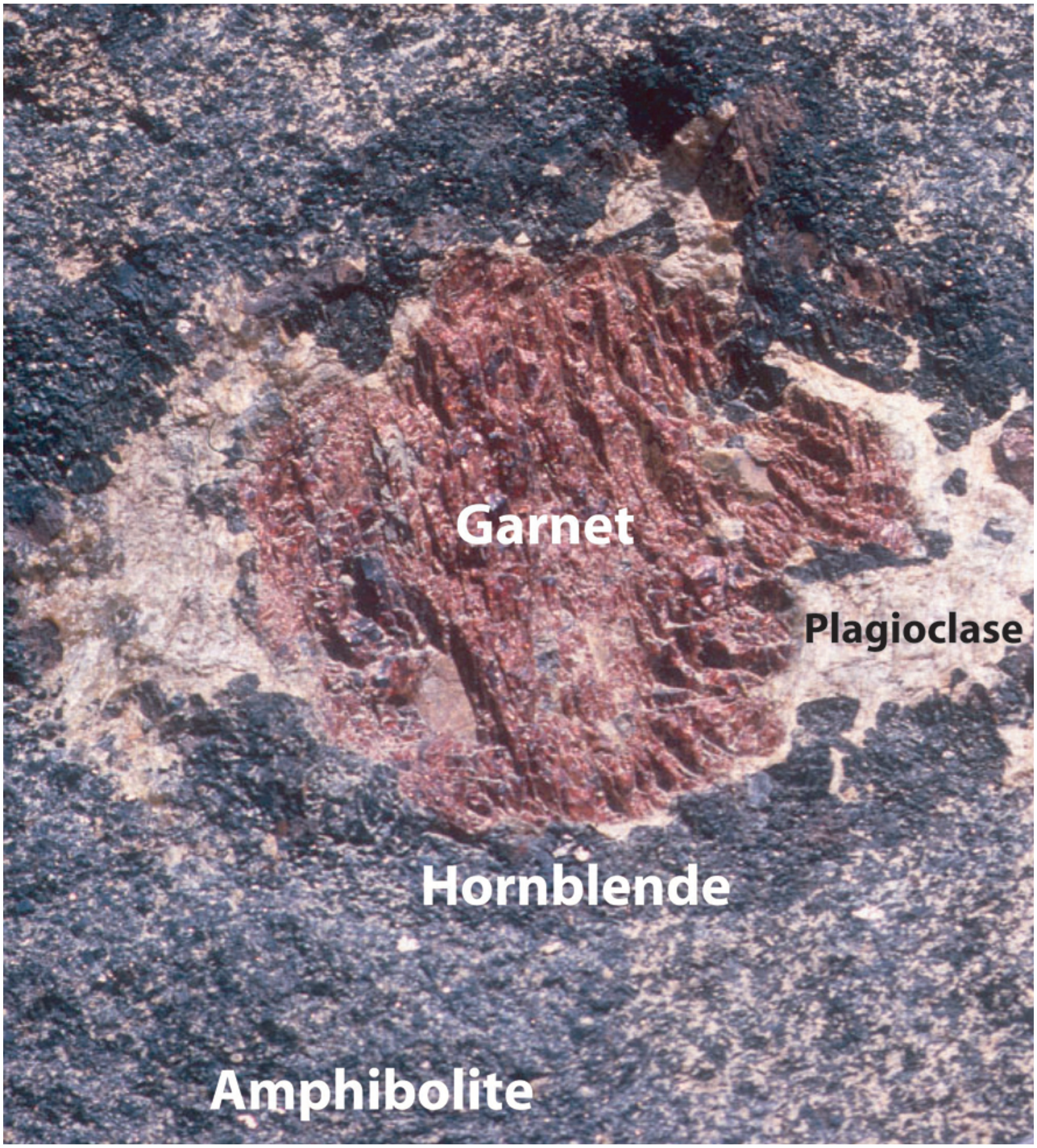
U.S. Industrial Garnet

Chapter L of
Contributions to Industrial-Minerals Research



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U.S. Department of the Interior
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By James G. Evans and Phillip R. Moyle

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James D. Bliss, Phillip R. Moyle, and Keith R. Long, Editors

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Abstract

The United States presently consumes about 16 percent of global production of industrial garnet for use in abrasive airblasting, abrasive coatings, filtration media, waterjet cutting, and grinding. As of 2005, domestic garnet production has decreased from a high of 74,000 t in 1998, and imports have increased to the extent that as much as 60 percent of the garnet used in the United States in 2003 was imported, mainly from India, China, and Australia; Canada joined the list of suppliers in 2005. The principal type of garnet used is almandite (almandine), because of its specific gravity and hardness; andradite is also extensively used, although it is not as hard or dense as almandite.

Most industrial-grade garnet is obtained from gneiss, amphibolite, schist, skarn, and igneous rocks and from alluvium derived from weathering and erosion of these rocks. Garnet mines and occurrences are located in 21 States, but the only presently active (2006) mines are in northern Idaho (garnet placers; one mine), southeastern Montana (garnet placers; one mine), and eastern New York (unweathered bedrock; two mines). In Idaho, garnet is mined from Tertiary and (or) Quaternary sedimentary deposits adjacent to garnetiferous metapelites that are correlated with the Wallace Formation of the Proterozoic Belt Supergroup. In New York, garnet is mined from crystalline rocks of the Adirondack Mountains that are part of the Proterozoic Grenville province, and from the southern Taconic Range that is part of the northern Appalachian Mountains. In Montana, sources of garnet in placers include amphibolite, mica schist, and gneiss of Archean age and younger granite. Two mines that were active in the recent past in southwestern Montana produced garnet from gold dredge tailings and saprolite.

In this report, we review the history of garnet mining and production and describe some garnet occurrences in most of the Eastern States along the Appalachian Mountains and in some of the Western States where industrial-grade garnet or its possible occurrence has been reported. Other natural and manmade materials compete with garnet in nearly all of the applications for which garnet can be used; garnet, however, has the advantages that it is reusable, nontoxic, and nonreactive. In addition, garnet produces much less dust than other abrasive materials, and spills are relatively benign and easy to clean up.

Introduction

Status of U.S. Industrial Garnet

Much of the following narrative is adapted from mineral information posted on the U.S. Geological Survey Web site (URL http://www.usgs.gov/), especially data from the *Minerals Yearbook* 1932–33 through 2005 and other sources identified in the text.

The United States currently consumes an estimated 16 percent of global garnet production. U.S. production of industrial garnet reached an all-time high of 74,000 t in 1998 (fig. 1), or 33 percent of global production for that year. The United States became a net importer of garnet in 2000, when net reliance on imports was 22 percent of apparent consumption. Since then, the United States has maintained its reliance on foreign sources of garnet to meet domestic demand. Apparent consumption reached a high of 83,200 t in 2003 and declined to 50,300 t in 2005. Imports were 60 percent of apparent consumption in 2003, 48 percent in 2004, and 40 percent in 2005 (Olson, 2006); imports reached a high of 36,500 t in 2004 and decreased to 30,400 t in 2005. As of 2005, the United States and India were tied for greatest production capacity at 120,000 t, followed by China (100,000 t). Australia produced 155,000 t in 2005 (Olson, 2006), presumably a measure of its most recent production capacity. The Crystal Peak garnet (andradite and grossularite) deposit in British Columbia has a targeted annual production rate of 60,000 t (Grond and others, 1991), which, if attained, would be a minimum estimate of Canadian production capacity.

Composition of Garnet

Several compositional schemes exist for garnet classification. In one scheme, garnets are grouped into two solid-solution series: the pyralspite series, which includes pyrope (Mg rich), almandite (Fe rich), and spessartite (Mn rich); and the ugrandite series, which includes grossularite (Ca rich), andradite (Ca-Fe-Ti rich), and uvarovite (Ca-Cr rich). No continuous variation in composition between members of these two series was considered (Winchell, 1945; Winchell and Winchell, 1951; Deer and others, 1967); however, some studies have suggested that the various members could be completely miscible under certain conditions (Hariya and Nakano, 1972).

Other workers have suggested quasi-ternary solid solution in the system pyrope-grossularite-almandite-spessartite, although the matter was debated (see summary in Wood, 1981). A second classification scheme groups the four end members grossularite, pyrope, almandite, and spessartite, which contain aluminum, separately from the nonaluminous garnets andradite and uvarovite. A third classification scheme, used in table 1, describes garnet by the general chemical formula $A_3B_2(SiO_4)$, where A is such divalent metals as Ca, Fe, Mg, and (or) Mn and B is such trivalent metals as Al, Cr, Fe, Mn, and, in rare garnets, V, Ti, Zr, and (or) tetravalent Si (Harben, 2002). Deer and others (1967) pointed out that garnet species are theoretically possible in which divalent metals, Ca, Fe, Mg, and Mn, are combined with trivalent metals, Al, Cr, Fe, and Mn.

Almandite [also almandine; $Fe_3Al_2(SiO_4)_3$; chemical formulas modified from Deer and others, 1967] is the principal garnet mineral for industrial uses because of its specific gravity (max 4.3; Carmichael, 1989), which is higher than that of other garnet minerals, and its hardness (7.5–9 Mohs and 1,498 Knoop; Winchell, 1945; Austin, 1994b; Harris, 2000; 7–>8 Mohs, Harben, 2002). The Knoop hardness scale is determined by measurement of the indentation made by a pyramidal diamond on a polished section of test material (Harben, 1978). Diamond has a hardness of 10 on the Mohs scale (or 40 if the scale were linear), equivalent to 8,200 on the Knoop scale.

Andradite [$Ca_3Fe_2(SiO_4)_3$], the least dense garnet mineral, is suitable for some industrial uses. Spessartite [$Mn_3Al_2(SiO_4)_3$] and grossularite [also grossular; $Ca_3Al_2(SiO_4)_3$] have also been included as species of industrial-grade garnet (see below). Andradite, almandite, and pyrope [$Mg_3Al_2(SiO_4)_3$] are the garnet minerals most likely to form gem-quality crystals.

Garnets come in every color but blue (table 1; Austin, 1994b), and some are colorless and transparent. They occur in a wide variety of metamorphic rocks, as well as in granites, pegmatites, highly siliceous volcanic rocks, and high-temperature veins. Because garnet, especially almandite, is dense and resists abrasion, it commonly occurs in detrital sediment, such as gravel and heavy-mineral sand deposits, worldwide.

Uses of Garnet

Garnet may have been used as an abrasive as early as 1810 in the United States (see subsection below entitled "New York"). Garnet was first used for coated sandpaper in 1878. Although garnet sandpaper is still in use, the industrial technology that employs garnet has expanded to include abrasive airblasting, water filtration, abrasive powder, and waterjet cutting. Abrasive-powder uses include glass and ceramic polishing, antislip paints, and antiskid surfaces. Industrial sectors that utilize garnet include the petroleum and petrochemical industry, for cleaning pipes, secondary recovery, and oil-field stimulation; filtration plants; aircraft and automobile manufacturing; shipbuilding; construction and maintenance of structural steel and steel pipelines; painting; power generation; wood-furniture finishing; electronic-component manufacturing; and roughing, frosting, and engraving of glass and dimension stone. A small amount of garnet is used in wellpacks in deep oil wells, where temperature, pressure, and acidity are high. In this application, garnet sand, a porous medium, is forced into fractures to keep them open for enhanced oil recovery. By 2002, use of garnet in waterjet cutting was second only to its use in abrasive airblasting in the United States. Garnet is used in conjunction with coal and silica sand for filtration media that can be cleaned by backflushing. After backflushing, the three minerals fall back into approximately the same arrangement, owing to their density differences.

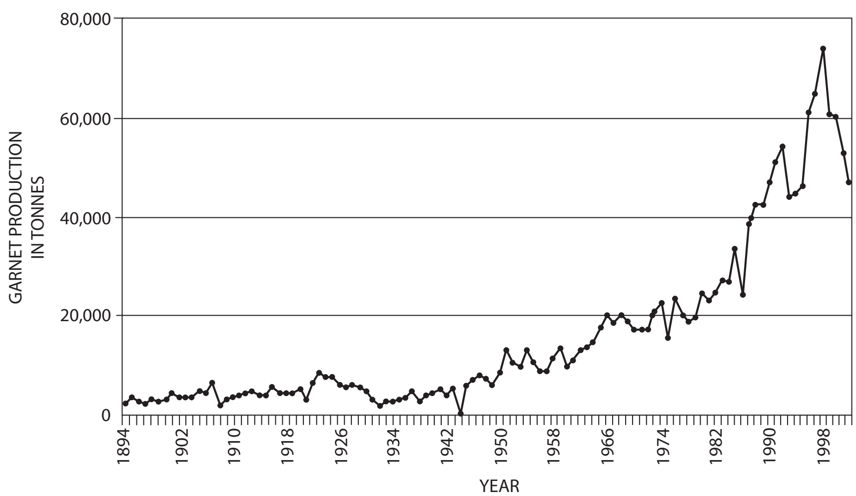

Figure 1. U.S. industrial garnet production for the years 1894–2002. Data from *Minerals Yearbook* 1900–2002.

Table 1. Principal garnet varieties and their characteristics.

[Do., ditto]

Mineral	Formula	Color	Luster	Crystal shape	Specific gravity	Hardness (Mohs)	Importance	Solid solution
Almandite (almandine).	$Fe_3Al_2(SiO_4)_3$	Dark red, brownish black	Transparent to translucent, vitreous to resinous.	Dodecahedrons or trapezohedrons.	4.1–4.3	7–7.5	Most important commercial garnet.	Crystals contain pyrope and spessartite molecules.
Andradite	$Ca_3Fe_2(SiO_4)_3$	Yellowish green; greenish brown, red-brown, dark gray, black.	Transparent to opaque, vitreous to resinous.	do	3.7–4.1	6.5–7	Second to almandite as a gem variety of commercial garnet.	Crystals contain grossularite and (or) spessartite. Melanite is dark brown or black and contains TiO_2.
Grossularite (grossular).	$Ca_3Al_2(SiO_4)_3$	Colorless, white, gray, yellow-brown, green, greenish brown.	– – –	do	3.4–3.6	6.5–7	Little commercial significance.	Substitutes with andradite.
Pyrope	$Mg_3Al_2(SiO_4)_3$	Pink, red, crimson to black purplish red.	Transparent to translucent, vitreous.	Rounded or embedded grains	3.5–3.8	6.5–7.5	Little commercial significance other than as an admixture.	Normally mixes with almandite and grossularite.
Spessartite (spessartine).	$Mn_3Al_2(SiO_4)_3$	Black, dark red, violet-red, brownish red, brown, yellow-orange.	do	Dodecahedrons or trapezohedrons, commonly striated.	3.8–4.3	7–7.5	Rare	Mixes with grossular and andradite.
Uvarovite	$Ca_3Cr_2(SiO_4)_3$	Dark red, emerald green	do	do	3.4–3.8	6.5–7	do	Mixes with grossularite and andradite.

Recent trends in the market include an increasing demand for fine garnet, including micronized garnet for the electronics industry, and an increasing number of small-volume users. As of 2005 (Olson, 2006), major domestic end uses for garnet were in abrasive airblasting (35 percent), waterjet cutting (30 percent), water filtration (15 percent), abrasive powders (10 percent), and other uses (10 percent) (fig. 2).

Industrial Specifications

Specifications for industrial garnet are directly related to specific end use, and testing procedures vary widely between different industries. For example, Austin (1994b) and Harben (2002) described organizations and standards for several industrial garnet markets and end uses. American National Standards Institute (ANSI) specification B74.18–1977 details testing methods and grading guides for grains used on abrasive-coated products (sandpaper). ANSI specification B74.12–1976 dictates the grain-size distribution and other qualities for abrasive use in various industrial tools, such as grinding and polishing wheels. Sandblasting media for U.S. Navy vessels must meet the standards of military specification MIL–A–22262(SH), including the contents of total metals and soluble metals, radiation, and certification by the California Air Resources Board (CARB), which requires all loose-grain abrasives used in California to be certified at the CARB testing facility. The CARB tests materials according to "Methods of Test of Abrasive Media Evaluation," "Test Method No. 371–A," and its title 17, subchapter 6, entitled "Abrasive Blasting"; copies of these requirements are available from the CARB office in Sacramento, Calif. As of 1993, air-pollution-control agencies in Louisiana, Minnesota, and Utah had adopted the CARB tests and permitted only CARB-certified abrasives to be used in State projects requiring sandblasting. Testing procedures and standards are focused on the environmental impact of sandblasting abrasives, not on such qualities as cutting performance or efficiency.

The International Organization for Standardization (IOS) has developed specifications for the preparation of steel surfaces before application of paint and (or) related products (International Organization for Standardization, 1992). As of 1996, the IOS was preparing specifications for nonmetallic blast cleaners that include garnet. According to their proposed specifications, specific gravity should range from 3.5 to 4.2, hardness should exceed 6.5 Mohs, moisture content should be

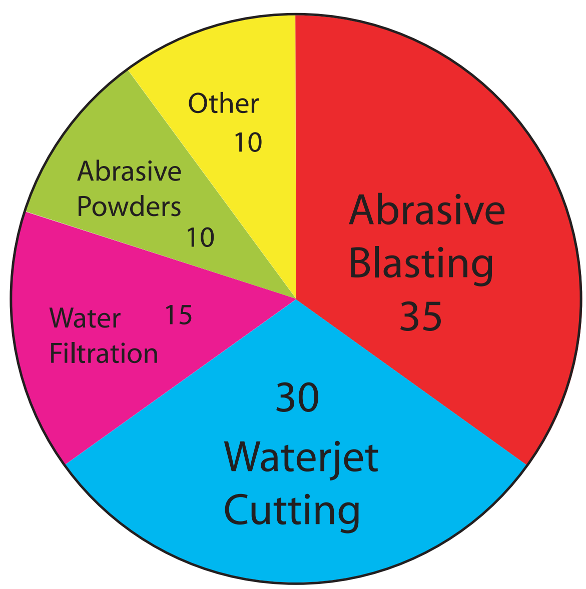

Figure 2. Pie chart showing principal domestic uses of garnet (in percent). Data from Olson (2005a).

less than 0.5 weight percent, and content of water-soluble chlorides should be less than 0.01 weight percent. The most widely used particle-size grades used in blast cleaning in the United States are 0.1–0.3, 0.2–0.6, and 0.2–1 mm (Austin, 1994b).

No definitive method exists for testing the quality of garnet or any other loose-grain abrasive except by application; however, tests and examinations that can indicate a garnet's probable abrasive performance are available. Fracture, sharpness, shape, and structure can be studied microscopically. Hardness and fragility can be evaluated by putting a sample between two glass slides and rubbing them together, which measures the relative scratch hardness of the grains and their degree of attrition (see ANSI standard B74.8.1965, "American Standard Test for Ball Mill Test for Friability of Abrasive Grains"). The U.S. National Institute for Standards and Technology has developed an apparatus for evaluating the abrasive quality of corundum that is adaptable for testing any loose-grain abrasive. Abrasive quality can be tested by measuring the amount of material removed either by weight or by volume. If it is either too hard or too coarse for use on a certain material, an abrasive will cause deep scratches that cannot be removed by subsequent finishing. If it does not have a proper grain shape or does not maintain sharpness during breakdown, an abrasive may burn or gouge the material being abraded.

The American Water Works Association (AWWA) has established specification B100–89, "Standards for Filtering Materials," which did not cover such high-density media as garnet and ilmenite as of 1993 (Austin, 1993b), although the AWWA planned to include garnet and ilmenite in an updated version. Specifications for garnet would include particle shape, specific gravity, effective grain size, coefficient of grain-size uniformity, content of acid-soluble impurities, and radioactive- or heavy-metal content.

Ives (1990) developed procedures to test the qualities of filtration media, including effective size (sieve size at which 10 percent of the weight is finer), uniformity coefficient (sieve size at which 60 percent of the weight is finer), specific gravity (1.4–3.9), settling rate at 20ºC, hardness (>2 Mohs), sphericity (0.65–0.85), acid solubility (<5 percent), and resistance to attrition (weight loss, <5 percent). The most common particle-size grades of garnet used for water filtration in the United States are 0.25–0.71, 0.3–0.84, and 1.41–4.75 mm (Austin, 1994a); garnet finer than 0.3 mm across is generally used in pressure-filtration systems. For additional information on industrial-standards organizations and on product specifications for industrial garnet, see Harben and Kuzvart (1996) and Harben (1999, 2002).

KTA-Tator, Inc. (URL http://www.kta.com/services), tests garnet and other abrasives for the AWWA and the Society for Protective Coatings (SPC, as of 1997; URL http://www.sspc.org/about/; founded as the Steel Structures Painting Council in 1950), which also provides comparative tests of garnet and other abrasives to determine whether they meet military specifications, how clean the abrasives are, how well they clean, their extent of degradation during use, and other qualities. The SPC, which is part of the Carnegie Mellon Research Institute, conducts its research carefully so as not to favor one abrasive manufacturer over another, because their representatives may be SPC members. Other abrasive-testing companies are Flow International Corp., Ingersoll Rand, and Jet-Edge, Inc.

Nearly all the grade-grain garnet processed for use as abrasive coatings is heat treated. Impurities picked up during processing generally stick to the garnet and may decrease its cleanliness and capillarity needed for adhesion to bonding agents. Investigations in the 1960s determined that heat treatment could clean garnet but that too high a temperature can damage its abrasiveness. In the mid-1960s, the abrasive-coating industry accepted uniform color standards that ensured the cleanliness of garnet surfaces; the standard color closely approaches the natural color of abrasive garnet.

In waterjet cutting, garnet grains are entrained in a high-velocity stream of water that impacts the material to be cut at high pressure (345 MPa). Waterjet cutting is most commonly used for inflammable materials, such as in oil refineries, but also for underwater steel structures and for shaping such materials as marble, granite, automotive glass, textiles, plastics, aluminum, and high-strength steel. Garnet for this use needs to be especially hard, such as almandite, with sharp, angular cutting edges. For ductile materials, softer and less expensive abrasives, such as slag, may be better than garnet (O'Driscoll, 1993). Garnet as coarse as 1 mm across is favored for cutting steel. For most other cutting, 0.18–0.25 mm (60–80 mesh) is the most popular particle-size grade, accounting for 90 percent of the garnet used in waterjet cutting in the United States (Austin, 1994b).

Evaluation of Garnet Deposits

Evaluation of garnet deposits to determine their suitability for industrial production includes the following factors: size and grade of reserves, mining conditions, garnet quality, location of the deposit relative to markets, and milling costs. Reserves should contain a minimum of 2 million t of ore with a cutoff grade of about 20 weight percent garnet. Various environmental, social, and physical factors can preclude mining, such as proximity to houses, historical sites, national monuments, archeologic or paleontologic sites, wildlife refuges, and municipal watersheds, and may include local zoning regulations, environmental regulations, and configuration and structure of the deposit. After initial crushing, almandite or almandite-pyrope should be present as fine- to coarse-grained discrete crystals that are free of such inclusions as quartz, mica, hornblende, feldspar, and alteration products. As discussed below, andradite and grossularite also have their uses but are inferior to almandite in specific gravity and hardness. The specific gravity and hardness of the garnet should be uniform, and the crystals should not be highly weathered or friable. Any cleavage within the garnet should be evaluated for its distribution in the deposit and its effect on product quality. If the deposit is not near major market areas, it must be near adequate inexpensive transportation; railways or waterways are preferred. The deposit should also be reasonably accessible by road. An ideal ore contains garnet that can be liberated with minimum crushing and recovered by gravity/density-based methods of mechanical concentration. Portions of the concentrate may have to be ground to smaller grain sizes in order to obtain garnet of appropriate purity.

Markets for Garnet

Domestic garnet consumption is estimated to have decreased from 83,200 t in 2003 to 58,600 t in 2004, and to 50,300 t in 2005, or by 40 percent since 2003 (Olson, 2006). The high in apparent consumption in 2003 was assumed to be a result of lower prices for stock sales from Patterson Materials Corp. and cheap imports.

The price of industrial garnet varies widely, depending on its type, source, quantity purchased, and end use (fig. 3). In 2004, the price for most crude concentrates ranged from $50 to $150 per tonne, and prices for most refined garnet from $60 to $450 per tonne (Olson, 2004a, 2006; $300–600 per tonne for garnet used in waterjet cutting; Grond and others, 1991).

In 2003, principal garnet uses worldwide were abrasive blasting, 60 percent; waterjet cutting, 20 percent; filtration media, 10 percent; and other uses, 10 percent (fig. 4; Olson, 2004). Global garnet production in 2005 was estimated at 312,000 t from Australia, Canada, China, India, and the United States (Olson, 2006; Gorill, 2003, estimated 440,000 t for 2003). Domestic garnet production was 28,400 t, or about 9.4 percent of global production, in 2004, in contrast to 74,000 t, or 33 percent of global production, in 1998, when domestic garnet production peaked; estimated production in 2005 was a little less than in 2004 (Olson, 2006), or 9.1 percent of global production. Global production of 312,000 t in 2005 (Olson, 2006), if consumed, indicates that worldwide use of industrial garnet has increased 39 percent since 1998 (224,000 t).

The United States currently exports more than 10,000 t of garnet per year (11,000 t in 2003, 10,900 t in 2004, and 13,300 t in 2005; Olson, 2006), most of which comes from New York and has special fracture characteristics. The garnet breaks down during use but fractures along a cleavage that preserves sharp cutting edges of the grains. The U.S. began exports of 10,000 t or more annually in 1996, and did so sporadically before then.

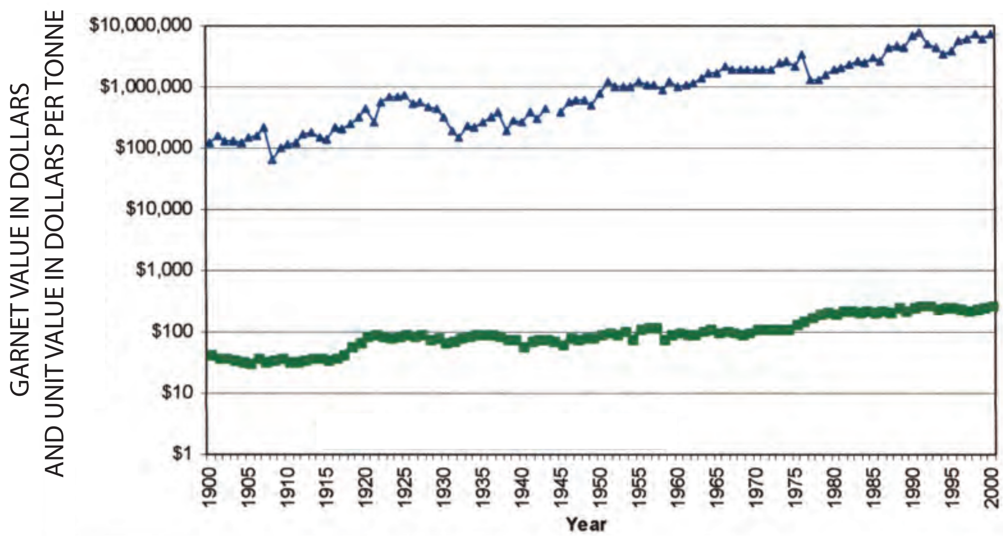

Figure 3. U.S. garnet value and unit value for the years 1900–2000, plotted using raw dollar value (not based on 1998 dollar values). Data from industrial garnet statistics, 1900 through 2000; last modified April 17, 2003.

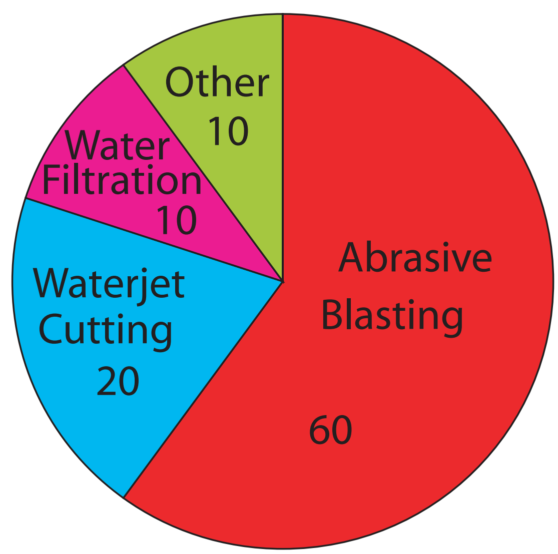

Figure 4. Pie chart showing principal uses of garnet (in percent) worldwide. Data from Olson (2004).

The U.S. garnet industry must compete with foreign suppliers that have extremely large, easily and cheaply mined garnet deposits. The largest garnet producers in Idaho and New York have become parts of international corporations (Barton Mines Co., LLC, and WGI Heavy Minerals, Inc.; see below), a move that may soften the economic impact of imports, at least for these two companies, although problems affecting production abroad may arise in foreign operations (see below).

Garnet resources are known in Australia, Canada, Chile, China, the Czech Republic, India, Norway, Pakistan, Portugal, Russia, South Africa, Spain, Sri Lanka, Thailand, Turkey, and the Ukraine. The first recorded U.S. import of industrial garnet was from Spain in 1910. Imports of industrial garnet have principally been from Australia, China, India, and, recently, Canada. Since 2000, the United States has been a net importer of garnet (Austin, 2002a, 2003a, 2004, 2005a, 2006). Of the garnet imported from 2001 to 2004, 39 percent was from Australia, 26 percent from India, 18 percent from China, 12 percent from Canada, and 5 percent from other countries (Olson, 2005a, 2006). At present, natural garnet, emery, natural corundum, and other natural abrasives, including abrasive coatings, are imported duty free.

International Garnet Reserves

In 2004, the United States had estimated garnet reserves of 5 million t and a reserve base of 25 million t (Olson, 2006). Large domestic garnet resources are concentrated in coarsely crystalline gneiss, schist, and granite in Maine, New Hampshire, eastern New York, and North Carolina. Garnet placers are important in Idaho, Montana, North Carolina, and Oregon. Garnet mined in southwestern Montana in 1996–2002 was from dredge tailings and saprolite; production in 2005 was from placers. Skarn deposits in southwestern New Mexico contain abundant garnet, some of which may be economic to mine, although a recent study of recovery of garnet in mill tailings (Cetin and others, 1996) was disappointing. In comparison, according to Olson (2006), Australia, the world's largest garnet exporter, has reserves of more than 1 million t and a reserve base of 7 million t; China has estimated moderate to large reserves and reserve base; India has official reserves of 90,000 t and a reserve base of 5.4 million t; and all other countries combined have total estimated reserves of 6.5 million t and a reserve base of 20 million t (Olson, 2006).

Canada has garnet deposits in British Columbia, Labrador, Manitoba, New Brunswick, Newfoundland, Nova Scotia, Ontario, and Quebec (Harben and Kuzvart, 1996). Garnet deposits in the Sudbury area, Ontario, and in Labrador, Newfoundland, Nova Scotia, and Quebec consist largely of almandite in high-grade regionally metamorphosed rocks, with garnet grades ranging from 15 to 100 weight percent. Garnet deposits (andradite and grossularite) in western Canada are mostly in skarns. One of these deposits, the Crystal Peak deposit on Mount Riordan, British Columbia, has at least 40 million t of reserves containing 80 volume percent garnet (andradite and grossularite; Grond and others, 1991; Mathieu and others, 1991) and an additional 60 million t of "geological" reserves (garnet content not indicated); total Canadian garnet reserves are probably much larger.

Australian and Indian garnet resources are overdue for a reevaluation. In 1997, one Australian garnet mine, GMA Garnet Pty Ltd. (formerly Target Mines Ltd.?; Austin, 1993b), a joint venture between the Barton Mines Co., LLC, in the United States and Hancock and Gore Ltd. (currently HGL Ltd.) in Australia, reported proven reserves of 4 million t and probable reserves much higher in high-grade placers in dunes (avg 23 weight percent garnet) that extend for about 12 km along the Australian coast at Port Gregory, 100 km north of Geraldton in Western Australia (Kendall, 1997; Harben and Kuzvart, 1996). In addition, GMA secured mining rights to probable reserves of about 16.9 million t of heavy-mineral-bearing alluvial sand averaging 19.5 weight percent heavy minerals of which almandite composes 90 percent; the remaining 10 percent is ilmenite, quartz, and zircon. Annual Australian garnet-production capacity has increased to 155,000 t (Olson, 2006), close to half of which may be from GMA. As of 1997, this garnet was used mostly for abrasive blasting; polishing powders, filtration media, and waterjet cutting account for smaller sales. Australia supplies the most popular size class of garnet exported to the United States for abrasive blasting (particle-size grade, 0.25–0.59 mm; Austin, 1993b).

Descriptions of the extensive garnet beach sands in southeastern India (table 2; WGI Heavy Minerals, Inc., 2002) suggest that India's recognized reserves (90,000 t) and reserve base (5.4 million t) are underestimated. WGI Heavy Minerals, Ltd., the parent entity of the Emerald Creek Garnet Co. in Idaho, has a subsidiary, Transworld Garnet India Pvt. Ltd., with lease areas estimated to contain resources of more than 10 million t of garnet. From April 1997 to December 2003, Transworld produced 258,000 t of almandite (annual production rate, approx 38,680 t; WGI Heavy Minerals, Inc., 2004). At that time, WGI anticipated a buildup to an annual production of 140,000 t of garnet, 140,000 t of ilmenite, 12,000 t of zircon concentrate, and 4,500 t of rutile from its Indian operations—a projection that would approximately double annual Indian garnet production, according to Roskill Information Services, Ltd. (2000), but triple it according to the smaller estimate (65,000 t for 2005) by Olson (2006).

In general, the garnet market is highly competitive, and so producers need to minimize production costs and develop the deposits from which garnet is produced in combination with other minerals (ilmenite, zircon, sillimanite, kyanite, staurolite). These conditions can be met in the beach deposits of southeastern India that are mined by government-mandated hand methods and hand loading of dump trucks (hoe and headbasket), among other stipulations (WGI Heavy Minerals, Inc., 2004).

Risks of Production Abroad

Unforeseen difficulties have cut into Transworld Garnet India Pvt. Ltd.'s production plans, illustrating some of the

Table 2. Mineral resources of WGI Heavy Minerals, Inc.

[All values in thousands of tonnes]

Location	Garnet	Ilmenite	Rutile	Zircon	Sillimanite
Benewah County, Idaho[1] -------	527	– –	– –	– –	– –
Tamil Nadu, India[1] --------------	1,105	168	– –	– –	– –
Andhra Pradesh, India[2] ---------	[3]8,636	[3]4,853	[4]760	[4]170	[5]4,830
Total --------------------------	10,268	5,021	760	170	4,830

[1]DDH Geomanagement Ltd. resource estimate.
[2]Reserve/resource value based on data from drilling to a depth of 2.9 m over an 11.2-km^2 area, representing less then 15 percent of mineral properties under existing or pending leases.
[3]Strathcona Mineral Services Ltd. resource estimate.
[4]Reserve/resource value based on data from drilling to a depth of 2.9 m over an 11.2-km^2 area.
[5]Internal calculation based on resource estimate; currently no market value.

risks that may curtail foreign garnet production. In 2002, because of the delay in bringing micronized garnet to market by way of its joint-venture plant in Chennai, India, over a 2-year period and small market demand, Transworld wrote off $580,000 in net expenditures connected to the plant (WGI Heavy Minerals, Inc., 2003). More serious issues (WGI Heavy Minerals, Inc., 2005b, c) include lease applications, manufacturing processes, unanticipated legal complexities in governmental processes, resolution of generations of undocumented ownership on numerous parcels of land, export permit, and increased professional fees related to a review of their Indian operations. All of the above-mentioned legal obstacles were believed to have been resolved in 2002 (WGI Heavy Minerals, Inc., 2003), clearing the way for Transworld to produce and export garnet. According to WGI, lack of reasonable and timely solutions to these difficulties in India may require Transworld to write off their substantial assets in Tamil Nadu and Andhra Pradesh.

Garnet resources that are also known in Sri Lanka have been pursued by WGI Heavy Minerals, Inc. After a late 2001 ceasefire between government forces and separatists in Sri Lanka, a 50-percent subsidiary of WGI received environmental clearance for the development of heavy-mineral deposits (garnet, ilmenite, rutile, and zircon; Kuo, 2002). Plans for 2002–3 included conversion of mining leases into permits, development of a mining program, and drilling of new areas for heavy minerals. WGI's operation received a 10-year mining lease on a heavy-mineral deposit at Hambantota on the southeast coast (Kuo, 2004), and an independent technical report was planned for early 2005. Some of the legal issues that Transworld encountered in India are also present in Sri Lanka (WGI Heavy Minerals, Inc., 2005b). In addition, as a result of the December 2004 tsunami that struck the coast of Sri Lanka, the Coastal Conservation Department asked the WGI subsidiary not to mine the dunes on their mineral leases (WGI Heavy Minerals, Inc., 2005c), and so WGI's Sri Lankan project is in doubt.

Competition from Other Natural and Manmade Abrasives

U.S. garnet has to compete with various natural and manmade abrasives for its share of the domestic abrasives market. Some materials compete with garnet but entail sacrifices in quality or cost. For abrasive airblasting, competing materials include fused alumina, Si carbide, steel shot, specular hematite, magnetite, silica sand, coal boiler slag, metallic slag, staurolite, corundum/emery, diatomite, feldspar, nepheline syenite, olivine, perlite, and ilmenite. For abrasive coatings, competing materials include fused alumina, Si carbide, and corundum. For waterjet cutting, competing materials include alumina, olivine, and several manmade materials. Precision abrasive powders, other than garnet, include Ce oxide, diamond, fused alumina, Si carbide, pumice, and tripoli. Filtration media, in addition to garnet, include activated carbon/anthracite, asbestos, cellulose, diatomite, ilmenite, magnetite, olivine, perlite, pumice, silica sand, and plastics. Effective backflushable filters use garnet, silica sand, and anthracite together. Diamond, corundum, and fused alumina compete in lens grinding and many lapping operations. Quartz sand, Si carbide, and fused alumina compete in finishing of plastics, wood furniture, and other products. For nonskid surfaces, competing materials include alumina, emery, and silica sand. Oil-well gravel packs can be made from calcined bauxite instead of garnet (Harben, 2002). The most commonly used abrasive in the United States as of 2001 is silica sand, followed by coal boiler slag (fig. 5). Garnet made up only 2 percent of the domestic abrasives industry then, and its usage has shown no sign of increasing substantially.

Advantages of Garnet

Garnet has many advantages that may not have been fully exploited industrially. For example, garnet is free from toxic elements and chemically inert. Airblasting with garnet produces less dust than with silica sand, which can cause silicosis and cancer—unless, of course, siliceous rock is being blasted. Slag can also be a potential source of toxic heavy metals (Grond and others, 1991). Low concentrations of dust allow operators of airblasting equipment to have a relatively unimpeded view of the target. Garnet is nontoxic if released, and no special equipment or precautions are required in managing a release unless the garnet was contaminated during use. In comparison with silica sand, which currently is the most commonly used abrasive in the United States, garnet requires a smaller storage area because less abrasive is needed to do the same job and garnet is not hygroscopic. Garnet can also provide greater cutting speed (Crandall, 1950). Hauling and removal of garnet and residue may be less costly than disposal of silica sand; however, volumetric considerations may be offset by the density of garnet. Some garnet can be recovered and reused as many as eight times; recycling systems are available that separate usable >100-mesh garnet from sludge and prepare the garnet concentrate for reuse (for example, Jet-Edge, Inc.; URL http://www.jetedge.com/products/abre-cycling.html). Recycling could negatively impact domestic markets if recycled garnet substitutes for newly mined garnet. At present, however, only a small amount of garnet is recycled (Olson, 2006). In addition, garnet characteristics can be tailored to end use. Many of these characteristics make garnet a tool that can improve production and safety on the job and potentially lower disposal costs.

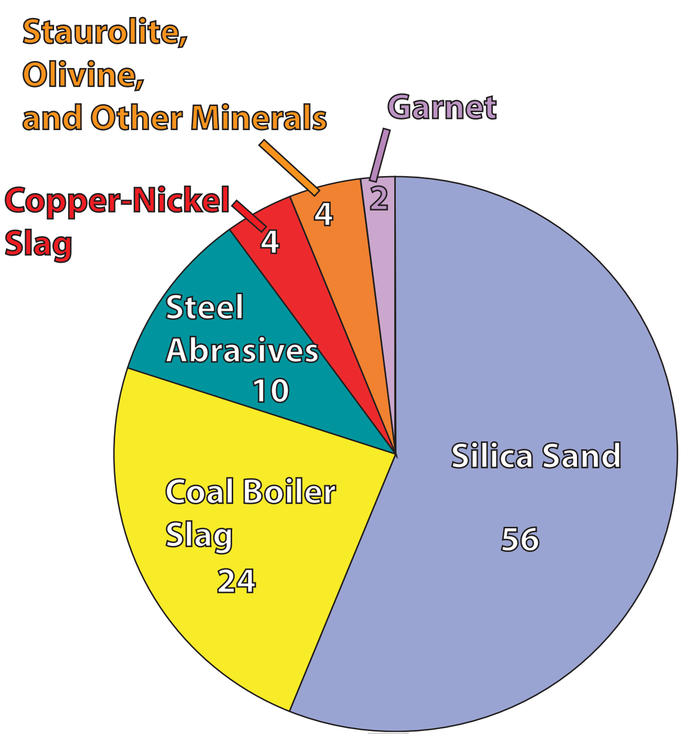

Figure 5. Pie chart showing U.S. abrasive-mineral demand (in percent) for the year 2001.

U.S. Garnet Deposits

Overview

The purpose of this report is to describe the status of U.S. industrial garnet deposits, their locations, history, and market forces. Information for parts of the following text is from the *Minerals Yearbook* 1931–32 through 2005 (Hatmaker and Davis, 1933; Bowles and Davis, 1934; Davis, 1935; Johnson and Davis, 1936, 1937; Johnson and Shauble, 1939; Metcalf, 1940, 1941, 1943a, b, 1949, 1950, 1951; Metcalf and Cade, 1945, 1946; Metcalf and Holleman, 1948; Chandler and Tucker, 1953, 1958a–d, 1959, 1960, 1961; Chandler and Marks, 1954, 1955, 1956; Cooper and Tucker, 1962, 1963; Ambrose, 1964, 1965, 1966; U.S. Bureau of Mines staff, 1967, 1981, 1987, 1993–94a, 1993–94b, 1995; Cooper, 1968; Wells, 1971; Clarke, 1972, 1973, 1974, 1975, 1976, 1977; Adams, 1978, 1980; Baskin, 1980; Smoak, 1982, 1983, 1984, 1985; Austin, 1988, 1989, 1990, 1991a, b, 1992, 1993a, b, 1994a, b; Balazik, 1995a, b, 1996, 1997a, b, 1998, 1999, 2000a, b; Harben and Kuzvart, 1996; U.S. Geological Survey, 1997, 2000, 2001, 2002a, b, 2003, 2004, 2005a–d; Harben, 1999, 2002; Olson, 1999, 2000, 2001a–c, 2002a, b, 2003a, b, 2005a, b, 2006).

Garnet deposits occur in Alaska, Arizona, California, Colorado, Connecticut, Georgia, Idaho, Maine, Montana, Nevada, New Hampshire, New Mexico, New York, North Carolina, Oregon, Pennsylvania, South Carolina, Tennessee, Utah, Vermont, and Virginia. As of 2005, four mines were in operation for industrial-grade garnet: one in northern Idaho, one in southwestern Montana, and two in New York.

The single most consistent U.S. producer of almandite is the Barton Mines Co., LLC, in Warren County, N.Y. Andradite has been produced as a byproduct of wollastonite mining from 1952 to 2005, most recently by NYCO Minerals, Inc., in Essex County, N.Y. The International Garnet Abrasive Co. Inc. in Clinton County, N.Y., processes and sells all the garnet produced by NYCO. The formerly active mine of Patterson Materials Corp. in Dutchess County, N.Y., was closed in 2002, but the company continued to sell stockpiled garnet. The Emerald Creek Garnet Co. (formerly Garnet Mines, Inc.) in Benewah County, Idaho, has produced garnet continuously since production began there in 1940. Garnet was produced from Idaho black sand placers in central Idaho from 1952 to 1966. One or more garnet-producing mines have been located in other States: New Hampshire, from 1928 to 1939, was the leading U.S. garnet producer of the 1930s; Vermont, from 1939 to 1941; Maine, from 1978 to 1988; Connecticut; and North Carolina, most recently the Celo Mines, with garnet production from 1936 to 1944 incidental to mining kyanite. Florida produced ilmenite from polymineralic beach and dune sand from the mid-1940s to the present, and garnet in 1952–55 and 1957. Garnet was mined sporadically in southwestern Montana in the 1990s through 2005. At present, garnet mines and occurrences in other States, including Alaska, Arizona, California, Colorado, Nevada, Pennsylvania, South Carolina, Tennessee, Utah, and Virginia, have largely been exploited for mineral specimens and gem stones.

New York

Geologic Setting

Currently, all active garnet mines in the Eastern United States are in eastern New York in the eastern Adirondack Mountains and the southern Taconic Range of the northern Appalachian Mountains. The oldest rocks in the Adirondacks are 1.6- to 1.9-b.y.-old anorogenic anorthosite, charnockite, and related rocks, the protoliths of which are interpreted as a bimodal caldera complex (McLelland, 1986). From 1.1 to 1.0 Ga, these rocks were affected by the widespread Grenville orogeny, which recorded closure of an ocean basin, subduction, crustal thickening, compression, and metamorphism (McLelland and Isachsen, 1985, 1986; McLelland and others, 1988, 2001). Smaller slices of similar rock occur along the crest of the Appalachian Mountains from central Vermont to east-central Alabama (fig. 6; Rankin and others, 1989a).

Bohlen and others (1980) drew isotherms, defined by the feldspar and coexisting Fe-Ti oxide geothermometer, for the Adirondack Mountains. Peak temperatures were 700–760ºC in most of the Adirondack Highlands and 750–800ºC in the High Peaks area during Grenville metamorphism. The active garnet-producing mines are in the eastern Adirondacks within a zone where maximum temperatures ranged from 650ºC to 770ºC.

The three quarries formerly operated by Patterson Materials Corp. are in the southern part of the Taconic Range, east of the Hudson River, in southeastern New York. Barth (1936) published an early account of these metamorphic rocks in Dutchess County. The Taconic Range is described in the subsection below entitled “Northern Appalachian Mountains and New England.”

Barton Mines Co., LLC

The following narrative is adapted from the reports by Harben (1978), Dickson (1982), Kendall (1992), the *Minerals Yearbook*, and other sources cited in the text.

The Barton Mines Co., LLC (most recent name), has mined almandite-pyrope garnet continuously since 1878. Its first garnet mine was at Gore Mountain, 5 km west of the town of North Creek in Warren County (fig. 7). In 1912 and 1922, the mine was called the Rogers Mine (Miller, 1912; Ladoo, 1922). In 1982, the mine at Gore Mountain closed, and the company moved its mining operations to Ruby Mountain, 8 km northwest of Gore Mountain (Kelly and Peterson, 1993) in northern Warren County. The garnet has a cleavage along which the grain breaks under stress; the cleavage is maintained after fracturing, so that the residual garnet retains its sharpness (fig. 8). This property makes the garnet especially suited for abrasive coatings. Because of its physical properties (hardness, structure), the garnet is in demand outside of North America (>10,000 t/yr). The Gore Mountain Mine is now the site of Garnet Mine Tours (URL http://www.garnetminetours.com/), which also features a shop containing a mineral collection and providing gemcutting demonstrations.

The Gore Mountain ore body was about 2 km long by 15 to 90 m wide and dipped 7–9º W. The garnet grade was 5 to 20 weight percent, averaging less than 10 weight percent (Harben and Kuzvart, 1996), although a published photograph (fig. 9) suggests that the average grade in the past may have been higher. Proposed geologic models include contact metamorphism of an olivine gabbro by a pretectonic syenite (Levin, 1950), prograde metamorphism (Bartholome, 1960), and localized influx of water at the margin of a competent metagabbro during amphibolite-facies metamorphism (Goldblum, 1988; Goldblum and Hill, 1992).

The Ruby Mountain Mine is in gabbroic gneiss (W.M. Kelly, written commun., 2003). The ore contains 5 to 15 weight percent garnet porphyroblasts, as much as 4 cm across, with the same type of cleavage as the garnet in the Gore Mountain pit (fig. 10). The amount of recoverable high-quality garnet on Ruby Mountain is estimated at 0.6 million t. The rock is mined by surface methods. The markets served by the Barton Mines Co., LLC, are, in decreasing volume, waterjet cutting, lapping television glass, finishes, and abrasive coatings; abrasive airblasting and filtration media are minor. In addition to industrial garnet, the attractive Garnet Gem Granite (garnetiferous granite) on Ruby Mountain is being quarried for polished slabs for heavily used surfaces, such as countertops and flooring. The granite contains deep-red garnets, 2 to 20 mm across, in a background of pale-green epidote or pyroxene or white feldspar and black hornblende; several color variations are available (URL http://www.bartonquarries.com/). The Garnet Stone Co. is mining the same granite near Lake Placid in northwestern Essex County for slabs for countertops, tabletops, tile, fireplaces, and landscaping.

The processes used by Barton Mines to produce industrial garnet were evolved from experience and improvements in technology. In 1924, Barton Mines constructed the first processing plant in which separation was done by jigs. In 1941, heavy-media separation was added; and in 1945, flotation. Currently, the ore is crushed and screened to a grain size of 3.36 to 3.38 mm, and the coarse fraction goes to a heavy-media circuit with a specific gravity of 3.02 for a second separation. This screened fraction goes to a flotation circuit, where it is first ground to a grain size of 0.3 mm in ball mills and then fed to flotation cells. The concentrate from the heavy-media circuit is roll-crushed, combined with float concentrate, dried, and heat-treated in a rotary kiln.

The garnet from Barton Mines supplies 10 plants that produce abrasive-coated papers and cloths: 2 each in New York and Virginia, and 1 each in Massachusetts, Michigan, Minnesota, Mississippi, Ohio, and Pennsylvania. Barton also provides most or all of the garnet for export (13,300 t in 2005).

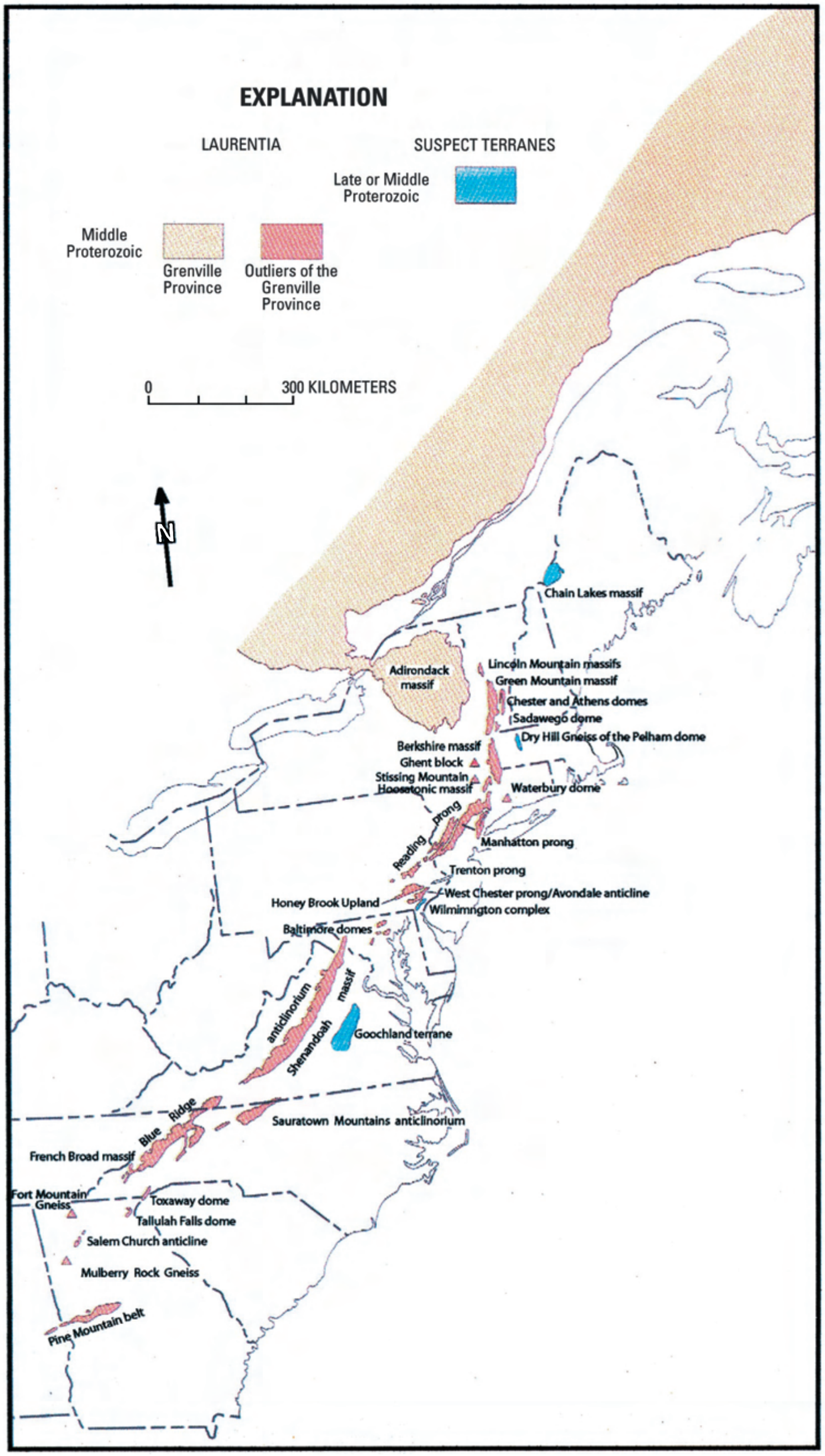

Figure 6. Sketch map of the Appalachian Mountains and New England, showing areas of basement rocks of the Proterozoic (Laurentian) continental margin and adjacent suspect terranes (adapted from Rankin and others, 1989a).

NYCO Minerals, Inc.

NYCO Minerals, Inc. (URL http://nycominerals.com/), a subsidiary of Fording Canadian Coal Trust (as of 2003; URL http://fording.ca/; formerly Fording Coal Ltd., with headquarters in Calgary, Alberta, Canada; W.M. Kelly, written commun., 2003), mines wollastonite ($CaSiO_3$; Deer and others, 1967) near Willsboro in Essex County, on the west side of Lake Champlain, producing andradite as a byproduct. The wollastonite deposit was discovered in 1810, before the mineral had been named. The deposit was initially mined for its garnet and not for wollastonite until 1936. The foregoing information suggests that garnet was used in the United States, probably as some form of abrasive, before its first use in sandpaper in 1878—possibly as early as 1810. The success of research on the uses of wollastonite at New York State College attracted the attention of Godfrey L. Cabot (Inc.), who purchased the original wollastonite deposit in 1951. Processing facilities were built within 2 years, and the product was sold under the trade name Cab-O-Lite. In 1969, the operation was sold to Interpace Corp. of New Jersey. Recognition of the lung disease asbestosis in the early 1970s led to increased sales of wollastonite, which was used in calking, sealants, joint cement, roofing, plastics, and other products for which asbestos had previously been used. In 1979, the operation was sold to Processed Minerals, Inc., which later became known as NYCO Minerals, Inc., a subsidiary of Fording Coal Ltd. of Alberta, Canada. Fording began managing the operation in 1989 and later bought it. Today, NYCO's wollastonite is used principally for ceramic tile, porcelain, and paint extender, in reinforcement fibers for friction materials and plastics, and in metallurgy.

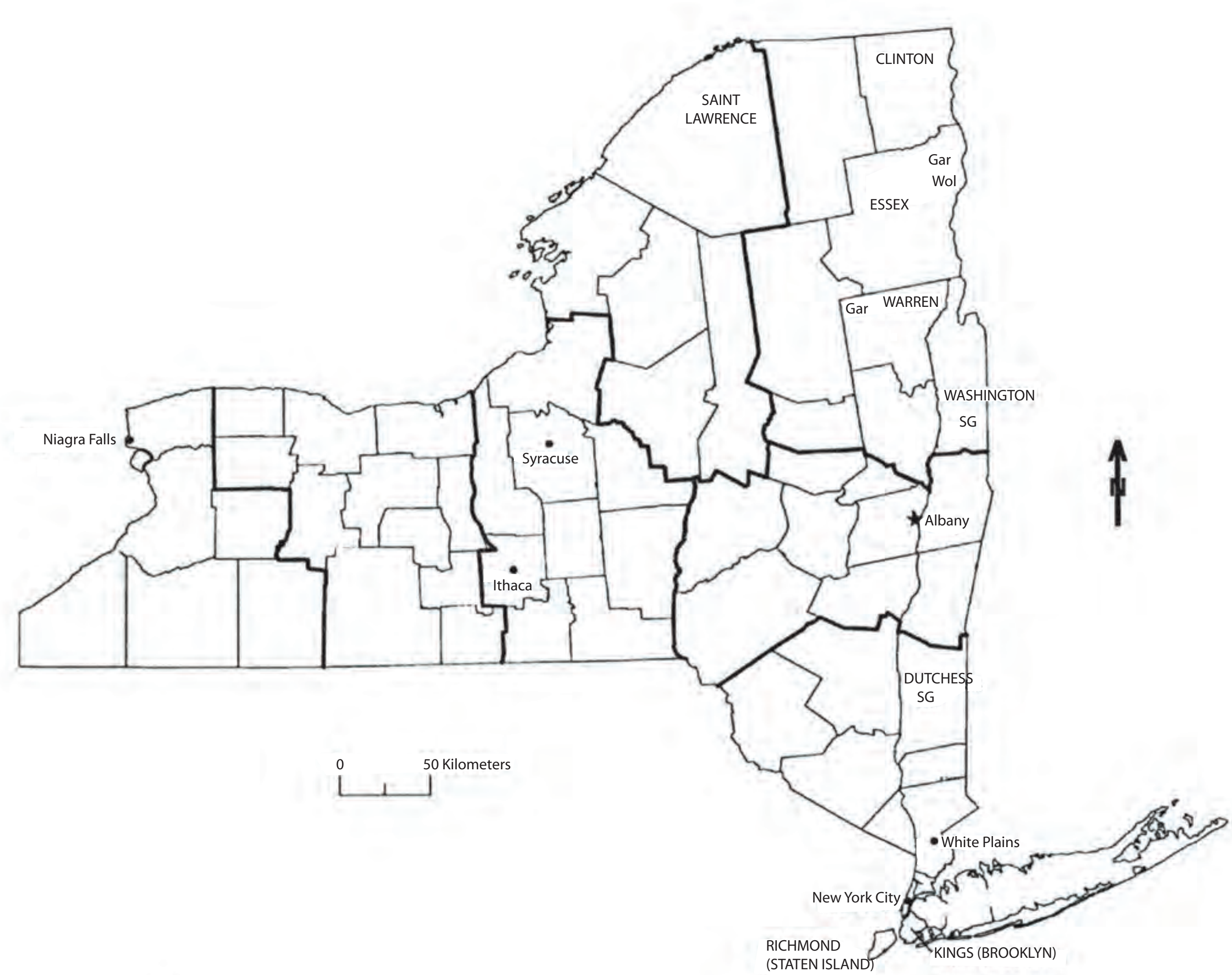

Figure 7. County map of New York, showing county boundaries and locations of counties (names in all caps) with deposits of garnet (Gar) and associated sand and gravel (SG) and wollastonite (Wol). In Dutchess County, sand and gravel includes crushed garnetiferous metamorphic rocks that are processed for andradite. Dots, cities and towns; star, State capital.

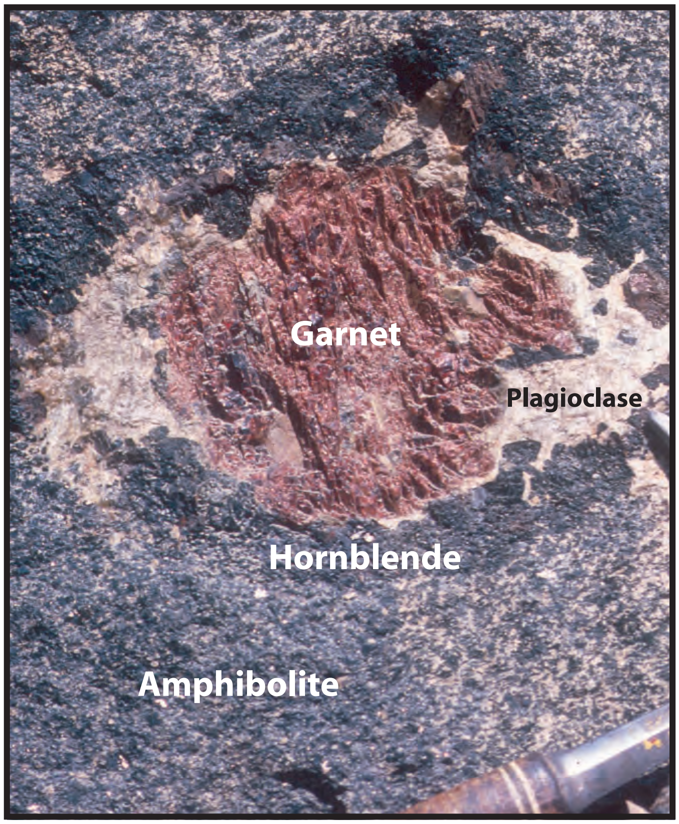

Figure 8. Garnet porphyroblast in the Gore Mountain deposit, N.Y., showing typical cleavage. Photograph courtesy of W.M. Kelly, New York Geological Survey.

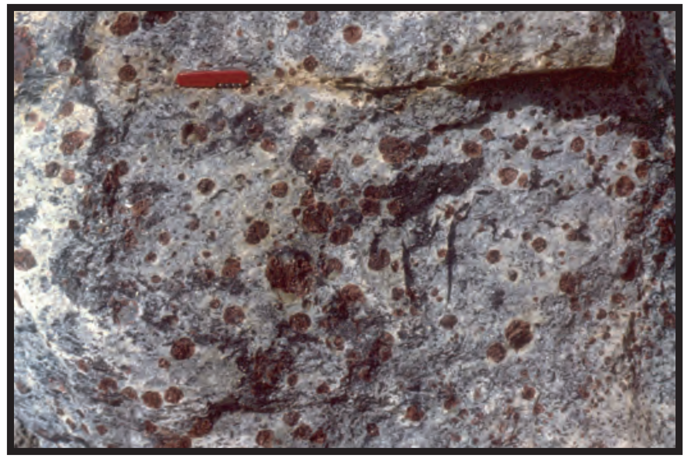

Figure 10. Garnet ore in the Ruby Mountain deposit, N.Y. Photograph courtesy of W.M. Kelly, New York Geological Survey.

The NYCO ore body is in a belt of wollastonite-bearing rocks, about 10 km long by 0.4 km wide. The largest zone of wollastonite within the belt ranges from 9 to 20 m thick, averaging 13 m. The wollastonite is intercalated with zones of andradite and Fe-rich diopside, both of which compose 10 to 20 weight percent of the ore. The ore at the Willsboro Mine in Essex County consists of as much as 60 weight percent wollastonite, with a mix of andradite, grossularite, and diopside. The ore is transported 22 km to NYCO's plant, where beneficiation of the wollastonite-garnet ore is in two stages. In the first stage, the ore is dried, crushed, screened, and then recrushed to a grain size of 1.19 mm; in the second stage, the ore passes over a series of screens for grain-size splits.

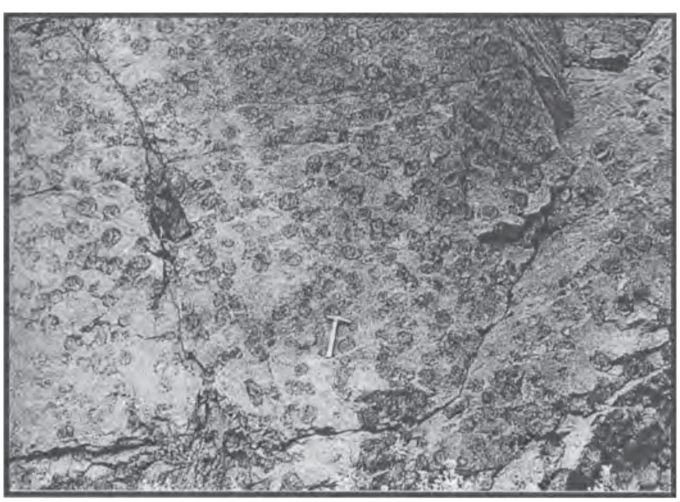

Figure 9. Garnet ore in the Gore Mountain deposit, N.Y. (Levin, 1950).

NYCO produced both refined garnet for use in abrasive airblasting and water filtration, and crude concentrate for further refining. In earlier operations, magnetic separators removed the garnet from the grain-size fractions. Four grain sizes of garnet concentrate were bagged for shipment. At present, NYCO electrostatically separates wollastonite and sells the tailings to Virginia Materials, Inc. (formerly International Garnet Abrasives Inc.), a division of Stake Technology, Ltd. Virginia Materials concentrates the garnet from tailings at its processing plant in Plattsburg in Clinton County and produces garnet that is a mix of andradite and grossularite; the crude concentrate may contain the pyroxenes diopside [$CaMg(SiO_3)_2$] and hedenbergite [$CaFe(SiO_3)_2$; chemical formulas modified from Deer and others, 1967].

Other Garnet Mines and Deposits

Patterson Garnet Corp. (formerly Patterson Materials Corp.; URL http://www.peckham.com/), a subsidiary of Peckham Industries, Inc., produced almandite as a byproduct of its construction-aggregate operations in mica-garnet schist. Peckham Industries was founded in 1924 by William H. Peckham, who began business as a highway contractor. Acquisition of aggregate facilities provided material support for highway construction. In 1968, the company changed its focus from highway construction to highway-building materials. Patterson Garnet Corp. operated aggregate quarries in Wingdale in Dutchess County, in the town of Patterson in Putnam County, and in Easton in Washington County; the quarry in Dutchess County is the one associated with garnet in the literature. As of 2002, production of byproduct almandite ceased, and the company began selling off its stock of garnet.

Patterson's almandite is especially hard, rated at 1,498 on the Knoop scale. In 2002, Patterson supplied 16- to 32-mesh garnet to WGI Heavy Minerals, Inc., to blend with their product from Emerald Creek, Idaho (Harben, 2002). In 2003, Patterson produced 50-, 80-, and 100-mesh garnet for the waterjet-cutting industry, its chief customers (URL http://www.peckham.com/); presumably, these garnet sales were from the company's stock.

Garnet ore similar to that at Gore Mountain (figs. 8, 9) was mined at the Hooper Mine, a quarry operated by the North River Garnet Co., about 5 km southwest of the town of North River in Warren County (Ladoo, 1922; Miller, 1938; Jensen and Bateman, 1981), about 1 km south of the Warren-Essex County line. When Ladoo examined the property, he considered this mine to be the principal garnet mine in the area. The ore was garnetiferous gneiss that contained almandite crystals, as much as 12 cm across but averaging less than 2 cm across. Garnet content averaged no more than 8 weight percent. The ore body was described as very large. By 1937, the Hooper Mine had been inactive for many years (Miller, 1938).

The Sanders Brothers deposit is on the north side of Mill Creek, about 3 km south of Riparius in Warren County (Ladoo, 1922). The deposit was operated on a small scale around 1922 by Warren County Garnet Mills. The ore was in a narrow band of light-red garnet and green pyroxene within fine-grained gneiss. Locally, the garnet occurred as nearly pure nodules. The garnet lacked cleavage and broke into irregular grains.

Garnet was mined on the northwest side of Humphrey Mountain in Warren County, about 13 km southwest of North Creek, before 1937 (Miller, 1938). The ore was mined along the contact between syenite and gabbro. The garnet porphyroblasts resembled the garnets at Gore Mountain (fig. 8) in having coronas of amphibole.

The Crehore Mine in Essex County, about 9 km northwest of North River, was operated by the American Glue Co. when Ladoo (1922) examined the property. The garnet occurred in a band of hornblende gneiss, about 13 m wide. Garnets, as much as 20 cm across, are in a black hornblende matrix, resembling the ore at Gore Mountain.

Other garnet deposits that were mined include those on Oven Mountain in Warren County, about 6 km south of North Creek (Miller, 1938); at a site a few kilometers south of Keeseville in Essex County; at the Rexford Mine, about 2 km south of North Creek; at the Parker Mine, southwest of Dagget Pond and about 7 km northwest of Warrenburg in Warren County; and at the Amasa Corbin Mine, about 5 km north of the town of Gouverneur in St. Lawrence County (Ladoo, 1922). At the Rexford Mine, garnets as large as 12 cm across occurred in small altered lenses of metagabbro within gneissic syenite (Miller, 1938).

The locations of both active and inactive mines suggest that significant garnet deposits are relatively common in the Warren-Essex County area, which thus contains a substantial part of the U.S. reserves and reserve base of garnet (see above). New York is one of the few States with high-quality garnet reserves suitable for abrasive coatings.

Garnet was designated the official New York State gem stone in 1969.

Northern Appalachian Mountains and New England

Geologic Setting

The metamorphic history of the rocks in New England and eastern New York is complex because more than one metamorphic episode affected the region (figs. 11, 12; Drake and others, 1989; Osberg and others, 1989). These thermal events also affected the Grenville basement (fig. 6). The Taconic orogeny consisted of a complex series of orogenic episodes from Middle Ordovician to Early Silurian time (fig. 11; Rodgers, 1971); earlier orogenic episodes may have been obscured or obliterated by deformational and metamorphic processes. Sutter and others (1985) suggested that the thermal peak for the dominant metamorphism in western New England occurred about 465 Ma, the generally accepted date for the Taconic orogeny. Radiometric and petrologic data indicate three metamorphic and structural domains of Taconic age (fig. 11): (1) a small area of relict high-pressure, low-temperature metamorphism in northern Vermont; (2) a broad area of normal Barrovian metamorphism in Vermont and eastern New York, with chlorite to garnet isograds representing a low thermal gradient; and (3) a narrow zone of Barrovian metamorphic rocks representing a steep geothermal gradient that trends northeastward from Dutchess County in New York, through Connecticut, to the Berkshire massif in western Massachusetts. Maximum metamorphic intensity coincides with maximum crustal thickening from imbricate thrusting (Berkshire massif) and recumbent folding (Manhattan prong) of remobilized North American continental crust.

The Devonian through Carboniferous Acadian orogeny in New England was accompanied by regional metamorphism (fig. 12) that occurred in two pulses (Osberg and others, 1989). Structural and textural relations date the earlier episode at about 394 Ma and the younger episode at about 360 Ma. At higher structural levels, metamorphism is discontinuous and occurred over a period of 30 m.y. Contact metamorphism associated with plutonism ranges into the Carboniferous.

Maine

For years, rockhounds collected specimens of several minerals, including garnet, from the vicinity of old mines, quarries, and mine dumps, mostly in Oxford County (fig. 13; Fulkerson, 1974, 1976). Gem and specimen garnet were also reported from Androscoggin, Washington, and York Counties (Metcalf and Otte, 1961).

In 1977, Industrial Garnet Extractives, Inc., developed a garnet quarry at Wing Hill, north of Rangeley in Franklin County, western Maine (Barton and Doyle, 1981). The ore body trends east-west, is 1,000 m long, and is as much as 700

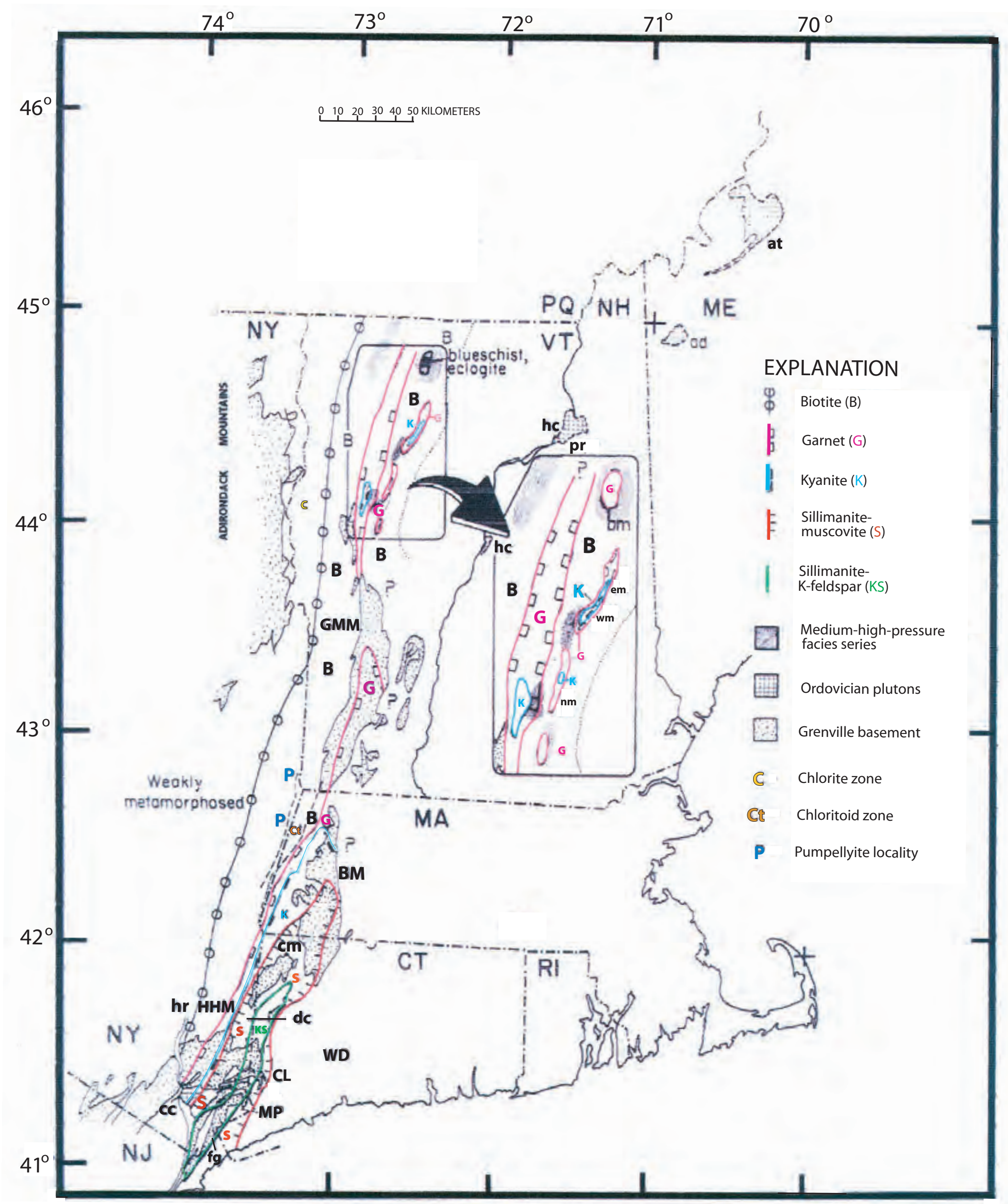

Figure 11. Isograd map of Taconic metamorphism in New England (adapted from Drake and others, 1989a). Metamorphic grade of rocks increases from eastern New York to Cameron's Line (CL) in Connecticut, through eastern margin of Grenville basement in western Massachusetts and southern Vermont, up to dotted line in northern Vermont. Isograds are based primarily on mineral assemblages in pelitic rocks; letter symbols are placed on higher-grade side of isograds. ad, Adamstown pluton, Maine; at, Attean pluton, Maine; BM, Berkshire massif, Mass.; bm, Belvidere Mountain, Vt.; cc, Cortland Complex, N.Y.; cm, Canaan Mountain, Conn.; dc, Dutchess County, N.Y.; em, Elsmore Mountain, Vt.; fg, Fordham Gneiss, N.Y.-N.J.-Conn.; GMM, Green Mountains massif, Vt.; hc, Highlandcroft pluton, Vt.; HHM, Hudson Highland massif, N.Y.-Conn.; hr, Hudson River, N.Y.; MP, Manhattan Prong, Conn.-N.Y.; nm, Northfield Mountain, Vt.; pr, Pliny Range, N.H.; WD, Waterbury Dome, Conn.; wm, Worcester Mountains, Vt.

m thick (Austin, 1993b). The garnet ranges in specific gravity from 3.6 to 4.3, and in hardness from 7 to 8 Mohs. Mining began in 1979 (White and Anderson, 1981) and continued until 1988. The ore is garnet granofels and garnet-bearing diorite associated with the contact zone of a gabbro pluton. The ore averaged about 60 weight percent almandite and 40 weight percent combined andesine, pyroxene, cordierite, and xenoliths. Garnet reserves were estimated at 1.8 million t. The rock had been exposed by glaciers, and so no overburden needed to be removed. The quarry produced garnet for abrasives, outdoor airblasting, filtration media, and nonskid aggregates. Raw crushed rock from the quarry was used for heavy aggregate and ornamental use. Some coarsely crushed grit was used for nonslip traction on snow and ice. Crushed garnet was transported to a mill in West Paris, in Oxford County, 120 km south of Rangeley (Prosser and others, 1983).

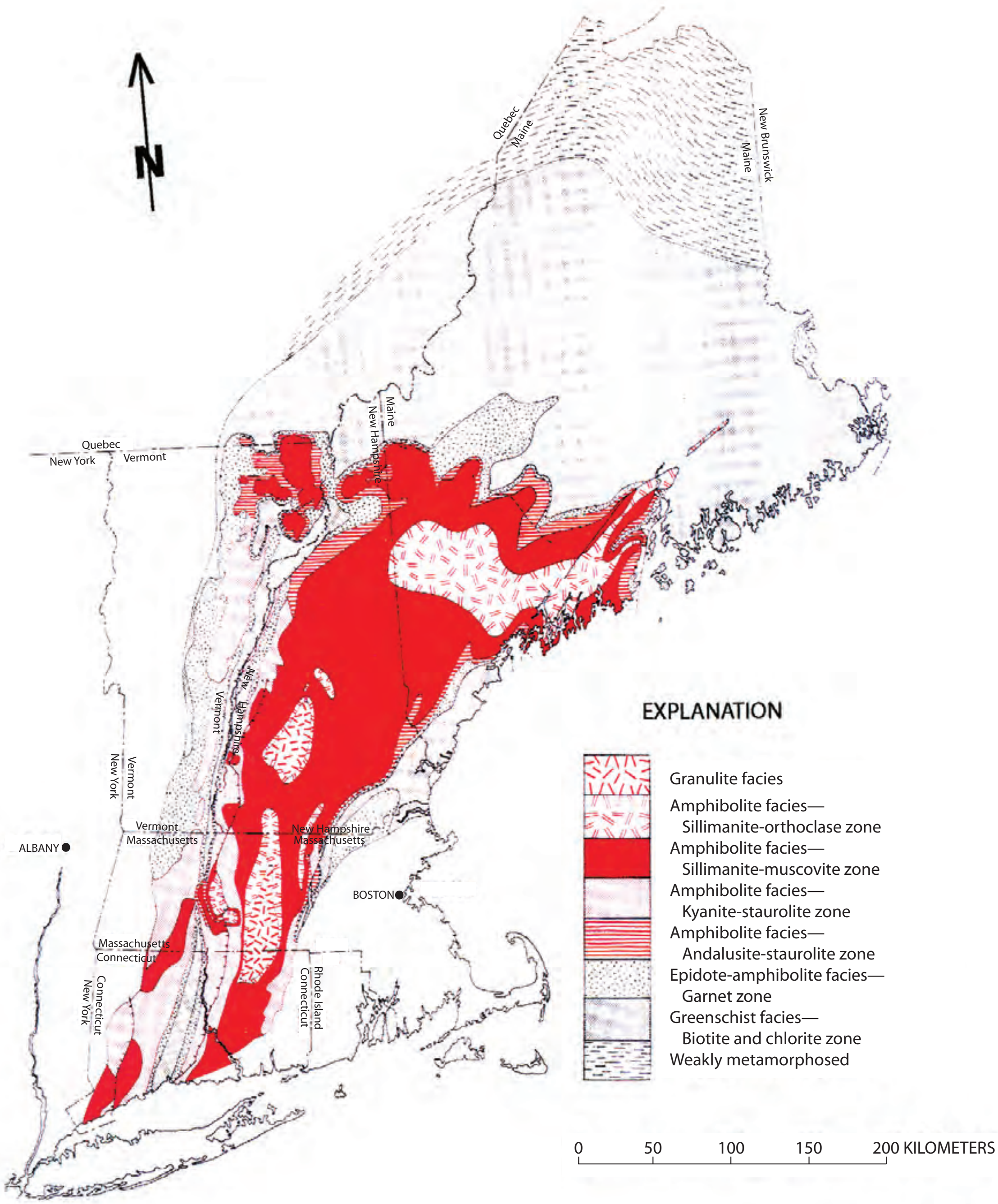

Figure 12. Isograd map of Acadian metamorphism in New England (adapted from Osberg and others, 1989).

In 1983 and 1984, Maine was the second-largest garnet-producing State (Prosser and others, 1985, 1986). Although domestic garnet production was 24 percent higher in 1985 than in 1984, Industrial Garnet Extractives increased its output by 61 percent during the same period (Prosser and others, 1987), possibly owing to an equipment upgrade in the previous year (Prosser and others, 1986). International Garnet Extractives ceased processing garnet at its West Paris plant in early 1988 (Harrison and others, 1991), when mining near Rangeley also ceased. In 1991, the Pittston Mineral Ventures Co. of Greenwich, Conn., announced plans to reactivate the dormant garnet quarry and construct an adjacent processing plant. Before they could proceed, however, the area of operations had to be rezoned by the town of Rangeley, and Pittston's plans had to be approved by the State's environmental authorities. In 1993, the Rangeley Minerals Resources Co., a subsidiary of the Pittston Mineral Ventures Co., surrendered its lease on the garnet quarry in Franklin County to the Rangeley Mining Co., Inc., the owners (U.S. Bureau of Mines staff, 1993–94a).

The Rangeley area is near the north end of the Bronson Hill-Boundary Mountain anticlinorium near the United States-Canadian border (BHBM, fig. 14; Cady, 1969). The anticlinorium can be traced southward along the New Hampshire-Vermont State line into western Massachusetts and northward into Quebec. Sedimentary and volcanic rocks composing this structure range in age from Cambrian through Devonian and are intruded by several calc-alkalic plutons of Ordovician and Devonian age and alkalic plutons of Jurassic and Cretaceous age. The volcanic rocks are interpreted to be parts of two volcanic-sedimentary-intrusive terranes, one of Middle Ordovician and the other of Upper Ordovician through Lower Silurian age (both affected by Taconic-age events). The Paleozoic terranes may have devel-

Figure 13. County map of Maine, showing county boundaries and locations of counties (names in all caps) with garnet deposits or occurrences. Gem, gem-stone localities that may contain garnet. Dots, cities and towns; star, State capital.

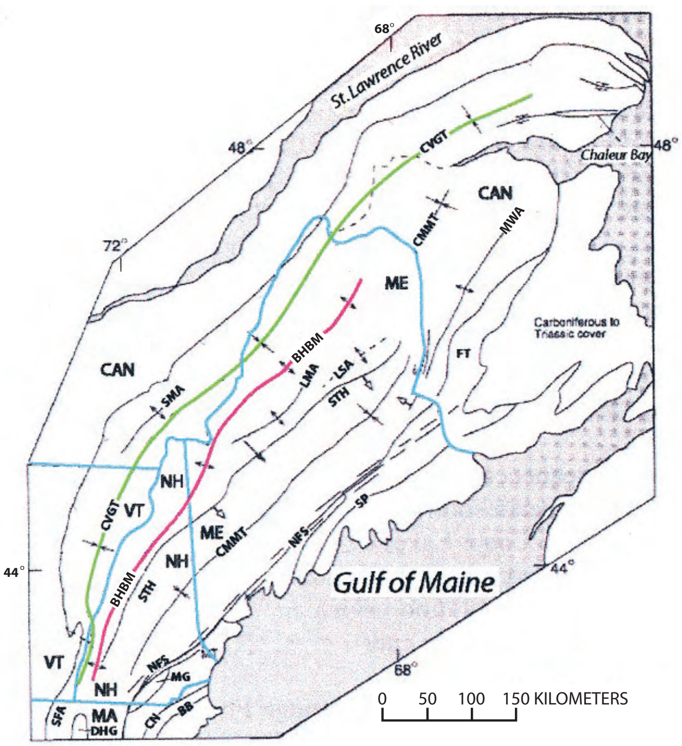

Figure 14. Regional structures in northern New England (adapted from Moench and Aleinikoff, 2003). Blue, State and national boundaries: CAN, Canada; MA, Massachusetts; ME, Maine; NH, New Hampshire; VT, Vermont. Geologic features: BB, Bloody Bluff Fault; BHBM (red), Bronson Hill-Boundary Mountain anticlinorium; CMMT, Central Maine-Matapedia synclinorium; CVGT (green), Connecticut Valley-Gaspe synclinorium (same as Townsend-Browning syncline of Cady, 1969); DHG, Gneisses of Pelham Dome; FT, Frederick and Merrimack suture; LMA, Lobster Mountain anticlinorium; LSA, Lunkoos anticlinorium; MG, Massebesic Gneiss Complex; MWA, Munsungun-Winterville anticlinorium; NFS, Norumbega fault system; SFA, Shelbourne Falls arc; SMA, Stoke Mountain anticlinorium; SP, southeastern margin of Grenville basement; STH, Silurian tectonic hinge.

oped along subduction zones of opposing polarities (Drake and others, 1989; Moench and Aleinikoff, 2003).

New Hampshire

During the 1930s, New Hampshire was the leading garnet-producing State. Ladoo (1922) mentioned only one garnet locality in Merrimack County, near North Wilmot (fig.15); at the time of his report, the property was operated by the Wausau Abrasives Co. of Wausau, Wisc. The almandite, as large as 2 cm across, occurs in a matrix of biotite, quartz, and albite. The ore graded as much as 65 percent garnet but averaged much less. The garnets contained quartz and biotite inclusions, and so the ore had to be finely crushed to obtain sufficiently pure garnet sand. The Garnet Products Co. mined garnet from 1931 to 1934; no production was recorded for 1935. In 1936, Garnet Products changed its name to the Davenport Garnet Co. and resumed mining until 1939. Another deposit near Danbury, also in Merrimack County, was operated by the Ford Motor Co. of Dearborn, Mich. From 1928 to 1930, Ford shipped a few thousand tons of garnet from its Danbury operation to its plant in Dearborn for polishing plate glass (Conant, 1935). Ford's garnet production was reported in the *Minerals Yearbook* 1931–32 (Hatmaker and Davis, 1933), although the garnet had been mined earlier. A garnet deposit near North Wilmot, also in Merrimack County, was mentioned in the *Minerals Yearbook* 1936 (Johnson and Davis, 1936); no production was recorded, and it is unclear whether this is the same deposit that was active in 1922 (see above). All of the mines are in western Merrimack County.

Conant (1935) reported that the garnet deposits in the Wilmot-Danbury area were in granitic gneiss and (or) migmatite and schist, containing as much as 80 volume percent garnet. The garnet content of the massive, higher-grade garnetiferous rocks ranged from 30 to 80 weight percent, averaging 50 weight percent. Garnet masses were elongated parallel to the schistosity of the enclosing rocks. The garnet contained inclusions of magnetite, biotite, and quartz and had numerous fractures lined with chloritic alteration. The inclusions and alteration may have presented problems in using the garnet for abrasive applications. Its specific gravity, however, was about 4.0, and its hardness 7.5 to 8 Mohs. The garnet was mostly almandite. The North Wilmot deposit was cut by vertical dikes of basalt (Triassic?) and pegmatite, neither of which appears to have altered the garnet; the rock also contains pyrrhotite-tourmaline veinlets. The Danbury deposit is migmatitic and of lower grade than the Wilmot deposit. Other indications of garnet potential, such as many garnet-rich boulders and, possibly, an outcrop, were observed in West Andover, about 5 km east of Wilmot in Merrimack County. Another garnet occurrence was reported near Bradford, about 24 km south of Wilmot, also in Merrimack County. The garnet deposits are in the Bronson Hill-Boundary Mountain anticlinorium (fig. 14; Cady, 1969; Moench and Aleinikoff, 2003), described previously.

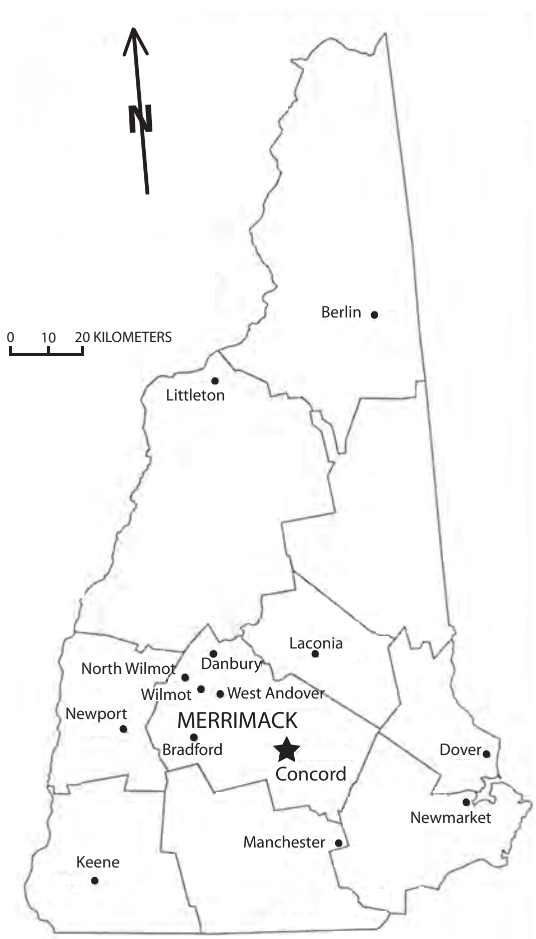

Figure 15. County map of New Hampshire, showing county boundaries and location of Merrimack County, which has garnet deposits. Dots, cities and towns; star, State capital.

Vermont

Green Mountain Mica Corp. in Gassetts in Windsor County (fig. 16) produced a small amount of garnet from 1939 to 1941 for use as abrasives and in sawing marble. Since then, only rockhounds have collected specimens in the State (Kerr, 1964). The mine is in the vicinity of the Chester dome (fig. 6) and close to the axial zone of the regional Townsend-Browning syncline (fig. 14; see Cady, 1969; same as the Connecticut Valley-Gaspe synclinorium of Moench and Aleinikoff, 2003), west of the Bronson Hill-Boundary Mountain anticlinorium. The core of the dome exposes complexly deformed and polymetamorphic upper Precambrian bedded shelf-facies rocks intruded by granitic plutons and pegmatite dikes. These rocks, which are considered to be outliers of the Grenville province (Rankin and others, 1989b), are overlain by Cambrian through Ordovician sedimentary rocks.

Connecticut

Garnet deposits near Roxbury in Litchfield County, and in Roxbury Falls in New Haven County (fig. 17), were worked before the report by Ladoo (1922). The garnet, andradite, occurs in mica schist as dodecahedral crystals, as large as 5 cm across, that are easily separated from the schist. The deposit was worked mainly to furnish garnet for shoe finishing and mineral specimens; other uses included grinding wheels, saws, and sandpaper. Gem-quality garnets continued to be sought in the Roxbury area as of 1977 (Barton, 1981). Gem and mineral collectors have recovered garnet at various places in Fairfield, Hartford, and Litchfield Counties (Feitler, 1961). Garnets are still abundant in Bolton and Stafford Springs in Tolland County and in Portland in Middlesex County.

Violet-red almandite was designated the official Connecticut State gem stone in 1977.

Central and Southern Appalachian Mountains

Geologic Setting

The metamorphic evolution of the central and southern Appalachian Mountains, as in the northern part of the range, occurred over hundreds of millions of years, during which oceans opened and closed and accreted terranes docked against the Proterozoic core of North America. Granulite-facies metamorphism in the southern Appalachians occurred about 480 Ma (Rb/Sr age; Drake and others, 1989), or Taconic in age; many studies have reported both earlier and later dates. The isograds for the southern Appalachians shown in figure 18 were determined from the highest metamorphic grade in areas where isotopic data indicate Ordovician metamorphism. Temperatures at peak metamorphism ranged from 540ºC (staurolite-kyanite zone) to 775ºC (granulite facies), and pressures from 3.8 to 9 kbars. Overall, Taconic metamorphism in the U.S. Appalachians was largely a medium-pressure-facies series, except for blueschist and eclogite in north-central Vermont (fig. 11) and a low-pressure-facies series in the central Appalachians (fig. 18).

The timing of Acadian metamorphism in the region is poorly constrained, ranging from Devonian through Mississippian. The isograds shown in figure 19 (from Osberg and others, 1989) were constructed during International Geological Caledonide Project 27. Acadian metamorphism is largely amphibolite facies superimposed on Ordovician and Precambrian metamorphic rocks. Garnets can be expected in rocks of appropriate composition for every metamorphic facies above greenschist. Acadian metamorphism, though not as intense as the Taconic, is widespread. Connections between the Acadian metamorphic belts in the central and southern Appalachians and similar belts in New England have not been reported.

In the southern Appalachians, Late Paleozoic and, possibly, Early Mesozoic dynamothermal metamorphism (Alleghenian through Pennsylvanian, Permian, and early Triassic?) is best known from the Raleigh and Kiokee belts

Figure 16. County map of Vermont, showing county boundaries and location of Windsor County, which has garnet deposits. Dots, cities and towns; star, State capital.

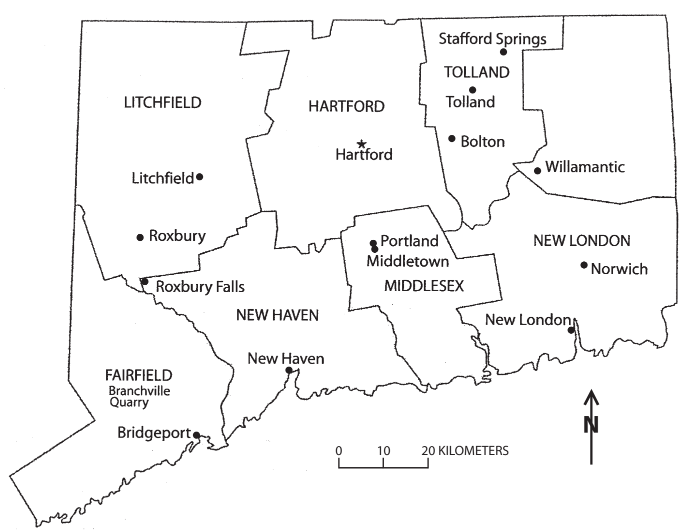

Figure 17. County map of Connecticut, showing county boundaries and locations of counties (names in all caps) with garnet deposits or occurrences. Dots, cities and towns; star, State capital.

of the eastern Piedmont (fig. 20; Hatcher and others, 1989). The Raleigh belt lies along the northwestern margin of the Atlantic Coastal Plain from central North Carolina to southern Virginia; the Kiokee belt lies along the northwestern margin of the coastal plain from Columbia, S.C., to Augusta, Ga., and extends southwestward of Augusta into east-central Alabama. Alleghenian regional metamorphism in these two belts is superimposed on previously metamorphosed rocks that contain mineral assemblages ranging from greenschist (Taconic?) to granulite (Grenville) facies. The Alleghenian metamorphism itself ranged from greenschist to amphibolite facies. Maximum temperatures in the Raleigh belt were 550–570ºC, and ambient pressure was about 5 kbars. In the Kiokee belt, maximum temperature was 575±50ºC in kyanite-staurolite schist at pressures of 7±1 kbars. Garnet deposits in these belts, if present, have not been described. On the basis of the metamorphic grades attained in these two belts, garnet deposits are possible (figs. 18, 19; see geologic details in Hatcher and others, 1989).

Pennsylvania

Before 1900, garnet was mined at several places in Chester and Delaware Counties (fig. 21). Judging from the size of the workings, one operation, about 2 km west of Chelsea in Delaware County, seems to have been the most important. There, almandite occurs within quartzose mica schist, locally composing 75 volume percent of the rock. The rock was heavily weathered at the surface (saprolite?) but became very hard at a depth of 7 m. A small amount of almandite was mined near Chester Heights, also in Delaware County. The ore was reached by tunnels and a shaft in heavily weathered gneiss (saprolite?; narrative from Ladoo, 1922). Rockhounds collected several minerals, including garnet, mostly in Chester (Cornog Quarry; Kerr, 1965) and Montgomery Counties. Mineral specimens, including garnet, were also collected in Lancaster, Lehigh, Luzerne, Monroe, and Northampton Counties (Yeloushan and others, 1963). The locations of collection sites and the varieties of garnet present were not reported. Garnet

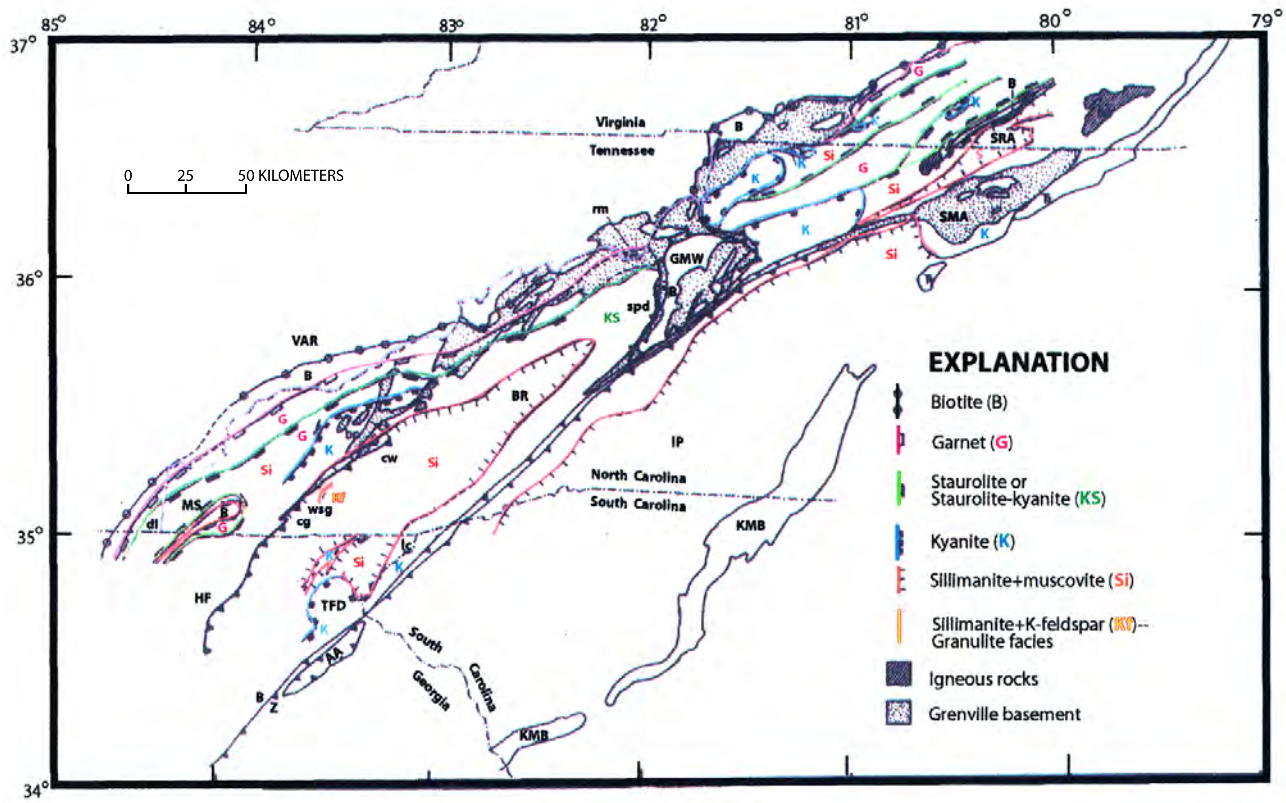

Figure 18. Isograd map of Taconic metamorphism in western North Carolina and adjoining States (adapted from Drake and others, 1989). Sillimanite-grade metamorphism also occurs in the Inner Piedmont of South Carolina, but it is unclear whether Taconic metamorphism is preserved there. AA, Alto allochthon, Ga.; BR, Blue Ridge, Ga.-Tenn.; BZ, Brevard zone; cg, Chunky Gal mafic/ultramafic complex, Cherokee County, N.C.; cw, Cullowee, N.C.; dt, Ducktown, Tenn.; GMW, Grandfather Mountain window, N.C.; HF; Hayesville fault, Ga.-Tenn.; IP, Inner Piedmont; KMB, King Mountain belt; lc, Laurel Creek mafic/ultramafic complex, Ga.; MS, Murphy syncline, Ga.-N.C.; rm, Roan Mountain, N.C.-Tenn.; spd, Spruce Pine District, N.C.; SMA, Sauratown Mountains anticline, N.C.; SRA, Smith River allochthon, N.C.; VAR, Valley and Ridge province, Tenn.-N.C.; wsg, Winding Stair Gap, N.C.

crystals occur in cavities within metamorphosed Triassic conglomerate in York County (Stose and Glass, 1938). These garnets were formed in contact-metamorphic aureoles of diabase intrusions. The rounded cavities were produced by solution of limestone pebbles in the conglomerate. Evidently, these garnets date to a much later metamorphic event than the Acadian and other previously mentioned events.

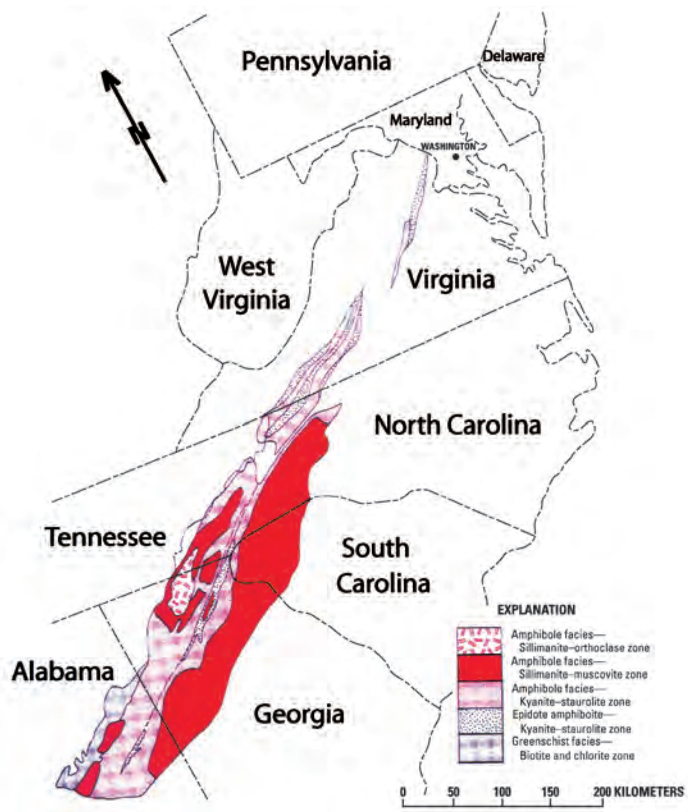

Figure 19. Isograd map of Acadian metamorphism in the central and southern Appalachian Mountains (adapted from Osberg and others, 1989).

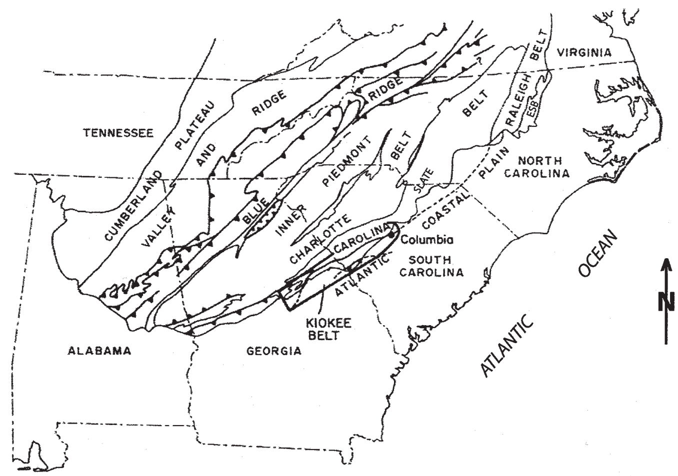

Figure 20. Southeastern United States, showing locations of the Raleigh and Kiokee metamorphic belts and their regional setting (adapted from Dallmeyer, 1989). ESB, eastern slate belt.

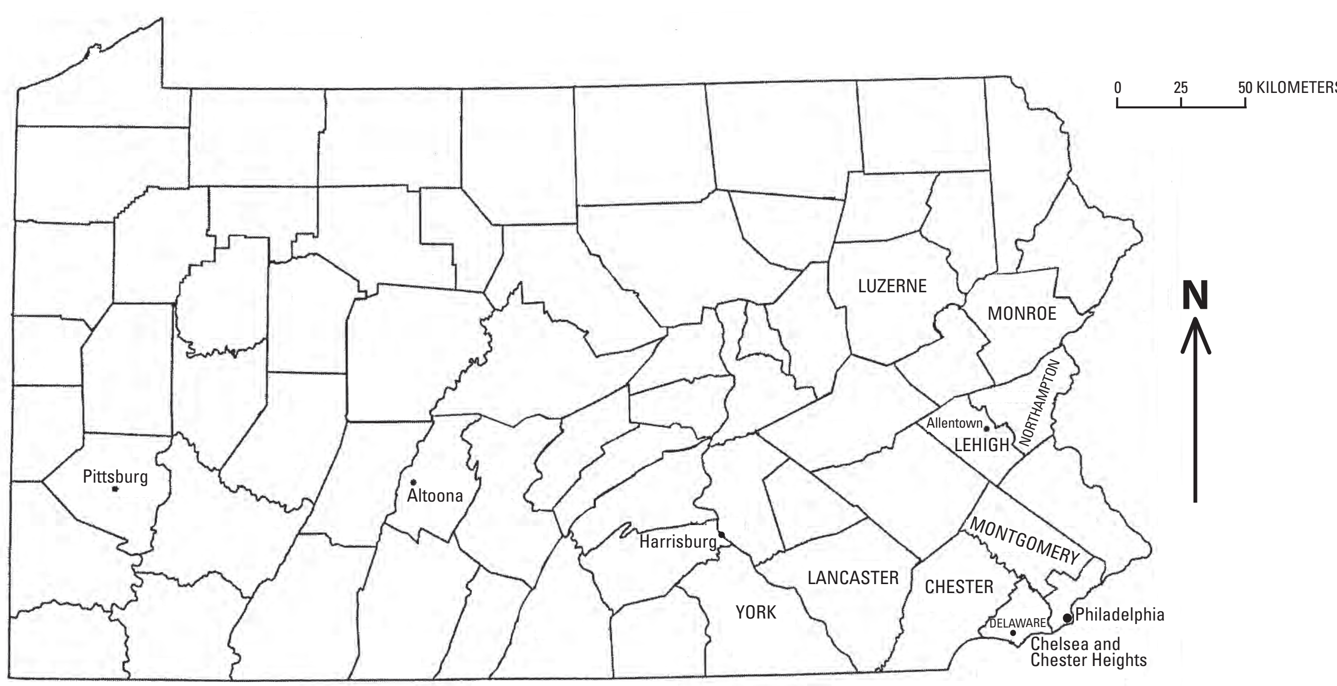

Figure 21. County map of Pennsylvania, showing county boundaries and locations of counties (names in all caps) with garnet deposits or occurrences. Dots, cities and towns; star, State capital.

Virginia

An attempt (in 1906?) was made to mine garnet from sericitic schist in a steep bluff on the northeast side of the Tyler River, about 6.5 km south of Arrington in Nelson County (fig. 22; Watson, 1907). No record of production is known. Euhedral spessartite crystals were collected from pegmatite dikes from which mica was mined near the Amelia courthouse in Amelia County and near Hewlett in Hanover County. The Morefield and Rutherford Mines in Amelia County produced gem-quality spessartite in the form of etched-crystal masses and fragments, ranging in size from 0.3 to 15 cm across, colored yellow-orange, red-orange, red, and brownish red (Ladoo, 1922; Metcalf and Calver, 1964). The mine still operates as a recreational collecting site (U.S. Geological Survey staff, 2005c). A shaft is driven into a quartz-feldspar pegmatite vein, and periodically material is blasted and dumped for collectors to sort. Minerals other than garnet include amazonite (blue-green microcline), amethyst, and beryl.

North Carolina

Garnet occurs in gneiss, schist, and igneous rocks in the central and southern Appalachian Mountains but is present in minable quantity and quality only in North Carolina (French and Eilertson, 1968; U.S. Geological Survey and U.S. Bureau of Mines, 1968). Counties named on the map of North Carolina (fig. 23) are associated in some way with garnet. Large deposits of almandite and rhodolite (a pink, rose, or purple to violet garnet intermediate in composition between almandite and pyrope) of gem and abrasive quality are known from Burke, Clay, Jackson, Macon, and Madison Counties. Garnet for abrasives was produced from some of these deposits from 1900 to 1926, but no production figures were reported. The U.S. Geological Survey and U.S. Bureau of Mines (1968) reported garnet deposits in the following counties (dots, fig. 23): one in southern Madison County, three in northern and western Jackson County, and two in eastern and southern Clay County. The largest deposits are in Clay and Jackson Counties, and the two largest deposits are at Penland Bald on Buck Creek and on Shooting Creek in Clay County. The deposits consist of almandite-rich hornblende gneiss containing garnet crystals, as large as 6 cm across. Rugged topography hinders development (Ladoo, 1922), or did so in 1922.

Three rhodolite garnet deposits occur on Sugarloaf and Doubletop Mountains, about 4 km south of Willets in Jackson County. Garnet crystals, as large as 3.5 cm across, occur in quartz-biotite gneiss, composing 25 to 50 volume percent of the rock. Mining began around 1900 and was intermittent until 1926. The Rhodolite Co. constructed a mill close to its quarry in the year before it closed. Reserves are estimated to be of high quality and easily accessible. The Savannah deposit at the head of Betty Creek and the Presley deposit near Speedwell in Jackson County operated intermittently for several years around 1900. Small garnet deposits southwest of Marshall near Little Pine Creek in Madison County were mined around 1900 or 1905. Garnet crystals, as large as 5 cm across, were mined from a zone, as much as 3 m thick, in chlorite schist. From 1934 or 1935 until 1944, garnet was produced as a byproduct from the Celo Mines Co.'s kyanite mine near Burnsville in Yancey County (Espenschade and

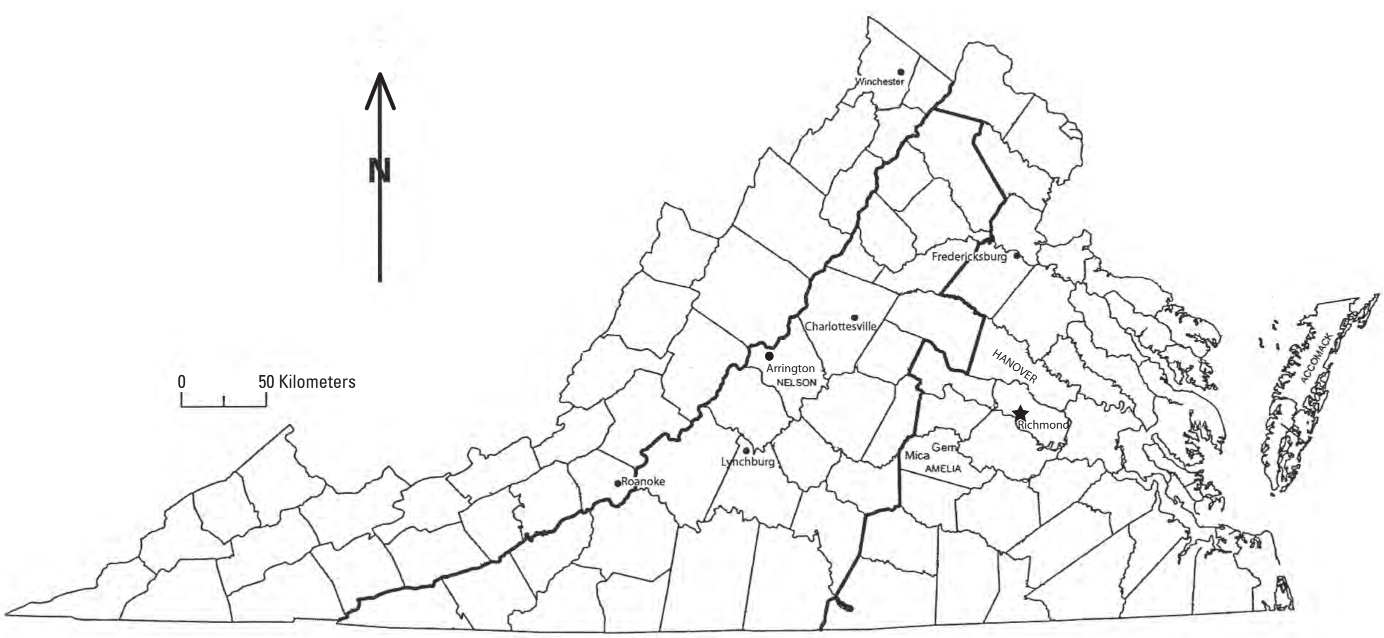

Figure 22. County map of Virginia, showing county boundaries and locations of counties (names in all caps) with garnet deposits or occurrences. Gem, gem-stone locality. Dots, cities and towns; star, State capital.

Potter, 1960; U.S. Geological Survey and U.S. Bureau of Mines, 1968). Production was suspended in 1941. The mine was reopened later that year by the Mas-Celo Mines Co. but was closed again in June 1942. The company was reorganized as the Yancey Cyanite [sic] Mine Co. and closed in January 1944, possibly owing to the declining grade of millfeed. Stuckey (1965), however, reported that Celo Mines produced byproduct garnet in 1944. Since then, only garnet for gems and (or) mineral specimens is known to have been collected in the State. Red gem-quality pyrope has been reported in mine waste from placer gold-mining operations in Alexander, Burke, and McDowell Counties. Pink rhodolite has been recovered from gravel in Cowee Creek near the town of Franklin and in Mason's Branch near Iotla in Macon County, and occurs in place on Mason Mountain.

Overstreet and others (1968) summarized research on fluvial monazite deposits in the Southeastern United States that also contain ilmenite, rutile, magnetite, zircon, garnet, sillimanite, and kyanite (fig. 23). Early studies reported that the garnet from southeastern monazite placers was of good abrasive quality, but it was rejected or brought only low prices because of small grain size and roundness. From that time (1908?) to 1968, no effort was made to reinvestigate the placer garnet for industrial uses. Eventually, monazite placers between the Savannah and Catawba Rivers, N.C.-S.C., were explored by drilling (Overstreet and others, 1968). In addition to other heavy minerals, the placers yielded from a trace to 287 kg of garnet per cubic meter. Alluvial samples from the same area were sieved into four grain-size classes: gravel, sand, silt, and clay. Garnet content ranged from a trace to 38 kg/m^3 in the sand-size fraction and from 2 to 67 kg/m^3 in the gravel. Extraordinarily garnet rich samples (>67 to ≤287 kg/m^3) were omitted from the average as anomalous and are not mentioned. The most common placer garnet composition was identified as a solid solution predominantly of spessartite and almandite.

Larsen (1993) reported high garnet concentrations in heavy-mineral suites in Mesozoic through Quaternary stream sediment on the Atlantic Coastal Plain of North Carolina (fig. 23; counties named in eastern North Carolina).

South Carolina

The garnetiferous region in South Carolina is a continuation of that in western North Carolina (fig. 24). Large garnet concentrations in Tertiary and Holocene monazite placers in the domain of metamorphic rocks of the Inner Piedmont occur in the Saluda, Pacolet, Enoree, and Tyger River drainages in northwestern South Carolina (fig. 24; Overstreet and others, 1968). Spessartite-almandite schist, a potential source of garnet placers, occurs in Cherokee and Spartanburg Counties. Relatively high garnet concentrations in heavy-mineral suites occur in Mesozoic through Quaternary stream sediment on and near the Atlantic Coastal Plain (fig. 24; Larsen, 1993); these garnet occurrences are adjacent to counties in North Carolina where garnet also occurs in coastal-plain heavy-mineral suites (fig. 23). No record of garnet production is known for the State.

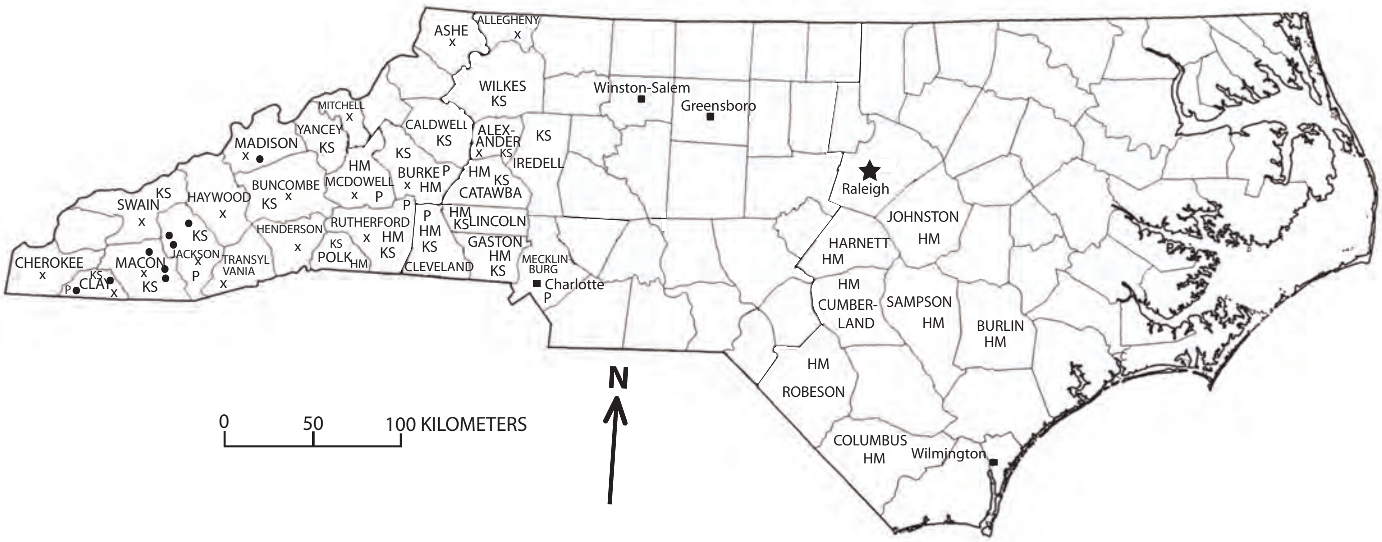

Figure 23. County map of North Carolina, showing county boundaries and locations of counties (names in all caps) with garnet deposits or occurrences. Squares, cities and towns; star, State capital; dots, mines (inactive); Xs, garnet-collection localities (French, 1968), as of 1968. HM, in western North Carolina, streams with heavy-mineral suites that contain more than 5 weight percent garnet (Overstreet and others, 1968), and in southeastern North Carolina, garnet occurrences in heavy-mineral suites (Larsen, 1993) ; KS, kyanite and sillimanite production; P, large placer deposits that may include garnet (Gair and others, 1989).

Georgia

Almandite and pyrope in schist are widespread near Dahlonega, about 2 km south of Porter Springs in Lumpkin County (fig. 25; Richard, 1911). Much of the garnet is in saprolite and has weathering rinds. Fresh garnet is dark red and has a hardness of 5 to 6 Mohs, possibly a result of weathering. The larger garnet crystals ranged in weight from 28 g to several kilograms. Abrasive-quality garnet deposits may be present along with corundum, kyanite, and zircon. The U.S. Geological Survey and U.S. Bureau of Mines (1968) located one garnet deposit in northern Lumpkin County. Smith and others (1969) mapped metamorphic isograds in crystalline rocks of Georgia north of the Fall Line (the geographic line east of the Appalachian Mountains that marks the end of the Atlantic Coastal Plain and the beginning of the Piedmont, marked by numerous waterfalls and rapids). Most counties north of the Fall Line are underlain by amphibolite-facies rocks grading as high as sillimanite zone. The garnet isograd traverses the northwestern part of the State (fig. 25). Rocks between the garnet isograd and the Fall Line compose a complex of outliers of the Grenville province and Middle through Late Proterozoic metasedimentary, metavolcanic, and intrusive rocks (Rankin and others, 1989a). Most of this region theoretically had the pressure-temperature conditions for garnet formation, but garnet neomineralization would also depend on protolith composition. The garnet isograd passes westward into Alabama, indicating possible garnet occurrences, if not deposits, in east-central and northeastern Alabama.

The southeastern part of the Atlantic Coastal Plain in Georgia (fig. 25) contains heavy-mineral beach-ridge and channel-fill deposits of Pliocene or Pleistocene age (Pirkle and others, 1989, 1993). Although all the heavy minerals present were not reported, garnet commonly occurs in heavy-mineral suites on the coastal plain in North Carolina and South Carolina and is expected in similar environments in Georgia.

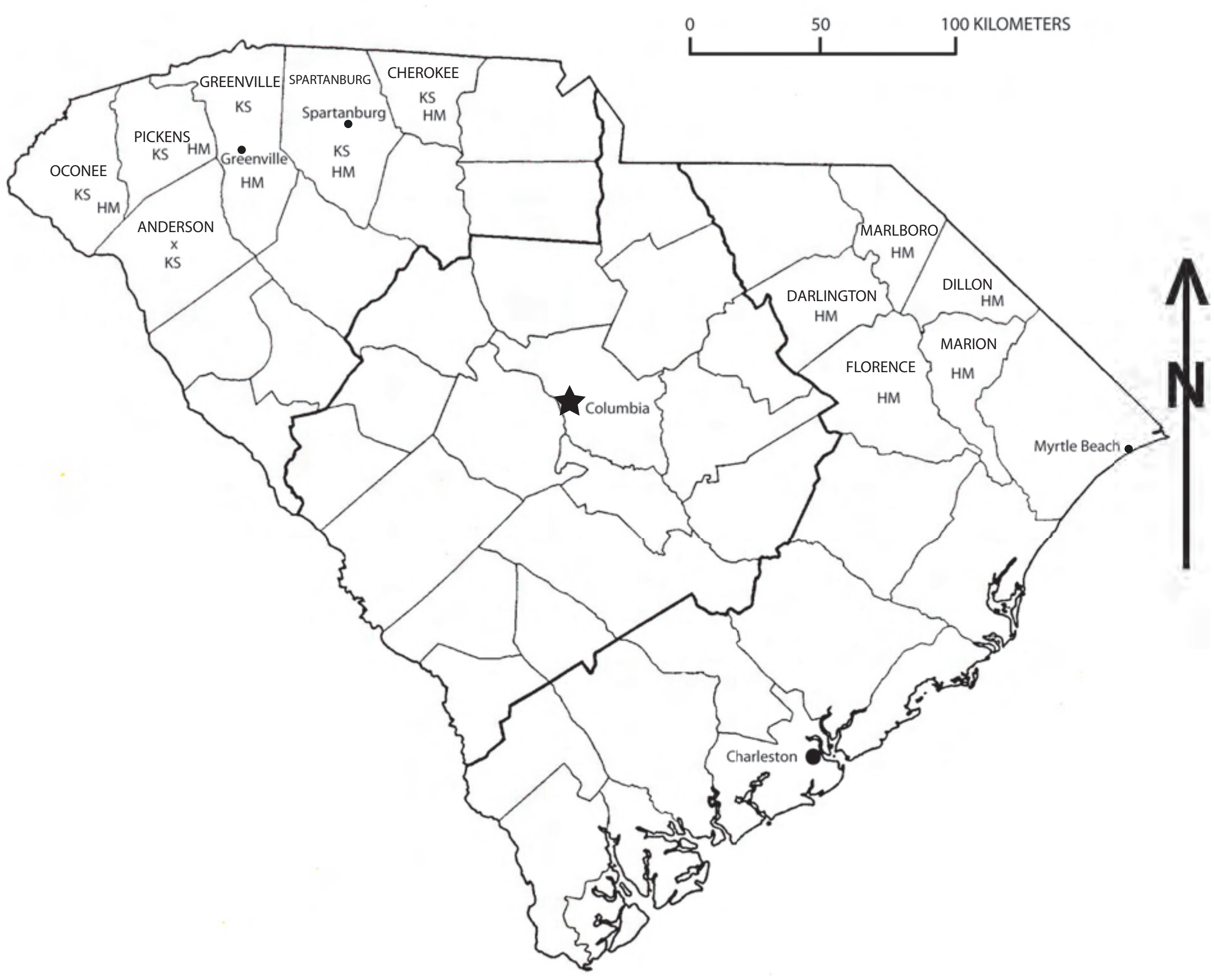

Figure 24. County map of South Carolina, showing county boundaries and locations of counties (names in all caps) with garnet occurrences. Dots, cities and towns; star, State capitals. Xs, garnet-collection localities (French, 1968), as of 1968. HM, garnet occurrences in heavy-mineral suites; KS, kyanite and sillimanite production.

Florida

Miller (1945) determined the abundances of heavy minerals of economic interest, including garnet, in 18 samples of dune and beach sand from Florida. Sampling sites were near Pensacola in Escambia County, at Clearwater Beach in Pinellas County, at Tampa Bay in Hillsborough County, at Fort Pierce in St. Lucie County, and at Vero Beach in Indian River County; on beaches along the coast of Flagler and St. Johns Counties; and in older dunes 16 km west of Jacksonville Beach in Duval County (fig. 26). Miller (1945) sampled heavy-mineral concentrate at a mining operation in older dunes 16 km west of Jacksonville Beach. Quaternary dune sand was also sampled 6 km south of Jacksonville Beach and 150 m inland, 16 km south of Jacksonville Beach, and 6 km south of Atlantic Beach in Duval County. Heavy minerals are sparse in areas of Pleistocene sand inland from the coast and more abundant on modern beaches and in Holocene sand dunes along the coast. Some of the beach sand contains commercial deposits of heavy minerals.

Wave action on beaches concentrates heavy minerals in discontinuous lenses, from a few millimeters to 10 cm thick. Beach concentrations can change from one storm to the next, and heavy minerals may locally compose a large percentage of the sand. The Holocene dune deposits were initially concentrated on the beaches and later transported inland and sorted by the wind. Although the proportion of heavy minerals in the dunes is smaller than in the richer beach deposits, the large volume of the dunes may make them a potentially more attractive commercial source of heavy minerals than the beaches. Most production of rutile and ilmenite in 1945 was from the older dunes, but some beaches had also been productive. Heavy minerals still of interest in 2005 are ilmenite, rutile, and zircon, which are being mined in Baker, Bradford, Clay, and Duval Counties (fig. 26; U.S. Geological Survey and Spencer, 2004), and concentrates of staurolite were also produced.

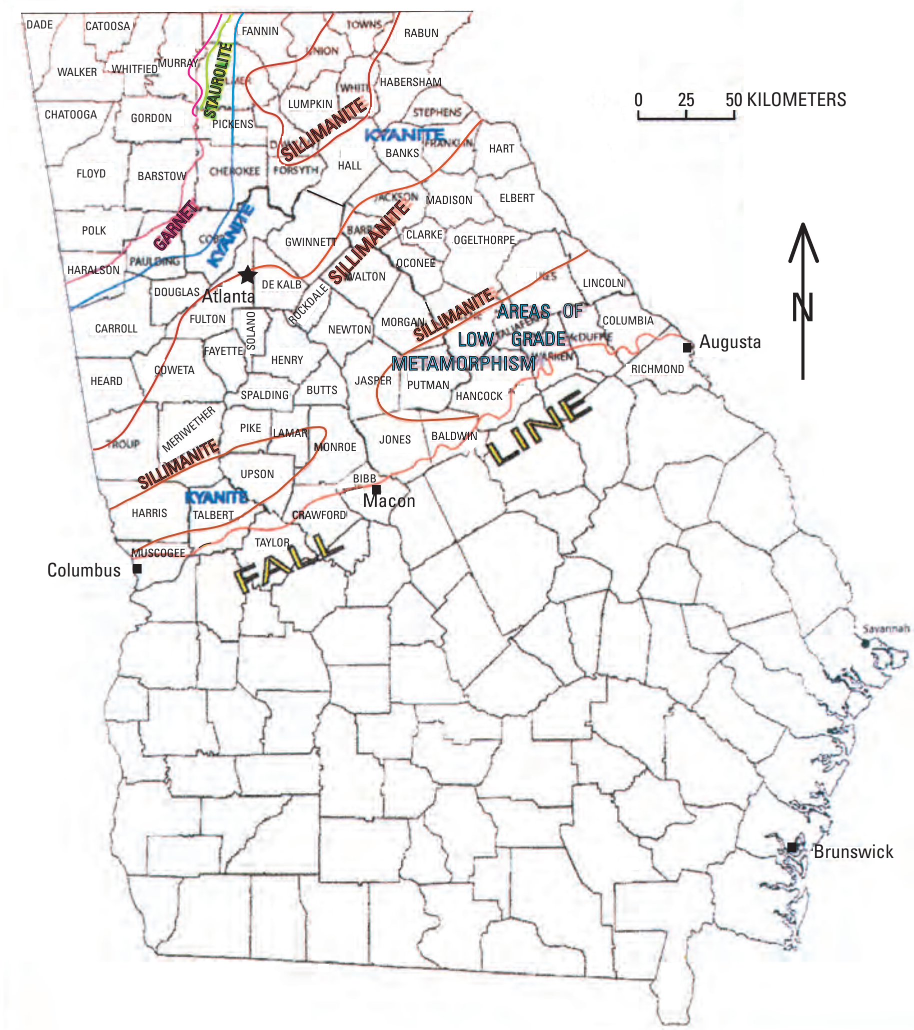

Figure 25. County map of Georgia, showing county boundaries and locations of counties (names in all caps) and isograds of Taconic metamorphism north of the Fall Line in northern Georgia (adapted from Drake and others, 1989). Dots, cities and towns; star, State capital.

Heavy minerals in the beach and dune deposits include garnet along with corundum, enstatite, epidote, hornblende, ilmenite, kyanite, monazite, rutile, spinel, staurolite, tourmaline, and zircon (Miller, 1945). On the basis of index of refraction, the garnet was identified as belonging to the spessartite-almandite group. Garnet contents of the east-coast beach and dune samples ranged from a trace to 8 weight percent; the highest east-coast concentration was in a sample from the south bank of Matanzas Inlet in Flagler County that also contained 51 weight percent ilmenite. In comparison, the garnet content in dune sand at the ilmenite and rutile mine sampled by Miller (1945) in Duval County was 1 weight percent, along with 26 weight percent ilmenite and 5 weight percent rutile. On the west coast, garnet contents also varied widely and were highest at Tampa (5 weight percent) and Clearwater (18 weight percent); ilmenite and rutile contents were 22 to 26 weight percent at Tampa and 23 and 1 weight percent at Clearwater, respectively.

The record in the *Minerals Yearbook* notes that garnet was produced from black sand in Brevard and Indian River Counties from 1952 to 1957 (Reed and Calver, 1955, 1958; Thoenen and Calver, 1956; Chandler and Tucker, 1958d; Vallely and Calver, 1958; Vallely and Vernon, 1959). These garnet sources were most likely beach and (or) dune deposits. Other abrasive minerals present in the dune and beach sand studied by Miller (1945) include kyanite, from a trace to 45 weight percent, and staurolite, from a trace to 47 weight percent. Both minerals are more abundant along the west coast, especially near Pensacola, where garnet is absent. In places, kyanite and staurolite could be mined as coproducts of heavy-mineral suites that include garnet.

Western United States

Much of the following narrative is derived from the *Minerals Yearbook* 1933–2004 (Kaufman and others, 1955; Baber

Figure 26. County map of Florida, showing county boundaries and locations of counties (names in all caps) with occurrences of garnet or other heavy minerals. Dots, cities and towns; star, State capital. Ti, ilmenite and rutile; Zr, zircon production from heavy-mineral deposits.

and others, 1956, 1959a, b; Fulkerson and others, 1962; Gray and others, 1964; Knostman and Peterson, 1965; Carrillo and others, 1967; Collins and others, 1967; Bennett and Mitchell, 1988; Gillerman, 2001).

Idaho

Placer Garnet Deposits of Northern Idaho

Emerald Creek Area

The garnet deposits at Emerald and Carpenter Creeks in Benewah County have accounted for as much as 10 percent of global garnet production, constituting the only continuously active garnet mine in the Western United States from 1940 to 2005 (fig. 27). The garnet-bearing gravel is from 1 to 1.2 m thick and contains as much as 20 weight percent garnet. The gravel is sandwiched between underlying dark-blue-gray lakebeds and overlying barren gravel or loess, ≥2 m thick (fig. 28). Unconsolidated garnetiferous gravel consists of poorly sorted pebbles and cobbles containing abundant sand-size grains of garnet in, locally, a matrix of blue-gray mud (fig. 29). The upper part of the garnet-rich gravel is commonly oxidized. Some thin hematite-cemented beds (ferricrete) are extremely hard and provide clasts for cannibalized gravel. The bedrock sources of the garnet are schists, estimated at 1,200 m thick (see next subsection). Processing is simple: the gravel is first run through trammels to sort by size and is subsequently con-

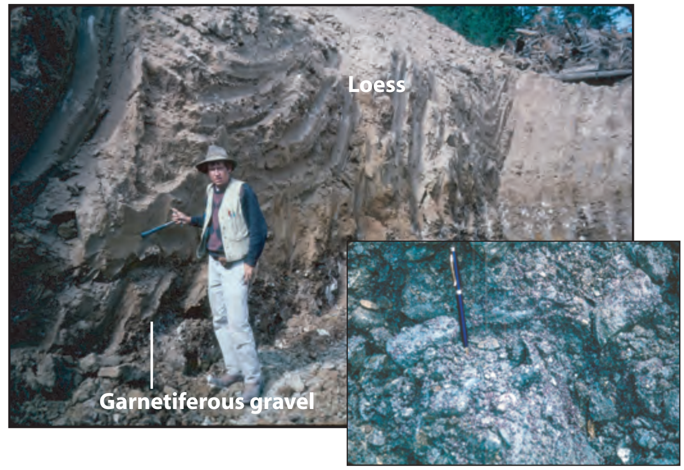

Figure 28. Recent cut through loess and garnetiferous gravel in the Emerald Creek area, Idaho. Inset, closeup of hematite-cemented gravel, showing evidence that garnet-bearing gravel was at the surface before burial by loess. Photograph courtesy of Michael Zientek, U.S. Geological Survey.

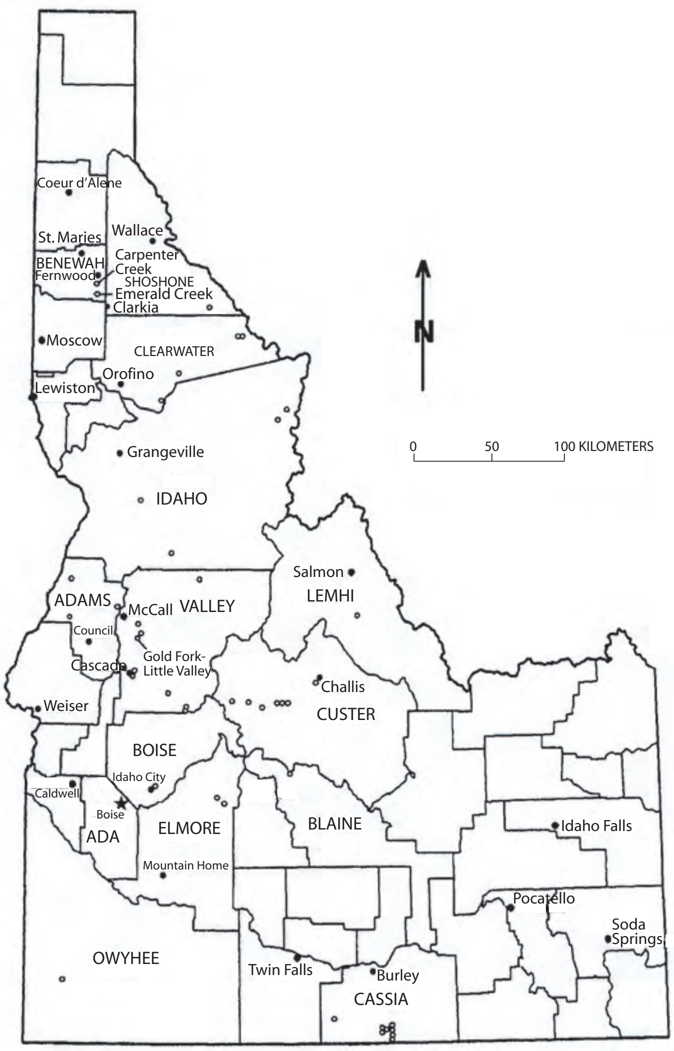

Figure 27. County map of Idaho, showing county boundaries and locations of counties (names in all caps) with garnet deposits (circles). Dots, cities and towns; star, State capital.

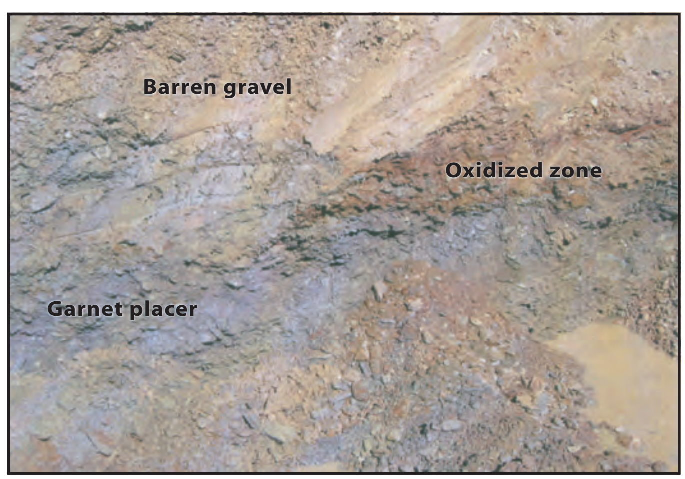

Figure 29. Recent cut through barren surface gravel to garnet placer with upper oxidized zone along Carpenter Creek, Idaho. Exposed thickness of unoxidized (purple) placer is about 1 m, although total thickness may be greater.

centrated in jigs and on shaking tables; the concentrate is then washed, dried, crushed, and screened.

Although garnet occurrences are relatively common in Idaho, the only active garnet mine is the Emerald Creek Mine between the towns of Fernwood and Clarkia in Benewah County (figs. 27, 30). Alluvial garnet placers were known from the Fernwood area in the 1880s, when gold prospectors found garnet clogging up their sluicing equipment. Garnet also occurs in parts of adjacent Clearwater, Latah, and Shoshone Counties and in the black sand placer deposits of central Idaho (discussed below). Commercial operations in northern Idaho did not begin until 1940. From 1944 to 1949, two companies worked garnet placers in two different creeks, Emerald Creek and adjacent Carpenter Creek to the north (fig. 30). From 1950 to 1960, only one company, the Emerald Creek Mining Co., continued mining in Emerald Creek; however, from 1961

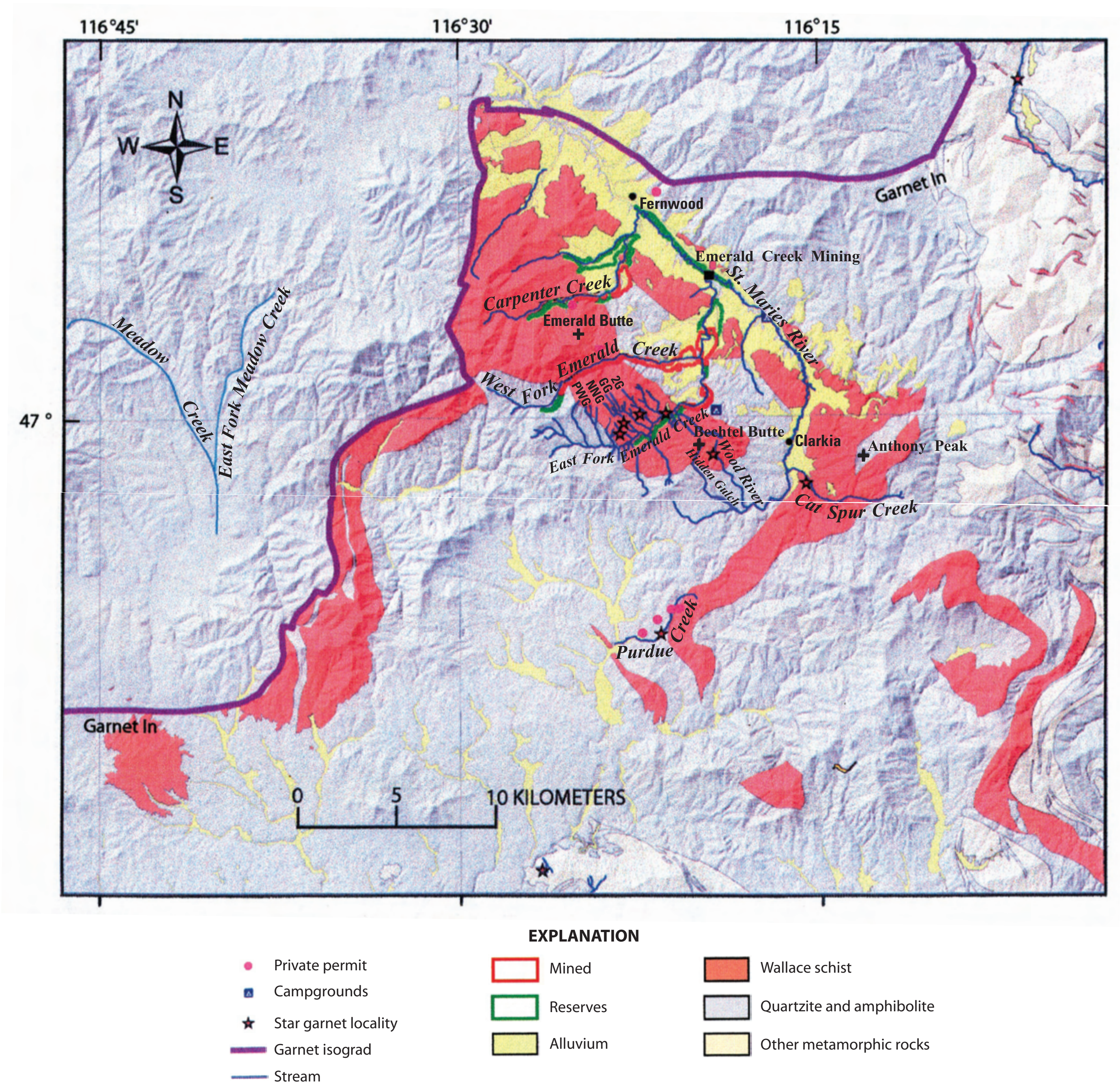

Figure 30. Geologic map of the Emerald Creek area, Idaho. Crosses, peaks. 2G, 281 Gulch; GG, Garnet Gulch; NNG, No Name Gulch; PWG, Pee Wee Gulch.

to 1980, the Idaho Garnet Abrasive Co. mined in Carpenter Creek. From 1964 to 1980, Idaho Garnet Abrasive was a division of the Sunshine Mining Co. From 1981 to 2005, the Emerald Creek Garnet Co. produced garnet from both Emerald and Carpenter Creeks; in 1991, the company became a division of World Garnet International, Ltd., subsequently renamed WGI Heavy Minerals, Inc. In 1997, proven reserves of garnet in the Emerald Creek area were 635,200 t, probable reserves 14,200 t, and indicated resources at least 78,462 t; a more recent (2002) estimate of proven reserves of garnet was lower (table 2). From December 1995 to March 1998, 58,017 t of dry garnet was produced from the Emerald Creek Mine (annual production, ~25,225 t). Other garnet deposits occur along the East Fork of Emerald Creek; along Meadow Creek, about 6.4 km from garnetiferous mica schist; along with gold in the North Fork of the Potlatch River; and along Garnet, No Name, and Pee Wee Gulches and the Little East Fork, south of the present public garnet-panning area in 281 Gulch (fig. 27). Pee Wee Gulch was the former site of the public panning area. Garnet, No Name, and Pee Wee Gulches contain old pits dug to obtain gem-quality garnet.

Star garnet (fig. 31) occurs in association with industrial-grade almandite in 281, Garnet, No Name, and Pee Wee Gulches; other star garnet localities are on Wood Creek, which drains the south flank of Bechtel Butte; on Cat Spur Creek in Benewah County; in Purdue Creek in Latah County; and at a locality along the East Fork of the Potlatch River, about 2 km southeast of Bovill, also in Latah County (fig. 30). The only other area in the world reported to produce star garnet is in India.

Star garnet was designated the official Idaho State gem stone in 1967.

The Emerald Creek Garnet Co. has two leases on private and U.S. Government land that were due to expire in 2005 and 2006, as well as two other leases in the St. Maries River area that are due to expire in 2009. In March 2004, the Section 404 operating permit issued pursuant to the Clean Water Act by the U.S. Army Corps of Engineers was granted a 10-year extension, which included operations on 132 ha in the St. Maries River area; the permitted area includes 54 ha of wetlands adjacent to the company's existing processing plant (WGI Heavy Minerals, Inc., 2005).

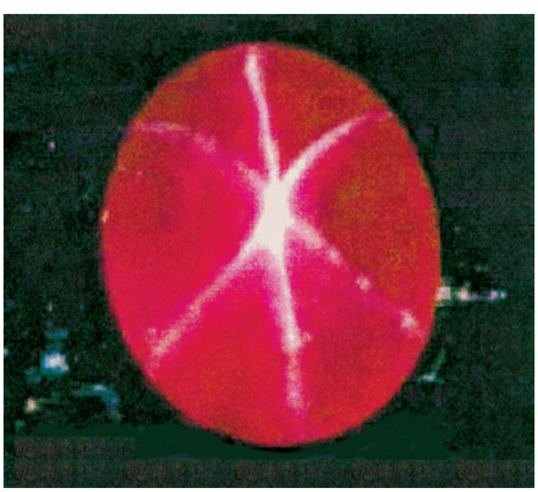

Figure 31. Star garnet.

WGI Heavy Minerals, Inc., imports garnet mined from beach sand from its holdings in India to blend with its domestic product from northern Idaho (Emerald Creek Garnet Co., written commun., 2003). About 90 percent of Indian production is for markets in Asia and the Middle East. WGI's main office and base of its international operations, which include Transworld Garnet Pvt. Ltd., of Tamil Nadu (URL http://transworldgarnet.com/), southeastern India, and Kominex Mineral Mahlwerk GmbH of Ermsleben, Germany, is in Coeur d'Alene, Idaho (Willis, 2003). Branch offices are in Seattle, Wash.; Whittier, Calif.; Rotterdam, the Netherlands; Frankfurt, Germany; and Dubai, United Arab Emirates. WGI's European operation mostly recycles and sells garnet for abrasive airblasting. In 2001, WGI established a subsidiary, WesJet International Services GmbH, so that its garnet customers could obtain needed waterjet parts. In 2005, WGI acquired International Waterjet Parts (IWP), Inc., of Ephrata, Wash., which has a long record of pioneering and service in the waterjet industry, and controls the entire manufacturing process of their equipment and replacement parts (WGI Heavy Minerals, Inc., 2005).

The place of the Emerald Creek-Carpenter Creek garnet placers in the overall resource picture of WGI Heavy Minerals, Inc., (2002) is summarized in table 2. Clearly, northern Idaho garnet resources are small (5 percent of total) relative to the garnet resources blocked out in India. In addition, the Indian operations include other heavy minerals; especially ilmenite, that are not mined along with garnet in Idaho.

Staurolite ($Fe_2Al_9O_6[(Si,Al)O_4]_4(OH)_2$, specific gravity, 3.74–3.83; hardness, 7.5 Mohs; Nesse, 2004) occurs in some of the pebbly gravel tailings along Emerald Creek, the West Fork of Emerald Creek, and Carpenter Creek, but no effort has been made to recover it, and it is unclear whether it can be produced profitably. At least one source of the staurolite seems to be a relatively small area in the central part of the Fernwood quadrangle. Field studies suggest that the detrital staurolite is mainly from a second generation of the mineral, most of which occurs in small grains; however, grains as large as 1 cm across are locally common in dredge tailings along Carpenter Creek, and as much as 3 cm long in metapelite exposed in nearby roadcuts.

Garnet Source

Garnet in the placer deposits in Emerald and Carpenter Creeks derives from weathering of metapelite (retains bedding; fig. 32) and schist (developed schistosity; bedding transposed or obliterated) believed to be the stratigraphic equivalent of shale of the Wallace Formation of the Belt Supergroup (Hietanen, 1963; Lewis and others, 2000). The garnetiferous rock was subjected to deeply penetrative weathering during the Tertiary that resulted in the formation of thick

Figure 32. Metapelite with well-preserved bedding. Inset, hand specimen of bedded metapelite containing garnet porphyroblasts.

saprolitic zones which are locally preserved beneath a varying thickness of overburden of Tertiary gravel and loess. Some of the garnet concentrations are within the saprolitic zones, but most are in the heavy-mineral fractions of gravel overlying and locally intercalated with Tertiary lakebeds in modern and, possibly, ancestral drainages (see below). The area has a history of sedimentation associated with Miocene Lake Clarkia (Rember, 1991) and, possibly, one or more other lakes created by damming of paleodrainages by Columbia River Basalt and (or) Tertiary fault movements. A program of trenching of alluvium in gulches and auger drilling along ridgetops was initiated by the U.S. Forest Service (USFS) in October 2002 under the direction of Christopher Dail to determine where to relocate the public panning area, now in 281 Gulch (fig. 33), if the need to do so arises (lack of garnet or dangerously undercut creekbank). Although the complete results of that study are still pending, perched gravel and sand were observed along several ridgecrests, and garnet-poor as well as garnetiferous gravel was penetrated during trenching. The preponderance of very well rounded granite pebbles and cobbles and abundant kyanite, sillimanite, staurolite, and other resistant heavy minerals (corundum?) in some samples may reflect either a separate provenance or, possibly, more than one cycle of erosion-deposition of the gravel during which the garnet was destroyed.

A USFS lidar survey of a large tract of northern Idaho, including part of the Emerald Creek drainage, provides evidence of recycling of garnet from paleoplacers. The slope map for part of the survey area in the vicinity of 281 Gulch (fig. 33) is interpreted to show an elevated ancestral drainage parallel to a northeast-trending segment of the East Fork of Emerald Creek. The paleodrainage encompasses old garnet diggings in Garnet,

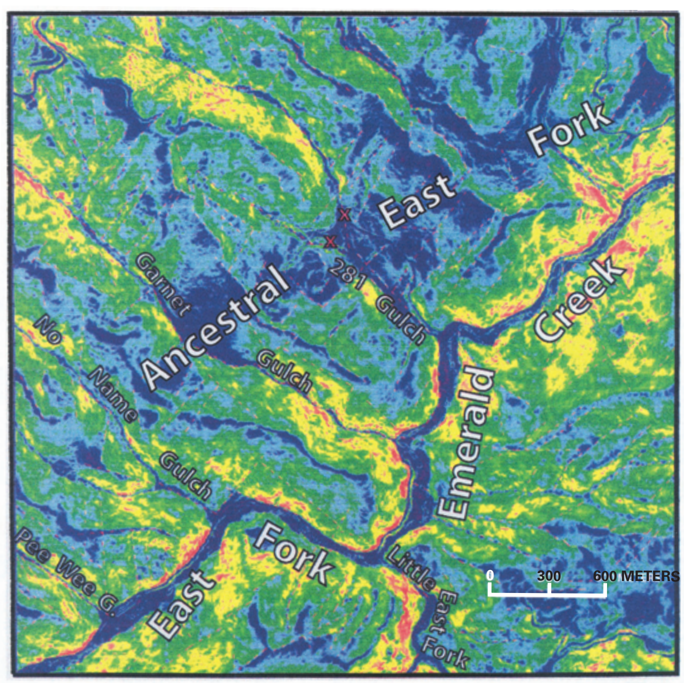

Figure 33. Slope map of part of the East Fork of Emerald Creek, Idaho. Purple and dark-blue areas, low slopes along streams and ridgetops; orange and red areas, steep slopes along roadcuts and bordering incised channels of the East Fork and its tributaries. Courtesy of Christopher Dail, U.S. Forest Service. Red Xs, public panning areas.

No Name, and Pee Wee Gulches and the two public panning sites along forks of 281 Gulch.

The evidence of multistage erosion-deposition suggests that some of the garnet in alluvial deposits of Emerald and Carpenter Creeks and of the St. Maries River in the Clarkia-Fernwood area may not have come from nearby rocks but from metamorphosed rocks to the south and (or) east of Clarkia that underwent garnet-grade or higher-temperature metamorphism. Cyclic erosional processing of garnet may explain the occurrence of garnet along Meadow Creek, which is west of garnetiferous metapelite of the Wallace Formation. Recognition of peak metamorphic grade in potentially garnetiferous rocks southeast of Clarkia is obscured by intensive biotite-grade metamorphism that destroyed traces of garnet and higher-grade index minerals, as well as earlier structural elements.

Description of Garnet

Garnets in the Emerald Creek area (figs. 30, 33) range in color from pink to dark red, purple, and dark maroon and are as large as 2 cm across. Some dark-red to reddish-black opaque garnets have the pronounced multirayed asterism of star garnet (fig. 31). At least eight localities where star garnets have been obtained are in and near the Emerald Creek deposits (fig. 30). Inclusions responsible for asterism are composed of rutile (Johnston, 1983).

Garnets occur in metapelites as euhedral to subhedral porphyroblasts and anhedral grain fragments. Textures suggest that they coexisted with the metamorphic aluminosilicate minerals kyanite, staurolite, and sillimanite, indicating garnet formation and (or) stability in the amphibolite facies; metamorphism as high as sillimanite-muscovite zone is locally accompanied by little or no garnet. The garnets have a specific gravity of 4.0 to 4.1 and a hardness of 7.5 to 8.0 Mohs (Emerald Creek Garnet Co., written commun., 2003). The garnets contain numerous solid inclusions of ilmenite, apatite, quartz, zircon, monazite, tourmaline, and fluid (fig. 34). Many garnets have highly fractured margins and an Fe oxide shell. Some garnets are so heavily weathered that they crumble under slight stress.

Garnets from 12 localities in the Emerald Creek area (fig. 30) range in color from light pink to deep red and consist of 80 weight percent almandite (West and others, 2005). Cores are relatively rich in Ca and Mn, and rims in Fe and Mg. Inclusions tend to be aligned in concentric growth zones in some garnets. The garnets are composed of 33 to 39 weight percent SiO_2, 20 to 23 weight percent Al_2O_3, 0.5 to 2.5 weight percent MnO, 34 to 38 weight percent FeO, and 0.25 to 4.25 weight percent MgO. Except for CaO, these compositions are close to the composition of almandite in the placer deposits of the Emerald Creek area, according to the Emerald Creek Garnet Co. (fig. 30; see above). Garnets that persist in the gravel are rich in alumina (>22 weight percent Al_2O_3) and manganese (1.5–2.5 weight percent MnO); many are rimmed with secondary minerals, chiefly Fe oxide minerals (fig. 34), that show zoning of Al content and fill veins in the garnet. On the basis of the differences in composition of the garnets, some of the garnet in placers did not come from local schist (N. Foley, oral commun., 2006). A crystallization temperature of 500–600ºC was estimated from two-mineral geothermometry, with the temperature increasing throughout garnet growth (Nicholson and others, 2003); the locations of the samples analyzed were not described.

Mineral relations in the Emerald Creek area (fig. 30) are complex because both prograde and retrograde reactions have occurred (fig. 35). Much of the heat and strain recorded in these rocks may be from emplacement of the Bitterroot lobe of the Idaho batholith (Barton and others, 1988), but one or more previous metamorphic events are suggested by widespread kyanite and sillimanite. Recently obtained Lu-Hf ages on garnet from the Emerald Creek area that range from about 1,065 to 1,285 m.y. support a protracted deformational and metamorphic history for metapelites in that area (Jeffrey Vervoort, written commun., 2006). A Mesozoic(?) granitic intrusion is exposed along the West Fork of the St. Maries River, about 3 km south of the garnetiferous metapelite on Bechtel Butte (fig. 30; Hietanen, 1963). The northeast-trending granite dike, 4 km long and 0.6 km wide at its broadest part, may be responsible for the epidote-amphibolite metamorphism of nearby calc-silicate rocks included in the Wallace Formation. Pegmatite veins and (or) thin granitic dikes occur in metapelitic and calc-silicate rocks in the Emerald Creek area. Some of the metapelitic rocks may have undergone late greenschist-facies metamorphism, accompanied by complex deformation that included modification or obliteration of earlier fabric elements.

Garnet in Black Sand Deposits of Central Idaho

The following narrative is adapted from the monograph by Savage (1961). Information for the period 1951–66 is from the

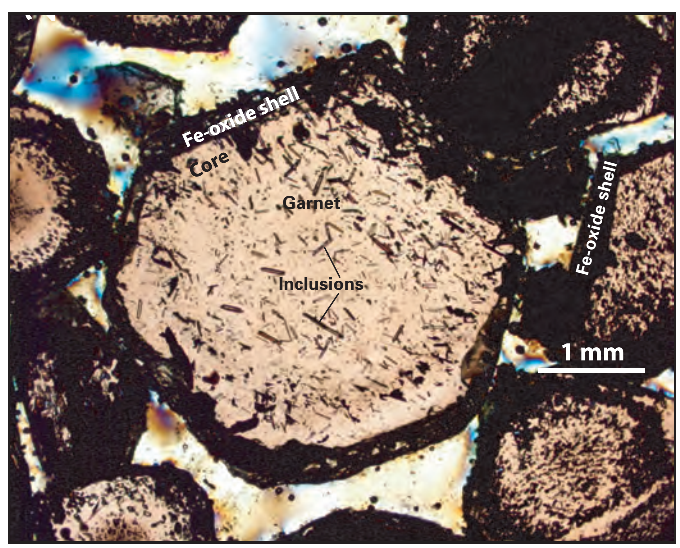

Figure 34. Inclusions in garnet from the Emerald Creek area, Idaho. Photomicrograph courtesy of Nicolle West, U.S. Geological Survey.

Minerals Yearbook (Baber and others, 1956, 1959a, b; Fulkerson and others, 1962, 1963; Gray and others, 1964; Knostman and Petersen, 1965; Carrillo and others, 1967; Collins and others, 1967).

From 1951 to 1966, one to three companies produced garnet as a byproduct of black sands in Valley County, central Idaho (fig. 27). Target minerals were ilmenite, monazite, and rare-earth-rich heavy minerals; garnet was also concentrated and sold. Gem-quality garnet occurs close to garnetiferous black sand deposits in the area of the North Fork and Little North Fork of the Clearwater River in Clearwater County.

The discovery of gold in sand and gravel deposits near Pierce in Clearwater County (fig. 27) started a widespread search for other placer and lode minerals. Since then, nearly all of central Idaho's black sands and many streams have been worked for gold. Overlooked in the past were dark heavy minerals that may potentially constitute resources of niobium, yttrium, zirconium, hafnium, uranium, thorium, titanium, and rare-earth elements. More than 50 minerals are present in the heavy-mineral suites. The black sand placers were formed as a result of erosion, sorting, and deposition of heavy minerals from disintegrating rocks of the Idaho batholith and associated meta-

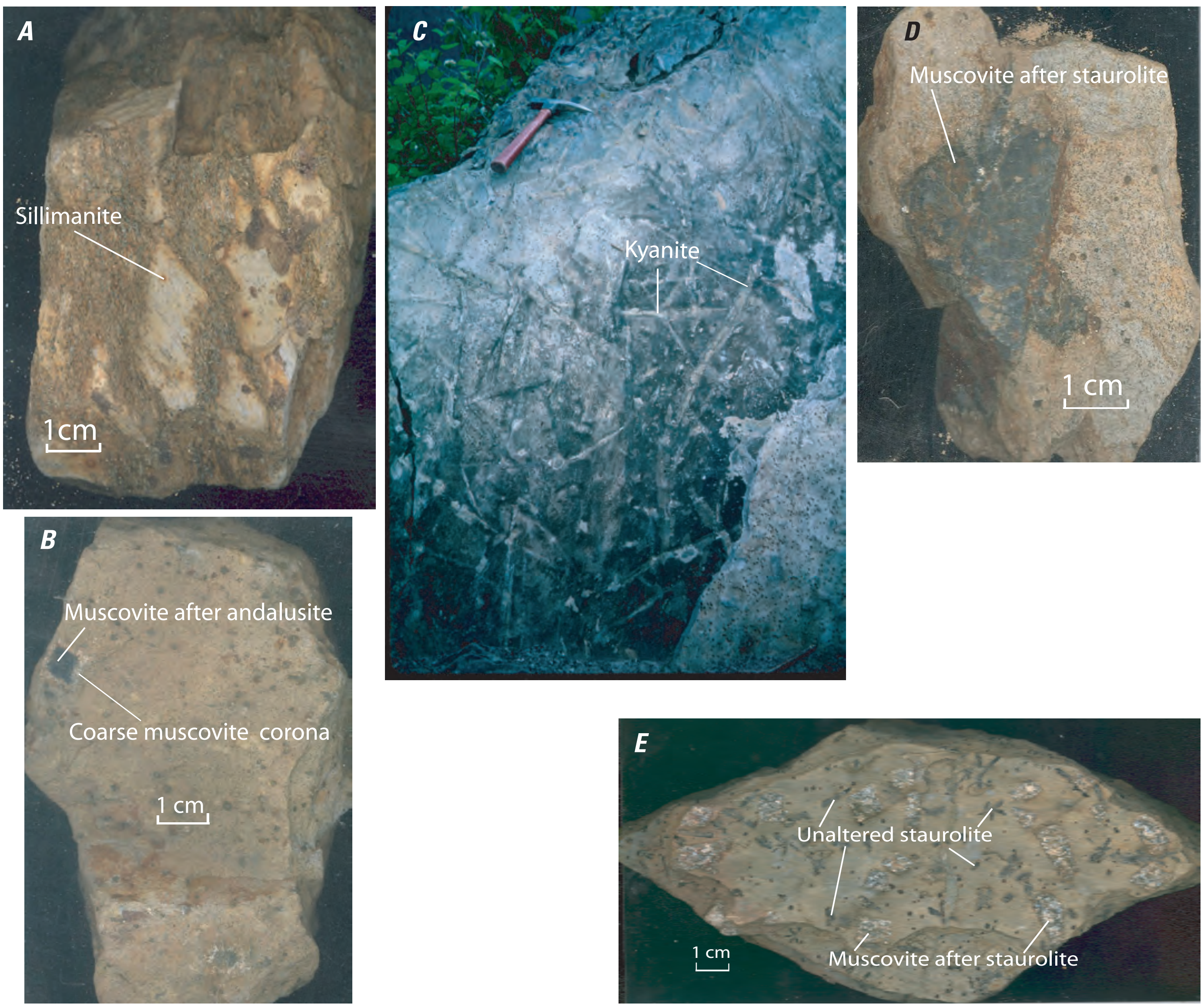

Figure 35. Metamorphic minerals in rocks from the Emerald Creek area, Idaho. *A*, Sillimanite in garnet-mica schist. *B*, Muscovite pseudomorph after andalusite; blue-gray core consists of fine-grained chaotic muscovite, in contrast to coarser silvery-gray muscovite along margins. *C*, Large kyanite porphyroblasts in metapelite, partly altered to sillimanite; small purple dots are garnet. Photograph courtesy of Michael Zientek, U.S. Geological Survey. *D*, Blue-gray muscovite pseudomorphs (such as described in fig. 35*B*) after twinned early staurolite. *E*, Two generations of staurolite: first-generation porphyroblasts are large and altered to muscovite; second-generation porphyroblasts are small and unaltered.

morphic rocks and the accumulation of heavy minerals during one or more cycles of uplift, erosion, and deposition. Garnet is virtually ubiquitous in heavy-mineral concentrates. Although no areas containing abundant garnet have been found in association with the black sand deposits, garnet sand is one of the mineral concentrates that have been produced from the placers and marketed.

Mining and processing of the black sands of central Idaho for garnet is recorded in the *Minerals Yearbook* as far back as 1946–48, when Baumhoff-Marshall, Inc., and the Idaho-Canadian Dredging Co., working jointly, saved part of their jig-concentrated black sands while dredging for gold near Centerville in Boise County (fig. 27; Savage, 1961). These black sands, stockpiled mainly for monazite, zircon, ilmenite, and other minerals containing rare earths, uranium, and thorium, were eventually reprocessed for garnet. In 1949, Rare Earths, Inc., planned to produce garnet as a byproduct of its monazite operations (Metcalf, 1951); no further mention of this company or operation was found. In 1952, three companies were dredging near the town of Cascade in Valley County: Baumhoff-Marshall, Inc., the Idaho-Canadian Dredging Co., and Warren Dredging (Kaufman and others, 1955). In 1953, the Idaho Titanium and Mining Co. recovered abrasive garnet at its plant in Idaho County. The concentrate was originally dredged by the K&D Mining Co. at Ruby Meadows near Burgdorf in Idaho County (Baber and others, 1956). In 1957, Baumhoff-Marshall produced concentrates of garnet, monazite, zircon, and ilmenite at its plant in Ada County. From 1951 to mid-1955, the company reprocessed stockpiles that were obtained from black sand deposits near Cascade in Valley County; all fractions were shipped out of State. Porter Brothers Corp. produced heavy minerals containing niobium and tantalum (columbite [niobite], tantalite); and rare earths, thorium, and uranium (euxenite, monazite) from sand dredged from Bear Valley in Valley County. The rough concentrate was shipped to Lowman in Boise County for final separation (Baber and others, 1959a). In 1958–59, Porter Brothers dredged heavy minerals from Bear Valley, and the rough concentrate was shipped to its plant at Lowman for final separation. Concentrates of columbite, euxenite, monazite, magnetite, ilmenite, and garnet, and zircon-quartz sand were produced. Columbite and euxenite were shipped out of State, and the rest of the sand concentrates were stockpiled at Lowman. The last shipment of euxenite concentrate was sent in 1959 to fulfill a government contract (476 t containing 90 weight percent Ni-Ta pentoxides; Kiilsgaard and Hall, 1995), and that part of the operation was shut down. In 1959, J.R. Simplot bought the Baumhoff-Marshall processing plant and continued to reprocess the stockpiles of rough concentrate that had been mined from Valley County. Over time, Porter Brothers' dredging decreased, crude concentrates were stockpiled, and heavy-mineral concentrates, including garnet, were produced from the stockpiles. The latest garnet production was in 1966, when a small shipment was sent by Porter Brothers from its stockpile at Lowman.

A few black sand deposits were examined by the former U.S. Bureau of Mines. The black sand deposits at Gold Fork in western Valley County, which were worked for gold, are no longer active. These deposits, which are near the margins of the Baker and Challis 1º×2º quadrangles (Fisher and Johnson, 1995, pl. 23), are included in an area of high potential for radioactive black sand placers. Ilmenite and other black sand minerals that occur in alluvium along the Gold Fork River on the east side of Long Valley, 18 km north of Cascade, were derived from schist, gneiss, amphibolite, and granitic rocks of the Idaho batholith. Storch (1958) studied the deposits along a segment of the river, beginning at the junction of the Gold Fork and Payette Rivers, as part of the 1951 Atomic Energy Commission's Western Radioactive Minerals Program, and later to determine how much of the black sand was unminable owing to inundation by highstands of water in the Cascade Reservoir. The deposits are in a segment of the Gold Fork River, about 10 km long by 300 to 1,200 m wide. A total of 31 holes, ranging in depth from 17 to 43 m, were drilled into the deposit, and core was recovered. The range of heavy-mineral content of unprocessed samples was not reported, nor was the composition of the garnet. The garnet content of composited black sand fractions from four holes drilled in 1956 ranged from 15 to 27.4 weight percent, second only to the ilmenite content (40–50 weight percent).

The Little Valley deposit, 30 km north of Cascade near the junction of Little Valley Creek (as named in Schmidt and Mackin, 1970; the North Fork of the Gold Fork River in Storch and Holt, 1963) and Flat Creek, was mined for gold. The alluvial gravel underlies an area of 890 ha to an average depth of 9 m. The deposit is underlain by fine-grained lacustrine sedimentary materials with a low black sand content. The garnet content of the gravel was not reported (Storch and Holt, 1963).

Montana

Overview

Between 1996 and 2005, garnet was sporadically produced from two mines in Madison County, southwestern Montana (figs. 36, 37): the Ruby Garnet Mine (Cominco Ltd./Green Diamond Abrasives, the Montana-Oregon Investment Group, LLC, and Ruby Valley Garnet, LLC) at Alder, about 100 km south of Butte; and the Sweetwater Garnet Mine (Absolut Resources Corp., Cominco Ltd., and Stansbury Holdings Corp.), about 16 km east of Dillon (figs. 36, 37). At the Ruby Garnet Mine, garnet was recovered from the large gold dredge tailings immediately east of Alder. Other placer tailings are present for several kilometers along Alder Gulch east of Alder and south of Virginia City, but until the mid-1990s, no efforts to recover the heavy minerals, other than gold, that might be present there were reported. The Ruby Garnet Mine was initially constructed and operated by Green Diamond Abrasives, a subsidiary of Cominco Ltd. Later, the mine was sold to the Montana-Oregon Investment Group, LLC, which operated it for a few years and then sold it to Ruby Valley Garnet, LLC, in 2004. Ruby Valley Garnet abandoned the dredge tailings, began mining much higher grade Tertiary and (or) Quaternary alluvial deposits,

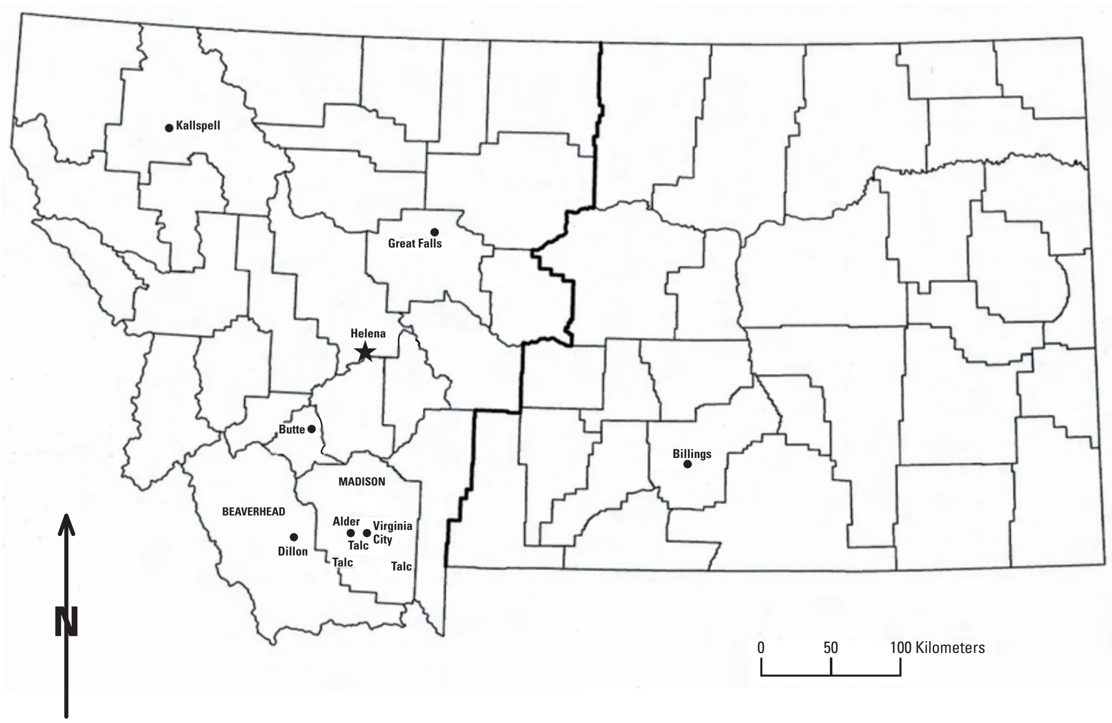

Figure 36. County map of Montana, showing county boundaries and locations of counties (names in all caps) with garnet occurrences. Talc, talc occurrences. Dots, cities and towns; star, State capital.

and processed garnet sand in the plant constructed by Green Diamond.

Ruby Garnet Mine

Part of the following narrative is adapted from the map by Van Gosen and others (1998). Mining in the Virginia City area of Madison County began in 1863 with the discovery of gold in Alder Gulch (Tansley and others, 1933), a tributary of the Ruby River (fig. 38). Gold-quartz vein deposits were discovered shortly afterward, and by 1870 several lode mines were in operation. The present tailings were created by a succession of gold dredges that began operations in 1889 near the town of Ruby (near Alder) and in 1896 expanded into Alder Gulch. The gulch, which extends for 21 km from its headwaters south of Virginia City to the Ruby River, was the largest gold placer deposit in Montana. About 90 million t of alluvium were mined from 1899 to 1922 by the Conrey Placer Mining Co. (Santini and Barker, 2003). According to Dingman (1932), placer mining was ongoing in 1932. Total production of placer gold from Alder Gulch was more than 2 million troy oz. Stacked tailings were produced by the dredges that separated gravel from auriferous sand and placed the gravel on previously processed sand. Most of the garnet occurs in the sand.

In the 1990s, attention switched to the garnet that occurs in the voluminous (~38,400 m^3) dredge tailings in Alder Gulch, especially in sec. 9, T. 6 S., R. 4 W., just

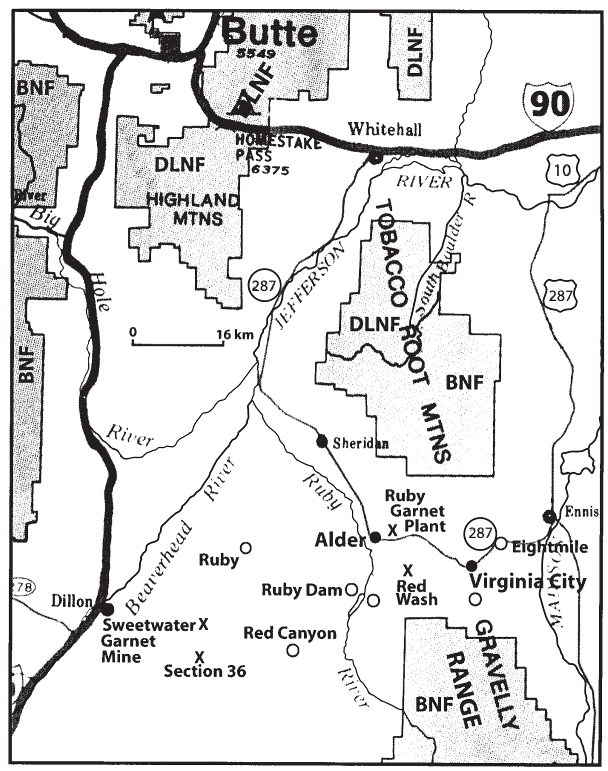

Figure 37. Part of Butte, Mont., area, showing locations of landmarks, including the Ruby Garnet Mine plant, Red Wash, the Sweetwater Garnet Mine, the Section 36 garnet deposit, and other sites mentioned in text. BNF, Beaverhead National Forest; DLNF, Deer Lodge National Forest.

east of the town of Alder and south of the town of Ruby. Cominco Ltd. bought the tailings in 1989. From 1992 to 1994, Cominco Ltd.'s Green Diamond Abrasives subsidiary sampled the tailings, including drilling 17 reverse-circulation holes in the tailings, experimented with beneficiation, tested pilot-plant operations, and conducted market-feasibility studies. On the basis of this work, proven reserves were estimated at about 29.5 million t containing 4.5 weight percent garnet. Construction of the plant began in 1994, and production started in 1996.

The garnet from tailings at the Ruby Garnet Mine consists of violet-red and reddish-brown almandite-pyrope that is chemically inert, has a specific gravity of 3.8 to 4.2 and a hardness of 7.5 to 8 Mohs, is angular to subangular in granularity, is reusable, and is nonhygroscopic (Santini and Barker, 2003). Most of the garnet sales were for waterjet cutting at a list price of $240/t free on board at the mine but the garnet is also suitable for abrasive airblasting. Green Diamond produced garnet from 1996 to 1999; by 1999, the property had been for sale for some time.

U.S. Geological Survey accounts for 1999 and 2000 conflict; either the property was sold to the Montana-Oregon Investment Group, LLC, in 1999 (U.S. Geological Survey staff, 2001), or Green Diamond Abrasives took an option on the Ruby Garnet Mine in 2000 (U.S. Geological Survey staff, 2002a). Inasmuch as Green Diamond Abrasives (see above) was a subsidiary of Cominco Ltd. that operated the Ruby Garnet Mine near Alder as of July 1996 (Green Diamond Abrasives, written commun., 1998), the first version of events is more likely. Santini and Barker (2003)'s version is that the mine was sold in 2000 to the Montana-Oregon Investment Group. The company produced garnet for nearly 3 years and stopped production in 2002. At that time, two potential buyers had been identified; one wanted to operate the mine, and the other wanted to salvage the equipment (Harben, 2002). As of spring 2003, the mill was to be salvaged (R. Berg, written commun., 2003), although a skeleton crew was still in maintenance mode at the mine in September 2003. At that time, about 5 percent of the extensive dredge tailings in sec. 9, just east of Alder, were closed to mining because they will be the site of a sewage-treatment plant for the town. Another small part of the western margin is being used as a local dump. A more substantial part of the western tailings has been processed for garnet.

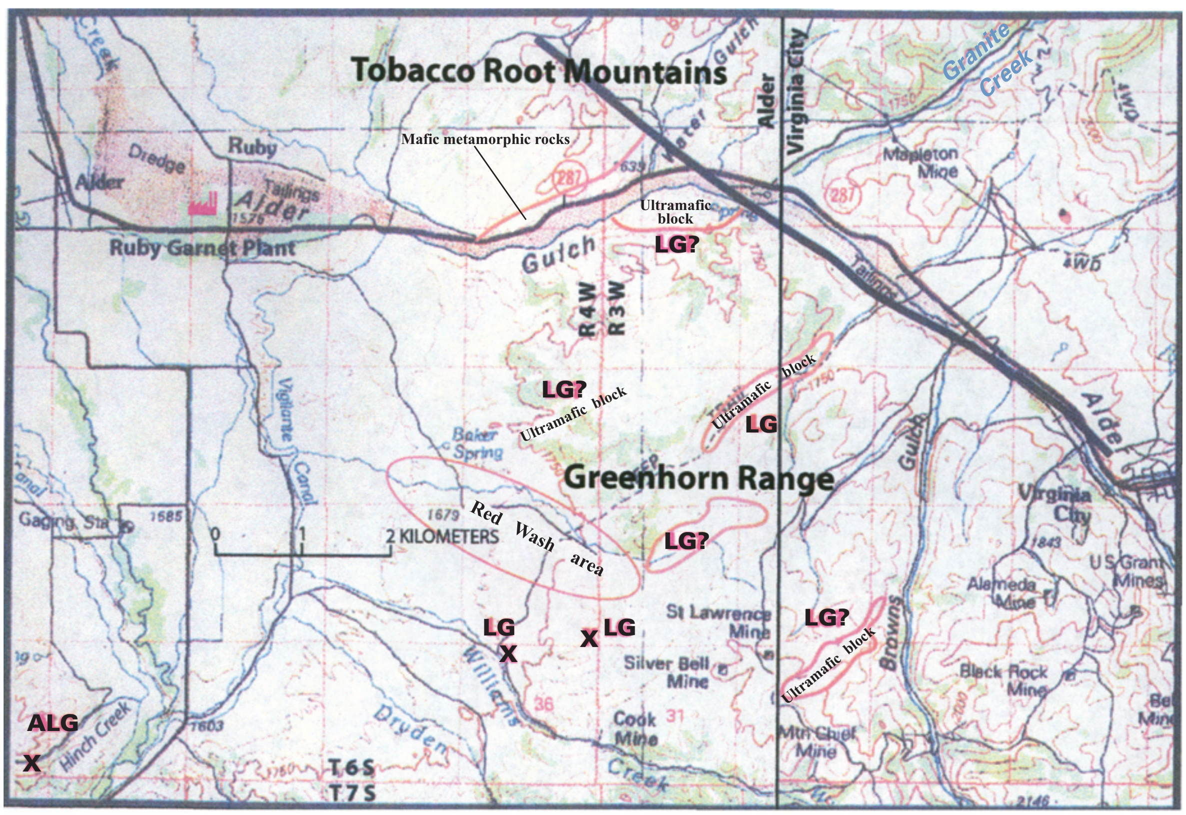

Figure 38. Alder, Mont., area, showing locations of garnet-rich rocks and garnet placers (geology adapted from Vitaliano and others, 1979, and Wier, 1882, supplemented with 2005 field observations). Red lines, approximate areas containing garnet and (or) garnet potential; thick black line, fault; red Xs, garnet-rich outcrops; AG, alluvial garnet deposit; ALG, combined alluvial and lode garnet deposits; LG, lode garnet deposit; LG?, potential lode garnet deposit. Locations of ultramafic blocks south of Alder Gulch from Wier (1982).

In 2004, the mine was sold to Ruby Valley Garnet, LLC (Hart Baitis, proprietor), which began mining garnet from alluvial deposits from a drainage about 4 km southeast of Alder informally named Red Wash (fig. 38). The garnet was processed at the existing Ruby Garnet Mine plant and sold for abrasive airblasting and waterjet cutting.

Bedrock sources of the garnet are Archean rocks, principally amphibolite, biotite schist (fig. 39), migmatite (fig. 40), and some contiguous pegmatite and granite that intrude the Indian Creek Metamorphic Suite (Vitaliano and others, 1979) in the southern Tobacco Root Mountains (north of Alder Gulch; see Brady and others, 2004, for details of the geology) and similar rock in the northern Greenhorn Range (south of Alder Gulch; Weir, 1982). At least one period of granitic emplacement that postdates the migmatite destroyed garnet and mafic minerals in its aureole by altering them to chlorite and talc and by potassic metasomatism. Garnet placer and lode deposits are commonly associated with such rocks as mafic and ultramafic metamorphic rocks (black garnet-hornblende and “blackwall” of Vitaliano and others, 1979). Much of Alder Gulch is flanked by garnetiferous rock (figs. 38–40), and so a large fraction of the garnet in the dredge tailings is not far from its bedrock source.

At Red Wash (figs. 38, 41), focus is on the younger channels in the Tertiary and (or) Quaternary sand and gravel. The apparent garnet source is the 100-m-thick section of exceptionally garnetiferous rocks in the N½ sec. 30, T. 6 S., R. 3 W. (fig. 38), on the north flank of upper Red Wash. The lode deposit contains much garnetiferous amphibolite, garnetiferous granitic dikes, and thin layers of garnetiferous biotite schist with sillimanite. Garnet porphyroblasts larger than 4 cm across are common.

Sweetwater Garnet Mine

The Sweetwater garnet deposit is on 753 ha of private land in secs. 16, 17, 20, and 21, T. 8 S., R. 6 W., at the northwest end of the Sweetwater Basin in Madison County, about 16 km east of Dillon and 35 km southwest of the Ruby Garnet Mine (figs. 37, 42). Absolut Resources Corp. (URL http://absolutresources.com/; a recent visit to their Web site did not reveal any existing garnet operations), the earliest owner of the Sweetwater Garnet Mine, began operations in 1996 with plans to market its product as airblast abrasives under the trade name Red Dog Garnet. Production facilities, equipment, and an open pit were located in the N½SW¼ sec. 17. The deposit was estimated to contain 8 weight percent almandite in alluvial deposits. The garnet source was believed to be the surrounding quartzofeldspathic gneiss (Ruppel and others, 1993); however, the quartzofeldspathic gneiss observed in that area generally contains little garnet. Soon after making plans for mining garnet, Absolut sold the mine to Cominco Ltd., which put its operations at the Sweetwater Garnet Mine up for sale in 1998 (fig. 42; U.S. Geological Survey staff, 2000) and ceased operations in August of that year. The mine was acquired by Stansbury Holdings Corp. and was inactive as of fall 2003. In 2004, the mine was turned back to the Helles family that owns the land, the production equipment was removed, and the surface was reclaimed.

The mine area (fig. 42) was mapped by James (1990) and is included in his broadly defined quartzofeldspathic gneiss

Figure 39. Biotite schist containing garnet-rich nodules and lenses (G) in the Alder Gulch area, Mont. (figs. 37, 38).

Figure 40. Migmatite in the Alder Gulch area, Mont. (figs. 37, 38). Fragments of garnetiferous amphibolite are separated by garnet-rich pegmatite veins.

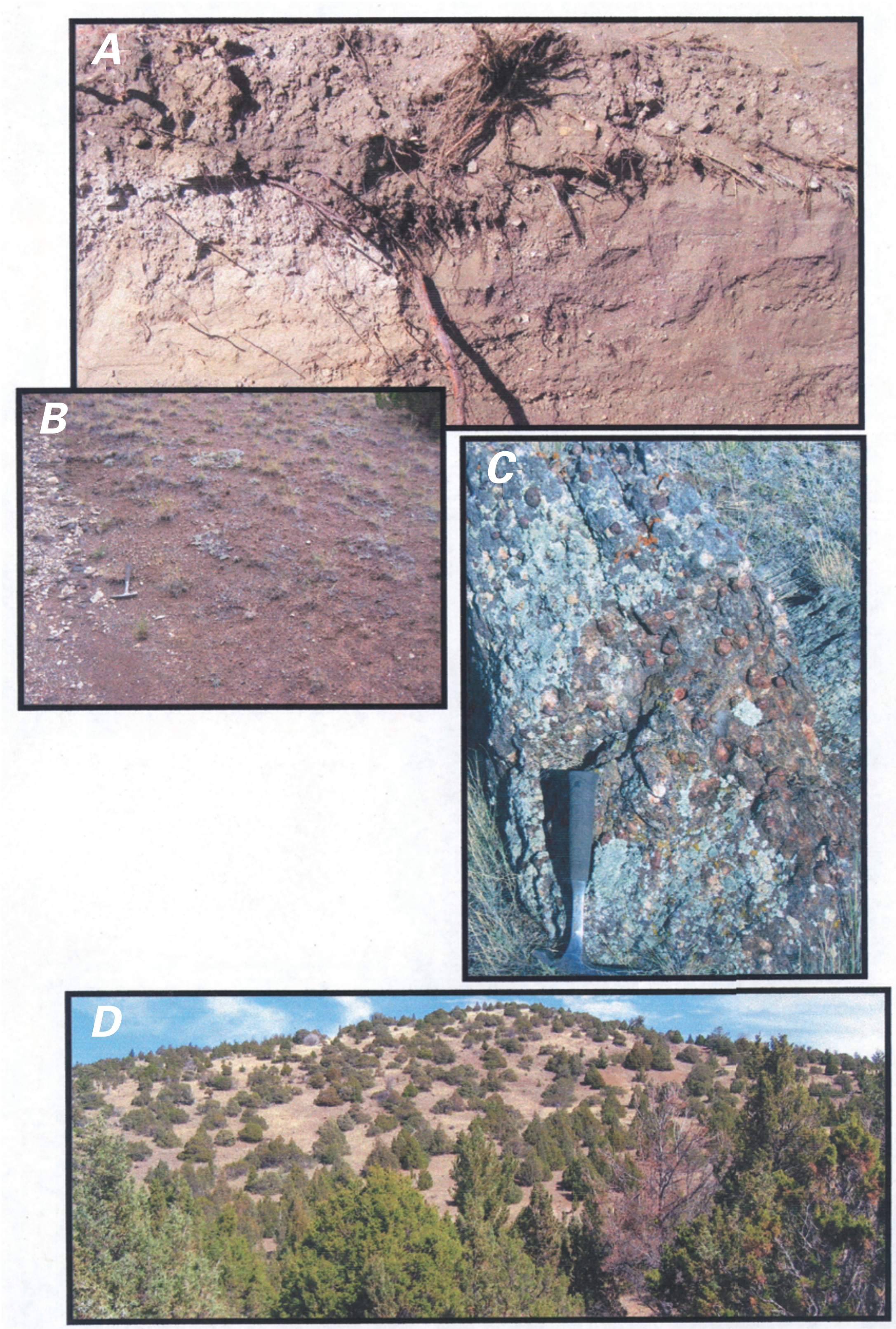

Figure 41. Red Wash deposit, Mont. *A*, Trench wall at right angle to trend of Red Wash. Reddish brown garnetiferous gravel (right) fills cut in pale-gray older alluvial-fan deposits (left). *B*, Undisturbed high-grade garnetiferous sand and gravel in upper Red Wash. *C*, Garnet amphibolite exposure near Red Wash. *D*, Ridge on north margin of Red Wash exposes a 100-m-thick section of exceptionally garnet rich rocks (brown); source of garnets in Red Wash.

(unit WVqg). Study of the deposit in 2003 by the first author indicated that the principal garnet-bearing zone at and near the mine is saprolitic mica schist, containing as much as 20 volume percent garnet, under an overburden of 0 to 4 m of barren surface gravel and sand (fig. 43); the saprolite may have been misinterpreted as Tertiary sand and gravel. Saprolitic mica schist and surficial lag deposits containing garnet (fig. 44) are widespread south of the mine. Garnet is also abundant in nearby biotite schist. Pegmatite and granite nearby are barren.

Evaluation of the Ruby Garnet and Sweetwater Garnet Mines

Garnet in the dredge tailings near Alder and in saprolite at the Sweetwater Garnet Mine do not clearly meet the criteria for an economic deposit, using 20 weight percent as the lower cutoff of the grade and the apparent sizes of the resources (see subsection above entitled "Evaluation of Garnet Deposits"). The dredge tailings at Alder surpass the minimum tonnage requirements, but the garnet grade (4.5 weight percent) is too low. The grade of the garnetiferous saprolite at the Sweetwater Garnet Mine may be as much as 20 weight percent or even higher, and garnetiferous saprolite may underlie the low ridges south of the mine to an unknown depth, but garnet resources in the saprolite have not been estimated.

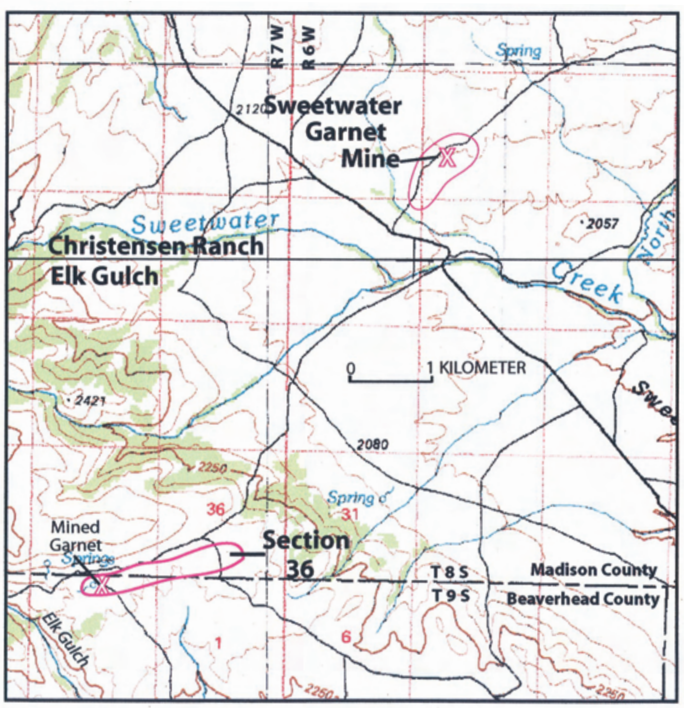

Figure 42. Sweetwater Creek area, Mont., showing locations of the Sweetwater Garnet Mine and the Section 36 garnet deposit. Red ovals enclose areas rich in garnet.

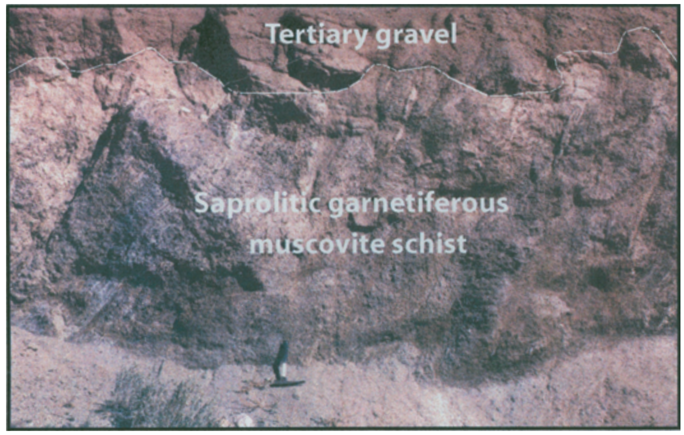

Figure 43. Pit wall at the Sweetwater Garnet Mine, Mont. (figs. 37, 42).

Section 36 Deposit

Ruby Valley Garnet, LLC, has claims covering a lode and alluvial garnet deposit informally known as Section 36 (fig. 42) northeast of Elk Gulch on the Beaverhead-Madison County boundary. The claim area is adjacent to part of the Elk Creek vermiculite deposit of Berg (1995; map scale, 1:6,000; formerly the Dillon nickel prospect of Sinkler, 1942). The garnetiferous rocks occur in a zone about 2 km long by 0.05 km wide, trending east-northeast, in sec. 36, T. 8 S., R. 7 W.; in the SE¼ sec. 35, same township; and in the NE¼ sec. 2, T. 9 S., R. 7 W. Lode ore consists chiefly of garnet-hornblende rock (figs. 45*A*, 45*B*). On the north and east, the ore body is partly enclosed in amphibolite, granitic gneiss, and biotite gneiss that contain small amounts of garnet; biotite gneiss is also present along part of the southwest end of the garnet amphibolite. Ultramafic rocks, largely harzburgite, and ultramafic metamorphic rocks (figs. 45*C*, 45*D*) nearby appear to compose a

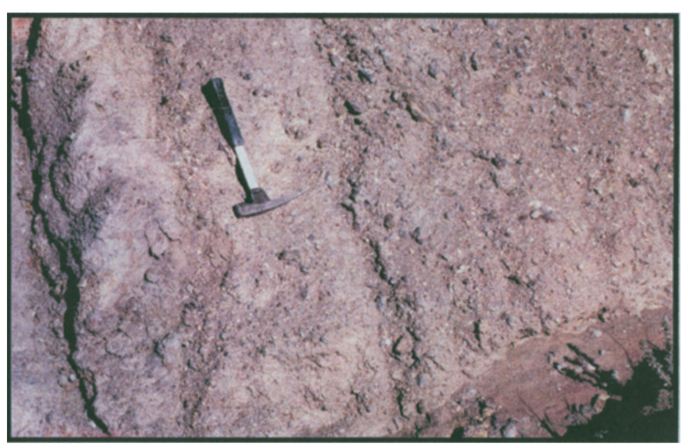

Figure 44. Garnet-rich saprolite south of the Sweetwater Garnet Mine, Mont. (figs. 37, 42). Garnet is further concentrated to 100 weight percent in small sand bars in ditch (lower right).

slab that overlies part of the garnet amphibolite on the east and south and truncates the amphibolite on the west (Berg, 1995). Desmarais (1976, 1981) described the ultramafic rocks as consisting of hypersthene megacrysts, amphiboles (actinolite/tremolite, anthophyllite/cummingtonite), spinel, and olivine. Most of the ultramafic rocks are metamorphosed to black hornblendite (no garnet); some of the hornblende forms pseudomorphs after orthopyroxene, the boundaries of which are etched on weathered surfaces, so that the coarse grains, crude layering, and folds in the harzburgite protolith can be identified despite the metamorphism. The garnet ore zone appears to be truncated on the west by ultramafic metamorphic rocks devoid of garnet. In 2003, Stansbury Holdings Corp. produced some garnet from a small (2,500-m^2 area) part of the ore zone, which has been reclaimed; its primary interest was in nearby vermiculite deposits (Willett and Potter, 2004). Garnet-rich colluvial and alluvial(?) deposits extend an unknown distance to lower elevations southeast of the garnet amphibolite.

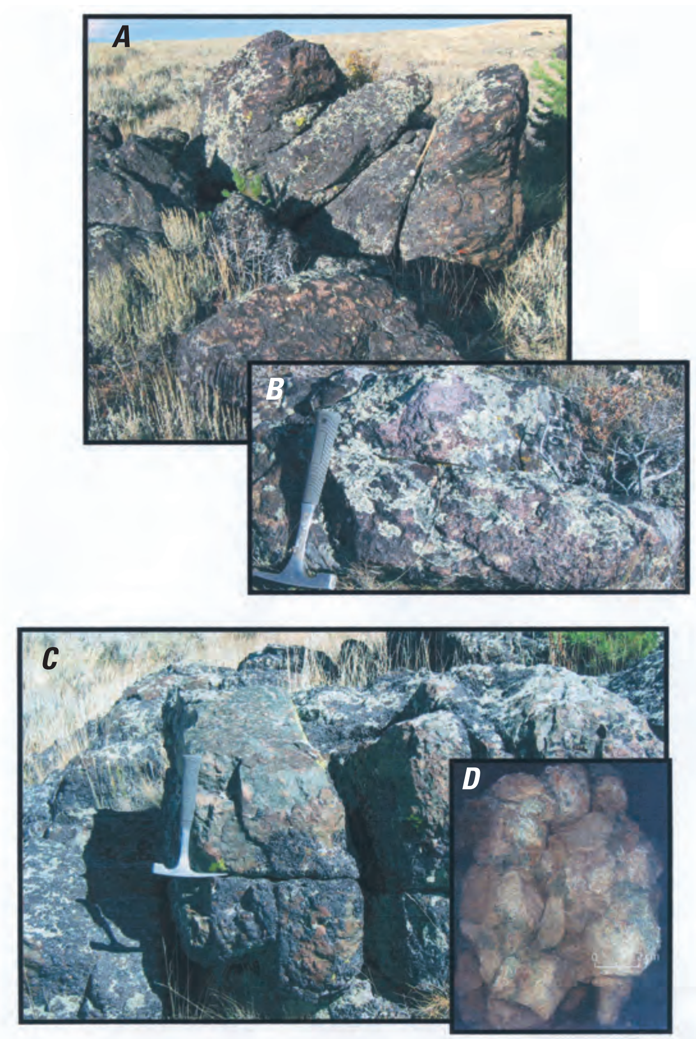

Figure 45. Rocks associated with the Section 36 garnet deposit, Mont. (figs. 37, 42). *A*, Garnet-hornblende rock, principal garnet source; red, garnet; black, hornblende. *B*, Large pink garnet in garnet-amphibolite. *C*, Coarse-grained harzburgite on southeastern flank of lode garnet deposit. Crude layering is approximately horizontal. *D*, Hand specimen of harzburgite; brown, enstatite; green, olivine.

Other Garnet Occurrences

The garnetiferous zones along Alder Gulch, in Red Wash, in the northwestern part of the Sweetwater Basin, and in Section 36 are four of several garnet-rich bedrock sources in the area. Substantial amounts of garnetiferous rock were discovered in the following localities (fig. 37): (1) at an unnamed pass 6 km east of Virginia City on Montana Highway 287 in the headwaters of Eightmile Creek; (2) in granite along the east flank of Alder Gulch, a few kilometers south of Virginia City; (3) in rocks on both sides of the Ruby Dam, about 10 km south of Alder, including along Hinch Creek (southwest corner, fig. 38); and (4) in the headwaters of the North Fork of Stone Creek, about 1 km east of the Treasure Mine (talc) in the Ruby Mountains. Stream-gravel and alluvial-fan deposits in the headwaters of Eightmile Creek and the Ruby River may contain large amounts of garnet derived from the highly garnetiferous bedrock, but no placer deposits from those areas have been described. Hinch Creek has a local reputation for containing garnets, and rocks along the north side of the creek, including such garnet-hornblende rock as in the Section 36 garnet deposit (figs. 42, 45*A*), are rich in garnet. Quartzofeldspathic gneiss there also contains substantial amounts of garnet. Granite Creek in the southern Tobacco Root Mountains (fig. 38) was investigated for garnet placers, and rockhounds have recovered garnets from gravel in Barton Gulch in the Greenhorn Range, 11 km south of Alder (Berg, 1990).

Garnet Sources in the Southern Tobacco Root Mountains

Other garnet resources may be present in the southern Tobacco Root Mountains (figs. 37, 38). The geologic map of the area (Vitaliano and others, 1979) shows the distribution of garnetiferous rocks, such as amphibolite and garnet gneiss between Alder Gulch and the Tobacco Root batholith about 20 km to the north. On the basis of their geochemistry, the protolith of the mafic metamorphic rocks (part of the Indian Creek and Pony-Middle Mountain Metamorphic Suites) was largely tholeiitic basalt (Mogk and others, 2004). These rocks (fig. 38; mountains north of Alder Gulch) may have supplied one or more alluvial garnet deposits in the southern Tobacco Root Mountains, including the suggested deposits in the headwaters of Eightmile Creek and Granite Creek (see above). The Spuhler Peak Metamorphic Suite, 20 km north of Alder Gulch, and especially the orthoamphibole-garnet gneiss pictured by Burger and others (2004, fig. 2) and Cheney and others (2004, fig. 5), may be a source of placer garnet. On the basis of their geochemistry, the protolith of these rocks is interpreted to be mostly mafic volcanic rocks deposited in a marine environment (Burger and others, 2004). The 12-km-long exposure of the

Spuhler Peak Metamorphic Suite suggests a potential for other alluvial garnet deposits in drainages emerging from this part of the southwestern Tobacco Root Mountains. Ultramafic metamorphic rocks (formerly harzburgite, lherzolite, and peridotite), such as the ultramafic rocks in and near bedrock garnet deposits in the northern Greenhorn Range (fig. 38; mountains south of Alder Gulch) and in the Section 36 deposit (fig. 42; southwest of Sweetwater Basin), also occur in the southern Tobacco Root Mountains. On the basis of their geochemistry, the protolith of the ultramafic metamorphic rocks in the Tobacco Root Mountains is interpreted to be an ultramafic cumulate rich in orthopyroxene resulting from a magmatic event in a continental setting (Johnson and others, 2004). Although such rocks do not appear to be an important component of the metamorphic suite in the southern Tobacco Root Mountains at a scale of 1:62,500 (Vitaliano and others, 1979), they are relatively common in the northern Greenhorn Range (Weir, 1982) and adjacent to the Section 36 deposit.

Alaska

Nearly perfect dark-red almandite, called Wrangell garnet after the nearest town, which is on Wrangell Island, occurs in schist near the east side of the mouth of the Stikine River, 12 km north of Wrangell (Bressler, 1950) in the Wrangell Mining District (fig. 46). The schist is part of the Wrangell-Revillagigedo belt of regionally metamorphosed rocks on the west side of the Coast Range batholith. The area is known for its gem-quality garnets but less well known as a source of industrial garnet. The garnets were mined for abrasives intermittently since before 1910, but little garnet has been mined in the area since about 1925. The amount of industrial garnet produced is not recorded but was most likely small. The garnet deposit was included in studies of the Wrangell Mining District (Wright and Wright, 1908; Buddington and Chapin, 1929), but actual discovery by gold prospectors as early as 1862 is likely. Five of the most promising claims at Garnet Creek belong to the Alaska Garnet Mining and Manufacturing Co. Two of these claims near the mouth of Garnet Creek are estimated to contain 79,570 m^3 of schist grading 4.85 to 9.26 weight percent garnet. The garnets are as much as 4.4 cm across, are dark red, have a specific gravity of 4.1 and a hardness of 7.5 Mohs, fracture parallel to schistosity, and contain many inclusions of quartz, which make most of the garnet unsuitable for gems and, possibly, for abrasive applications.

Brooks (1910) mentioned small shipments of garnet from the Wrangell Mining District in 1910. In 1982, a garnet lode deposit east of Wrangell and several garnet-bearing beach sand deposits were investigated as possible sources of garnet for abrasives and filtration media (Pittman, 1984).

On the south side of Port Houghton in the Juneau Mining District, about 90 km northwest of Wrangell, is a 10-km-wide zone of garnetiferous quartz-mica schist (fig. 46) that contains red garnets, as large as 1 cm across, which compose 10 to 20 volume percent of the rock in especially rich zones and, locally, garnetite layers. The garnets have been subjected to dissolution, as indicated by truncation of growth zones in the crystals. Staurolite and kyanite are minor components.

Andradite in the Ketchikan Mining District, south of the Wrangell Mining District, forms the principal gangue mineral in contact-metamorphic deposits and occurs mostly in limestone in the contact aureoles (fig. 46; Wright and Wright, 1908). The garnet is massive or occurs in dodecahedral aggregates. The garnet crystals are zoned, ranging in size from 1 to 5 cm across. At Coppermount, andradite forms a massive belt of garnetite, 7 to 15 m wide, between diorite and the limestone host. Included in the garnet are small nodules consisting of chalcopyrite, magnetite, pyrrhotite, and pyrite.

In 1987, industrial-grade garnet was produced as a byproduct of processing beach sand for gold along the Gulf of Alaska (fig. 47; Pittman, 1989). In 1989, a small strandline gold placer operation near Yakataga on the Gulf of Alaska also uncovered concentrations of garnet and ilmenite (Pittman, 1991).

The Continental Shelf adjacent to Alaska, including the areas off southeastern Alaska and along the Gulf of Alaska, the Bering Sea, the Chukchi Sea, and the Beaufort Sea (fig. 47; Beauchamp and Cruikshank, 1983), has a potential for placer gold deposits. Although offshore placer gold is of principal interest in Alaska, placer deposits in which gold occurs may contain other marketable heavy minerals, including ore minerals of antimony, copper, lead, platinum, silver, tin, tungsten, and zinc. Beauchamp and Cruikshank (1983) suggested that industrial heavy minerals may be present in association with offshore placer gold, as in Oregon (see below). Although garnet is not mentioned in their report, garnet would be expected in Alaskan heavy-mineral suites. Thus, although the following discussion focuses on gold, the presence of heavy minerals, including garnet, is implied.

The eastern Bering Sea adjacent to western Alaska may have the greatest potential for placer gold of any area in the United States (fig. 47). Onshore placers, which have produced about a third of the gold in Alaska, probably supplied gold to beach and offshore sediment. The shelf areas off Nome and Goodnews Bay and from 15 km west of Nome to Cape Nome 21 km east of Nome seem especially promising. Other areas important for placer gold include a shoal north-northeast of Cape Prince of Wales in the Chukchi Sea; the offshore area around Sledge Island, several kilometers west of Nome; cliffs once mined for gold and silver near Bluff, 76 km east of Nome; and the areas off the Southeast Cape on St. Lawrence Island and off the west end of the island. Other areas where onshore lode deposits of gold occur near the Continental Shelf merit attention, including Captains Bay, the Aleutian Islands, the shelf west of Kodiak Island, around Unga and Popof Islands, the lower part of Cook Inlet in Kamishak Bay, the shelf adjacent to the southern part of the Kenai Peninsula, and Resurrection Bay near Seward. Reimnitz and Plafker (1976) reported concentrations of gold in beach sediment of the Copper River Delta. Much of the shelf in the Gulf of Alaska is underlain by gold-bearing glacial deposits of the Yakataga Formation. Locally intense glaciation, large lode gold occurrences, and extensive drainage onto the Continental Shelf suggest that the

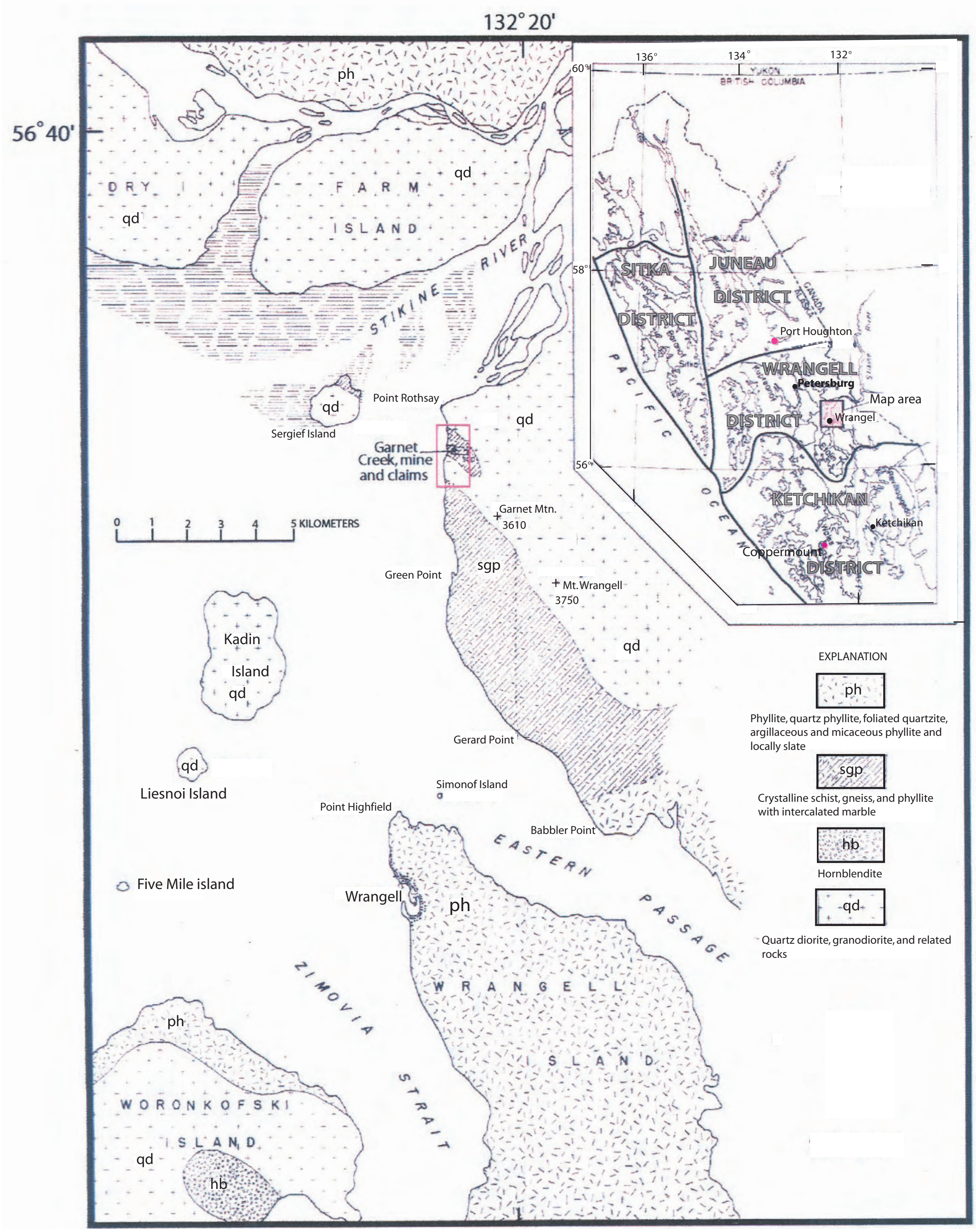

Figure 46. Southeastern Alaska, showing locations of onshore garnet deposits (adapted from Wright and Wright, 1908).

shelf areas near Juneau may be favorable for placer gold deposits and, by inference, heavy minerals, including garnet. The heavy-mineral placers about 50 km northeast of Cape Prince of Wales have produced minerals containing lead, silver, tin, and tungsten (fig. 47).

California

Small amounts of garnet, principally grossularite, were produced from tungsten mill tailings in the Bishop Mining District in Inyo County from 1938 to as late as 1950 by Huntley Industrial Minerals, Inc. (fig. 48; Braun, 1950; California Division of Mines staff, 1950). The garnet was marketed for abrasive blasting. In 1954–55, industrial garnet was produced by Otis A. Kittle & Associates, Ltd., as a byproduct of a tungsten mine, also in the Bishop Mining District, and shipped to the U.S. Navy in Oregon (California Mining Journal, 1954). Operations at the processing plant, located 10 km from Bishop, consisted mainly of dry screening, conveying, and sacking. The product contained 75 weight percent highly abrasive, dense garnet. By May 1, 1954, the company had shipped 39 railroad cars containing an estimated 2,000 t of concentrate.

Localities in 26 counties (fig. 48) were reported to contain several varieties of garnet, including almandite; topazolite (a greenish-yellow to yellow-brown variety of andradite); melanite (a black variety of andradite); aplome (a dark-brown, yellowish-green, or brownish-green variety of andradite); green andradite; essonite (a yellow-brown or reddish-brown transparent variety of grossularite); green, opaque white, and colorless grossularite; spessartite; and uvarovite (see Murdoch and Webb, 1956).

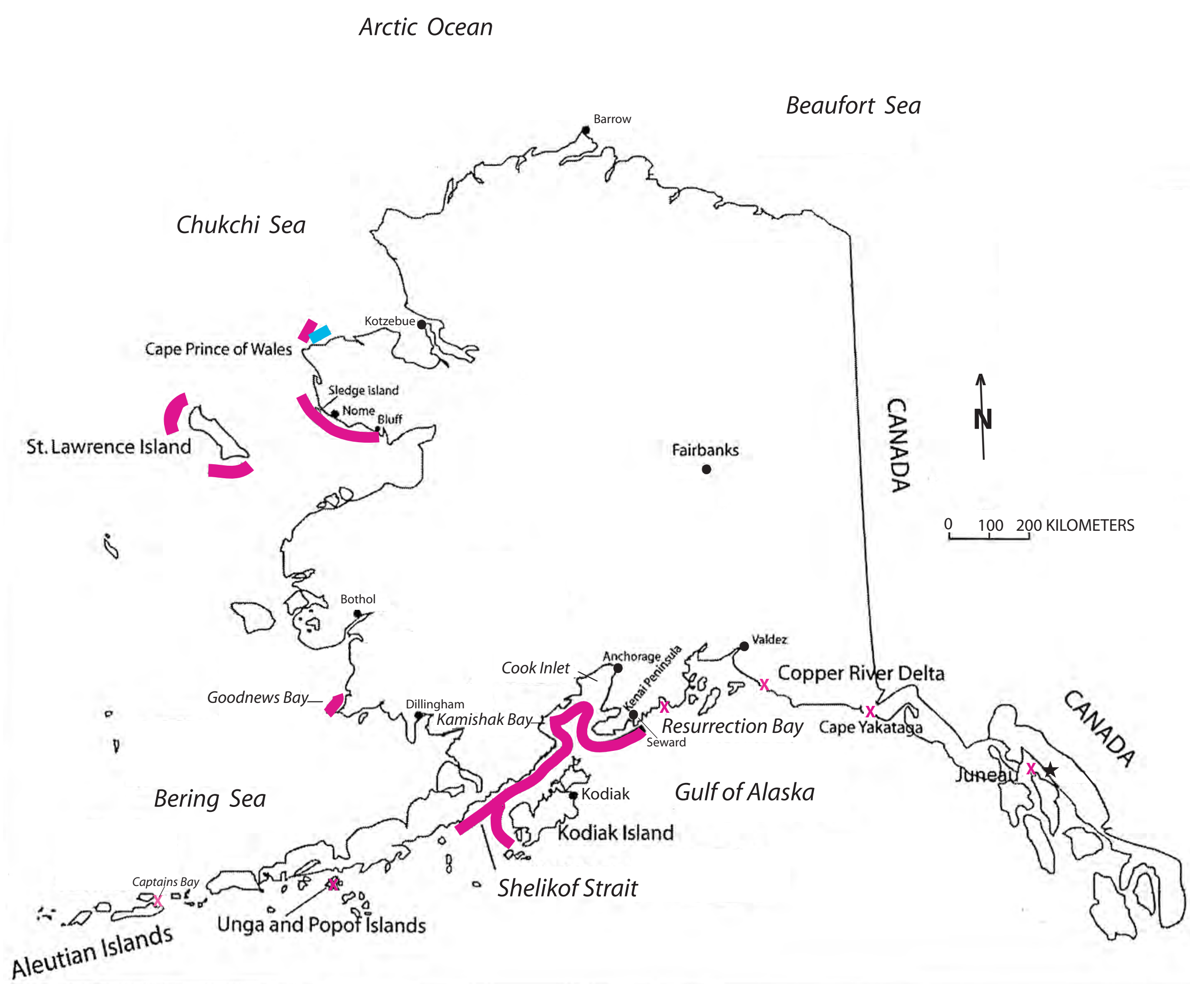

Figure 47. Sketch map of Alaska, showing locations of offshore areas with possible heavy-mineral potential. Thick red lines and Xs, parts of shelf with possible potential for gold and platinum; ore minerals for antimony, copper, lead, silver, tin, tungsten, and zinc; and heavy minerals including garnet. Small blue area northeast of Cape Prince of Wales has produced minerals containing lead, silver, tin, and tungsten. Dots, cities and towns; star, State capital.

Nevada

Garnet-rich rocks are recorded from two localities in White Pine County (fig. 49). Small amounts of garnet were produced for mineral-supply houses and tourists at Garnet Hill, about 8 km northwest of Ely (Smith, 1976). The garnet was obtained from the walls of vesicles in rhyolite and panned from soil nearby. Another garnet occurrence is on the east flank of Mount Moria in the Snake Range, about 65 km east of Ely. The garnet is contained in quartz-garnet-mica-staurolite schist that makes up part of the canyon walls and forms alluvial deposits along Hampton Canyon (Castor, 2003). Test lots of almandite for use as an abrasive were produced from this area. Dark-brown spessartite occurs at several other localities in White Pine County. Many skarn deposits in Nevada are rich in garnet, such as in the Yerrington Mining District in Lyon County.

New Mexico

The skarn deposits of southern New Mexico are in the Basin and Range Province, south of the Colorado Plateaus Province, and west of the Great Plains (Lueth, 1996). The entire Paleozoic section rests unconformably on metamorphosed Late Proterozoic rocks. The Lower Paleozoic section is dominated by dolomite and clastic sedimentary rocks. The Upper Paleozoic rocks are shelf carbonates that grade upsection into clastic rocks. The Mesozoic section consists of terrigenous clastic rocks and sedimentary rocks reflecting Cretaceous marine incursions. The garnet deposits formed adjacent to polyphase granites that range in age from Late Cretaceous to Miocene. The Cenozoic rocks are largely volcanic and volcaniclastic rocks that cover older rocks and may conceal some garnet deposits. Tertiary and Quaternary extensional tectonics, especially the Rio Grande Rift, were superimposed on compressional tectonism of the Laramide orogeny and younger volcanic arcs of the Sierra Madre Occidental and Mogollon-Datil volcanic provinces. Tertiary block faulting exposed garnet deposits on both sides of the Rio Grande Rift and in the Basin and Range Province of New Mexico.

Royalstar Resources, Ltd., began limited garnet production from skarn at their San Pedro Mine in the New Placers Mining District in Santa Fe County (fig. 50) sometime before 1992. Proven reserves are reported as 7 million to 8 million t containing 85 weight percent andradite (Lueth, 1996). The company ended 1993 with its garnet operation on standby, owing to legal difficulties: the County Planning Commission insisted that Royalstar obtain a new mining permit under the county's recently adopted mining regulations (U.S. Bureau

Figure 48. County map of California, showing county boundaries and locations of counties (names in all caps) with garnet deposits or occurrences. Dots, cities and towns; star, State capital.

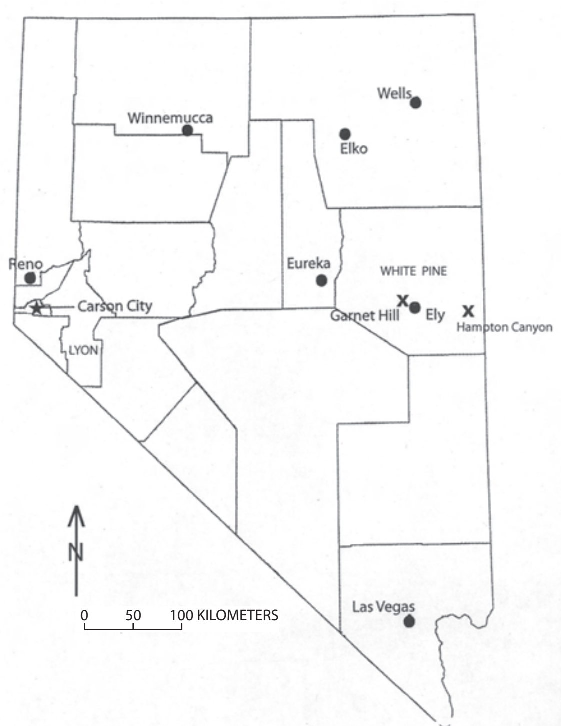

Figure 49. County map of Nevada, showing county boundaries and locations of counties (names in all caps) with garnet deposits or occurrences. Dots, cities and towns; star, State capital. Xs, garnet localities.

of Mines staff, 1993–94b), while Royalstar insisted that their earlier permit should be “grandfathered” in. In 1996, when San Pedro Mining Corp. applied for and received a mining permit from the New Mexico Department of Energy, Minerals, and Natural Resources to reprocess mine dumps at the San Pedro Mine for industrial garnet, the corporation still needed a mining permit from the Santa Fe County Mining Commission, which claimed that mining was not an appropriate use of the area (U.S. Bureau of Mines staff, 1995). No industrial garnet production in the State was noted from 1996 to 2003 (U.S. Geological Survey staff, 1997, 2002b, 2003). From 2000 to 2003, at least one company was reportedly examining other parts of the State for potential resources of industrial garnet (U.S. Geological Survey staff, 2002b, 2003, 2004, 2005b).

Industrial-grade andradite and grossularite occur in skarn in southern and central New Mexico and are major constituents of tailings piles from metal mining (see Lueth, 1996). The garnet occurs in various skarn types, including copper, porphyry copper, lead-zinc, iron, and tungsten (Einaudi and others, 1981), in Upper Paleozoic limestone. The largest garnet deposits are in copper skarn associated with Cretaceous porphyry copper deposits in southwestern New Mexico. The garnet ranges in composition from pure andradite at igneous contacts to pure grossularite in metamorphic pods; compositions generally average greater than Ad_{80}. The garnets range in size from 1 to 100 mm across, averaging about 4 mm across. Garnet near postmineralization faults shows retrograde metamorphism and is commonly altered to clay and epidote. The next-largest type of garnet deposit is associated with lead-zinc skarn, mostly in the Hanover-Fierro Mining District, about 20 km northeast of Silver City in Grant County, and in the Orogrande Mining District in Otero County. Garnet in these deposits has compositions of $Ad_{10\text{–}100}$, and the rest is spessartite. Garnet grains generally are less fractured in lead-zinc skarn than in copper skarn and commonly have reverse zonation, small grain size, fewer inclusions, and widely varying composition. The best-quality garnet is in iron skarn, the least abundant type of skarn. Iron skarn also occurs in the Hanover-Fierro and Orogrande Mining Districts. The garnet grains in the iron skarn resemble those in the copper skarn but are less fractured and zoned. Past metal-mining efforts commonly left barren garnetite at the surface. The Iron Mountain Mining District (beryllium and tungsten skarn/sulfides) in Sierra and Socorro Counties also has large resources of andradite garnet (Jahns, 1944). Skarn layers, as much as 30 m thick, are exposed for as much as 3 km along strike. Layers of garnetite, as much as 4 m wide, average 70 weight percent garnet. These deposits can be mined by open-pit methods. Deeper garnetite is also minable where previous mining left underground workings.

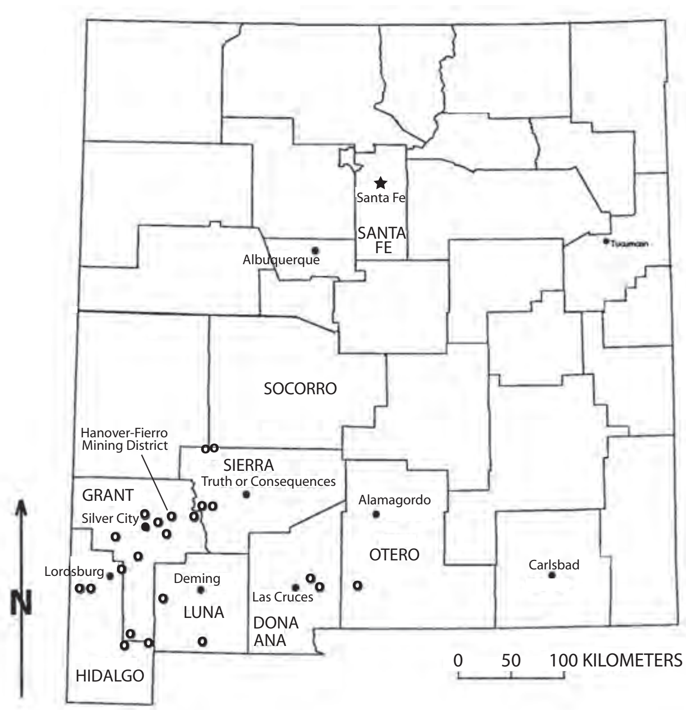

Figure 50. County map of New Mexico, showing county boundaries and locations of counties (names in all caps) with garnet deposits. Dots; cities and towns; star, State capital. Circles, skarn deposits.

Garnets in southwestern New Mexico formed during two stages of skarn formation: (1) isochemical contact metamorphism associated with initial magmatic emplacement and (2) the metasomatic main stage of skarn formation associated with exsolution of magmatic fluids and influx of meteoric water. Calcic skarn in Late Paleozoic shelf carbonates hosts the garnet deposits, in contrast to the unmineralized dolomite in the Lower Paleozoic section. A late stage in skarn evolution includes retrograde alteration, which destroys garnet, and extensive sulfide deposition.

A study was made to determine whether garnet and sphalerite in the Hanover mill tailings ponds could be recovered to offset some of the cost of remediation (see Cetin and others, 1996). The mill is located about 20 km northeast of Silver City in Grant County. In the early 1980s, accumulated mine and mill wastes at the Hanover millsite were identified as potential sources of surface and ground-water pollution. The tailings contained abundant lead and copper and were the source of air release of significant amounts of heavy metals, especially lead. In 1996, the tailings were owned by the Mining Remedial Recovery Co. (MRRC) of Price, Utah, one of several companies created in 1992 as a result of the Sharon Steel Corp. bankruptcy resolution (ACZ Laboratories Inc., 1993). MRRC initiated studies of heavy-metal mobility in the tailings and concluded that the tailings were geochemically stable. Underlying bedrock consists of limestone intruded by granite, and the tailings were rich in acid-neutralizing carbonates. Eolian and fluvial release of contaminants, however, could affect nearby Hanover Creek and the surrounding soil.

Garnet resources of the five mill tailings ponds totaled 135,000 t of material containing 20 to 36 weight percent garnet. Most of the tailings were produced by the Empire Zinc Co., a subsidiary of the New Jersey Zinc Co., during two periods of production: 1902–31, 450,000 t of zinc ore; and 1937–48, 113,000 t of zinc ore. The mill was operated briefly during 1974 by UV Industries; later, the mill was bought by Sharon Steel. The mill also processed ore from other mines in the Hanover-Fierro Mining District, from the Orogrande Mining District, and from the Magdalena Mining District in central New Mexico. The principal garnet in the tailings ponds is andradite accompanied by small amounts of grossularite. Samples of the tailings were reground to free mineral grains, chiefly garnet, from gypsum cement. The Pb, Zn, Cu, Fe, and Cd sulfides were removed by flotation; then garnet was concentrated by gravity from the tailings. However, the marketability of the garnet for abrasives and filtration media is unlikely because it contains widely distributed impurities (inclusions?, alteration products?); grains of appropriate purity are too small to use. In addition, the final tailings could be considered hazardous waste (Cd, Pb, Zn), requiring further treatment by a phosphate process to be made nonhazardous.

When it became clear that the garnet was unmarketable, tailings from the four small ponds were moved to the main pond, where they were scheduled to be recontoured, stabilized, capped, and revegetated. The largest pond was considered stable under seismic-load conditions.

Development of the New Mexico andradite/grossularite deposits, such as described above, depends on detailed studies of garnet geochemistry, texture, density, angularity, hardness, and resistance to abrasion. Compositional zones within the skarn need to be delineated because properties change with composition. Garnet from New Mexico, at least in a few mining districts, may not have the characteristics of almandite, but it may be competitive with abrasive slag, manufactured abrasives, silica sand, olivine, and staurolite.

Oregon

Sand in beaches and marine terraces, as much as 65 m above sea level, in Coos and Curry Counties was mined for gold as early as 1852, and later for platinum and ilmenite (fig. 51; Gray and Kulm, 1985; mining began in 1872 according to Griggs, 1945). Gold anomalies (≥0.005 ppm) are still detectable offshore at Gold Beach, Sisters Rocks, and along the coast from Port Orford northward to Black Rock Point. In the early 1940s, black sands were mined chiefly for chromite, with byproduct gold and platinum. From the late 1940s to 1980, focus again was on the gold and platinum, but chromite was stockpiled. Total known production of gold from the black sand placers was at least 4,000 troy oz. Black sand placers that contain from 10 to more than 30 weight percent (max 56 weight percent; Kulm and others, 1968) heavy minerals, including garnet, occur mostly along the coast of Curry County discontinuously from Brookings to Bullards Beach State Park just north of the mouth of the Coquille River. Some of the black sand concentrations include modern beach deposits, as at Boardman State Wayside and in the Gold Beach area from the mouth of the Rogue River to the mouth of the Pistol River. The most extensive placer deposits are in the Gold Beach area from the Pistol River to Sisters Rocks, north of the mouth of the Rogue River. On the basis of interpretations of magnetometer surveys and the assumption that magnetite in the black sands is the primary source of the magnetic anomalies, Kulm and others concluded that the largest and richest concentrations of heavy minerals are 2 to 13 km offshore in water as deep as 92 m. Less likely, the magnetic anomalies are from intrusive or extrusive rocks. Kulm and others (1968) completed seven east-west traverses ranging in length from 1 to 9 km and five north-south traverses ranging in length from 1 to about 4 km. Gray and Kulm suggested running north-south magnetometer-survey lines in the offshore area from 140-m depth to the shore to locate buried and (or) submerged stream channels that could contain heavy-mineral placers.

The highest concentrations of black sand deposits are on the outer margin of the Continental Shelf between the Rogue River and Cape Blanco, under 146 to 185 m of water. Samples of black sand deposits contained as much as 56 weight percent heavy minerals. The deposits on the inner shelf are interpreted as relict beach deposits, created during Pleistocene glaciations when sea level was lower.

The heavy-mineral black sands of the Oregon coast were included in early studies of black sand placer deposits by Day and Richards (1906a, b). Garnet was included in the heavy-mineral suites mentioned in their more detailed publication (Day and Richards, 1906b). For their study, they solicited samples, generally no heavier than 2 kg, of heavy-mineral sand from placer miners. Samples were received from Alaska, Arizona, California, Colorado, Idaho, Indiana, Kansas, Maryland, Mississippi, Montana, Nebraska, Nevada, New Mexico, New York, North Carolina, Ohio, Oklahoma, many counties in Oregon, South Dakota, Texas, Utah, Washington, and Wyoming. In some States, including Oregon, samples several tons in size were collected and shipped to a laboratory in Portland by railroad carload to take advantage of the free transportation provided by various railroad companies. The "Remarks" column of Day and Richards' (1906b) main table indicates that some samples consisted of several tons, but the weight of each sample was not mentioned. In addition, many samples came from sluiceboxes or were otherwise already concentrated. However, some of the sample sets may have some general value. Garnet content ranged from 0 to 21.4 weight percent in 56 samples from Clatsop County, mostly described as "natural beach sand." The highest grade was in a sample near Hammond, located on the south bank of the Columbia River near its mouth. Garnet content ranged from 0 to 80 weight percent in 21 samples from Coos County. The highest grade was in a sample from the old seawall at Randolph, located about 30 km south of Coos Bay; however, this and most other samples from Coos County were described as concentrates. Garnet content ranged from 2.7 to 44 weight percent in seven samples of beach sand from Lincoln County, from 25.3 to 31.6 weight percent in three samples from Yaquina Bay, and from 2.7 to 24.2 weight percent in three samples from Newport. The data

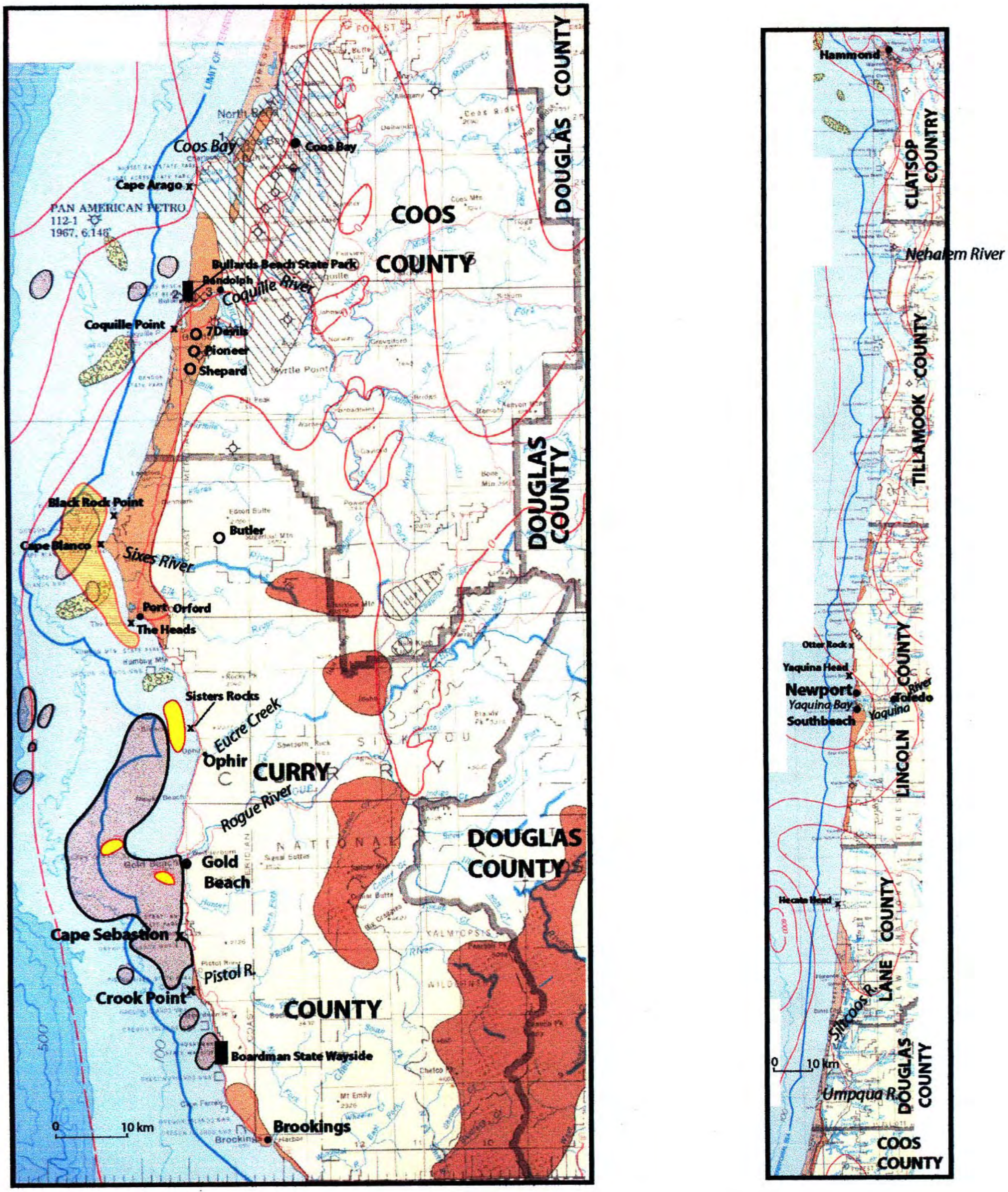

Figure 51. Oregon coast, showing locations of beach, offshore, and marine-terrace deposits of black sand and offshore gold anomalies (from Gray and Kulm, 1985). Yellow areas with red margins and pale-yellow, red-striped, and transparent area off Cape Blanco, anomalous gold (≥0.005 ppm); brown stippled areas, black sand deposits. Darker blue line offshore, limit of U.S. Territory (but not of the Exclusive Economic Zone); light-blue area along coast, Continental Shelf; red lines, isopachs of sediment (in meters; contour interval, 500 m); darker brown areas in southern part of map, mineralized rock; oval black-crosshatched area, coal deposits. Circles, mines mentioned in text. (Locations may represent more than one mine.)

are unclear whether the high-grade sample (44 weight percent garnet) from Toledo was a concentrate or from river sand (fig. 51). Garnet content ranged from 0 to 55.2 weight percent in 12 samples from Curry County; the highest grade was in a sample from tailings after gold extraction in the Port Orford area. Otherwise, the highest grade of black sand from beaches in the Port Orford area was 10.3 weight percent garnet. One sample from Lane County contained 11 weight percent garnet.

In a later study, beach sands along 70 km of the Oregon coast were analyzed for contents of chromite, zircon, garnet, and ilmenite (Dasher and others, 1942). Samples were obtained from the Shepherd and Pioneer Mines, from two drill holes at Coos Bay in Coos County, from the Butler (or Baker) Mine north of the Sixes River, and from Ophir Beach near the town of Ophir in Curry County. The deposits of interest occur in pockets of heavy minerals on the landward side of old beaches and inland along creekbeds. Minerals and rock types identified in the beach sand include chromite; quartz; chert; augite; diopside; hornblende, actinolite, and other amphiboles; epidote; zoisite(?); tourmaline; zircon; Fe-rich olivine; manganiferous and Fe-bearing garnet; ilmenite; magnetite and (or) chromitiferous and titaniferous magnetite; rutile; and uvarovite. Most of the study focused on determining the size of the chromite fraction. With hydraulic tabling before electrostatic separation, electrostatic rejects consisted of garnet and zircon, with traces of mafic minerals, quartz, rutile, and opaque minerals. The separation could be done by gravity, which can easily separate out products that may be of economic value, such as garnet and zircon abrasives. The proportion of garnet and zircon in the samples varied widely; however, samples that produced the largest chromite concentrates also contained the largest proportions of garnet and zircon. Grains of garnet are generally round, but that shape may not be undesirable because rounded garnets can still be used for low-dust airblasting and may be suitable for other applications.

Griggs (1945) studied chromite-bearing sands, including beach and marine-terrace deposits, along the Oregon coast from about 13 km south of Coquille Point to Coos Bay. Black sand deposits on the marine terraces range from less than 0.3 to 13 m in thickness (avg 2–3 m thick), from several meters to more than 305 m in width, and from several hundred meters to more than 1,600 m in length. These deposits are covered by 0.3 to 25 m of sand, clay, and gravel. Clean garnet concentrate from the black sand consists of round grains, from 0.5 to 2 mm across. Garnets in samples of black sand deposits near the Coquille River include the varieties almandite and spessartite. Garnet content ranged from 10.2 to 28.8 weight percent in the black sand; three samples contained more than 25 weight percent garnet. When these deposits were studied, roundness of grains, such as in these deposits, was thought to eliminate garnet from consideration as an abrasive; the garnet was considered worthless. Roundness is not necessarily an obstacle to the use of garnet, which has other applications that were unknown in 1945. At present, other characteristics of the garnet would need to be evaluated in order to determine its value. Griggs estimated 1.944 million t of reserves of black sand grading on average more than 5 volume percent chromite and 1.231 million t of reserves of black sand grading on average 3 to 5 volume percent chromite; he further estimated that the beaches contain 101,600 t of black sand grading on average at least 5 volume percent chromite. Griggs' focus was on chromite, and so he did not record in detail the garnet content of the black sand deposits he studied. His table 9, however, lists the results of 200-grain counts of minerals in 19 samples from beaches and marine terraces, of which garnet composed 1 to 58 grains. These data suggest that garnet concentrations are higher in the marine terraces.

Twenhofel (1943, 1946) studied the Oregon coast and observed that black sand deposits formed in relatively few places. In his first study (Twenhofel, 1943), which focused on the south coast from the Oregon State line to Coos Bay, black sand deposits were observed near the mouth of Five Mile Creek on the beach south of Cape Blanco, in the bay south of The Heads at Port Orford, around the mouth of Eucre Creek south of the headland of Sisters Rocks, around the mouth of the Rogue River, and around the mouths of Meyers Creek and the Pistol River in the bay between Cape Sebastian and Crook Point. In his second study (Twenhofel, 1946), which focused on the coast north of Coos Bay to the north bank of the Columbia River, relatively few black sand deposits were observed, ranging from 300 to 15,500 m^3 in volume, the largest of which were in the Newport area. Total garnet content was not estimated. The beach between Hecata Head and Otter Rock was judged to be one of the richest in heavy minerals along the Oregon coast north of Coos Bay. Garnet contents in the black sands along the north coast are as high as 19.6 weight percent but average much less.

Chromite-bearing beach sands were mined from raised beaches of the south coast of Oregon during World War II (Clifton and Mason, 1969; McKelvey, 1986). The U.S. Department of the Interior's Continental Shelf Mining Policy Task Force (1979) reported large identified offshore resources there of chromite (30 million t), gold (6 million troy oz), and platinum (350,000 troy oz). The amount of recoverable garnet was not mentioned and may not have been studied; however, garnet is known to occur in the heavy-mineral sand fractions. Other studies of offshore mineral resources indicated areas favorable for heavy minerals off the Columbia, Nehalem, Siltcoos, and Umpqua Rivers (Phillips, 1979; Beauchamp and Cruikshank, 1983). A joint Federal-State task force was set up in 1988 to evaluate offshore black sands for chromite, ilmenite, zircon, garnet, and gold. The study's aim was to determine the extent of black sand deposits off the coast and evaluate their economic and strategic importance. This information would permit the Department of the Interior to make informal judgments on the feasibility of commercially extracting key minerals (Rice and Lyons, 1990). This report, if it was produced, was not located. In 1992, Oregon Resources Corp., a subsidiary of Rare Element Resources Ltd., continued to acquire the needed permits and evaluate onshore black sands in the Seven Devils area in western Coos County (Minarik, 1992).

Conclusions

Industrial garnet has many valuable properties, such as hardness, sharpness, chemical inertness (under most surface conditions), and high specific gravity, all of which are employed in one or another of its uses. Garnet is also recyclable. Despite this assemblage of desirable qualities, garnet still has only a minor share of the abrasives market (fig. 5). This situation may change as concern increases for clean air (airblasting, waterjet cutting) and clean water (filtration media). Waterjet cutting and airblasting are expected to have the highest rates of growth (Austin, 1993a); worldwide industrial demand was projected to grow at 3 to 5 percent at least until 1998. As indicated above, world garnet consumption increased by about 40 percent between 1998 and 2004. Demand for garnet abrasive powders used for polishing television and computer-monitor screens is declining as flat-screen systems that do not need polishing take over the market. Worldwide increases in petroleum use and cost have stimulated an increase in exploration for petroleum. This exploration may be accompanied by a possibly increased use of garnet in airblast cleaning of drill pipes. Increases in defense spending or domestic passenger-airplane production could increase garnet demand in the aircraft and shipbuilding industries, both of which use significant amounts of garnet for airblast cleaning and finishing of metal surfaces and in waterjet cutting. Even if the demand for garnet increases, however, domestic industrial garnet producers will still have to contend with foreign garnet that may be more cheaply produced (India, China, Australia, Canada). However, as experienced by WGI Heavy Metals, Inc. (2005a), in India, government permits to mine may require use of cheap, but slower, hand methods. Either at home or abroad, legal issues and geologic hazards can eclipse business plans.

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