization. In addition, K, Cu, Fe, and other metals were leached from the pluton by Na–Ca alteration and carried upward. Presumably these metals were deposited along with gold in, or adjacent to, upper levels of the pluton. The eight normal faults cutting the north flank of the pluton (secondary breakaways) have displaced these high levels downward and northward, where the Little Ajo Mountains Fault could have cut them off and caused their burial by younger rocks and sediments. Mark Barton (oral commun., 1996) has also proposed that a prospective zone for Miocene deposits also exists north of the Little Ajo Mountains Fault (fig. 24*A*). These are likely to be iron-oxide Cu-Au deposits of the Candelaria, Chile, type (Barton and Johnson, 2000; Haynes, 2000). Sodic-calcic alteration may have been caused by influx of saline ground water at or near magmatic temperatures (Battles and Barton, 1989). The source of such water may have been evaporites interbedded with or lateral to the Locomotive and/or Darby units. The absence of a strong magnetic anomaly (Klein, 1982) requires that the target be a hematite-rich rather than a magnetite-rich variety. A hematite-rich target would also be expected because of the abundance of small hematite-copper occurrences in the region. The prospective zone is limited by increasing thickness of Sneed Andesite and younger Miocene volcanics 1.6 km north of the Little Ajo Mountains Fault.

Acknowledgments

The New Cornelia Branch of Phelps Dodge Corp. kindly arranged numerous geologic tours of the mine pit, provided access to surface properties, and furnished the geologic map of the pit included in plate 1. Also, discussions with Scott Gibson and Ronald Gibbs of Phelps Dodge and Veronica UyTana of the University of Arizona were helpful in understanding relations between the geology of the deposit and the surrounding Cenozoic rocks. John H. C. Bain of the Australian Bureau of Mineral Resources contributed greatly to the field mapping in the first year of the project. Eijun Ohta of the Geological Survey of Japan and his wife Katsue deserve thanks for their help and support in the field.

The authors thank John Larsen of BHP Minerals Inc. for graciously giving permission to publish the mapping done in 1995-1998. Keith Howard (USGS), Patrick Fahey, and David Maher of BHP and Mark Barton of the University of Arizona helped in clarifying our thinking on a number of problems of interpretation. Barry Moring (USGS) taught Cox how to digitize maps and greatly assisted in preparation of plate 1. Peter Stauffer and Michael Diggles edited the text, and Katherine Flynn helped with the spider diagrams.

Suggestions by reviewers Ted Theodore (USGS) and Steve Richard (Arizona Geological Survey) and comments and suggestions by John Dilles, Jon Spencer, and Philip Gans have greatly improved this report. Responsibility for the interpretations of the data, however, rests entirely with the authors of this paper.

Finally, thanks go to June Cox and Jane Force for assistance in the field.

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ISBN 1-411-31169-8

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