The Natural History of Gold

Carl A. Francis

Introduction

Gold, like all precious metals and gem minerals, has intrinsic value as a commodity. The current price is 845 Euros or 1155 US dollars per ounce. This makes specimens containing any appreciable quantity of gold particularly expensive and this is true of regardless of their beauty or mineralogical interest. Collectors simply must pay a premium to save specimens from being melted. Dealers frequently charge a low multiple of the bullion price for nuggets, but prices for crystallized specimens are typically astronomical with no relation to the bullion price. As a consequence (1) large and fine collections of gold can only be assembled by the wealthy, (2) few are formed, (3) when those collections change hands they are typically sold and dispersed rather than donated to museums, so (4) few museums hold fine representations of gold. Fortunately for Harvard University Albert C. Burrage, class of 1883, (Figure 1) became wealthy, collected minerals, specialized in gold specimens and bequeathed them to his alma mater.

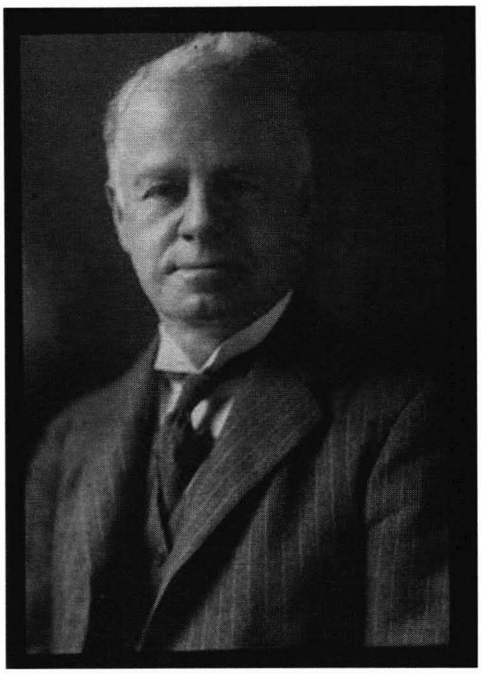

Figure 1. A.C. Burrage

Gold is the third most common mineral in the Harvard collection after quartz and calcite! There are about 1200 specimens, with representation from 50 different countries, including 4 specimens from Norway. Most are reference quality specimens that you might find interesting but not exciting. A couple of dozen are very showy. Insufficient security limits what can safely be displayed, but the best specimens have been loaned for numerous exhibitions, so the collection is well known in the specimen community. Unfortunately, little academic use has been has been made of this extraordinary resource. So I undertook a “gold program” to learn more about gold from the specimens, from the literature, and from people who know about gold, which has resulted in several talks and a few papers. I hope to prepare a monograph on the natural history of gold based on the Harvard collection, so the invitation to speak at this symposium is very welcome.

We'll look at a variety of gold specimens, mostly in the Harvard collection, to think about gold's natural history beginning with the nature of the specimens and then moving to larger questions such as, "What kinds of deposits produce gold?" and "Why gold is rare?" I'll end with some pictures from the Tucson show and remarks about what kinds of specimens are available on the market.

Table 1. Minerals containing essential gold and their formulas.

Anyuite	Au(Pb,Sb)2
Auricupride	Cu3Au
Aurostibite	AuSb2
Bezsmertnovite	Cu(Au,Ag)4(Te,Pb)
Bilibinskite	Cu2Au3PbTe2
Bogdanovite	(Cu,Fe)(Au,Te,Pb)3
Buckhornite	AuTe2Pb2BiS3
Calaverite	AuTe2
Criddleite	Ag2Au3TlSb10S10
Fischesserite	Ag3AuSe2
Gold	Au
Hunchunite	Au2Pb
Kostovite	CuAuTe4
Krennerite	(Au,Ag)2Te2
Maldonite	Au2Bi
Montbrayite	(Au,Sb)2(Te,Bi)3
Muthmannite	AuAgTe2
Nagyagite	(Au,Te)3Pb3(Pb,Sb,Bi)3S6
Penzhinite	(Ag,Cu)4Au(S,Se)4
Petrovskaite	AgAu(S,Se)
Petzite	Ag3AuTe2
Sylvanite	(Au,Ag)2Te4
Tetra-auricupride	CuAu
Uytenbogaardite	Ag3AuS2
Weishanite	(Au,Ag)3Hg2

Gold Minerals

Gold is both an element and a mineral. Because it rarely combines with other elements to form compounds either naturally or synthetically, it is called a noble metal. It is in Group 1B on the periodic Chart falling under copper and silver. Each of these elements has the same outer electronic configuration but copper forms about 500 minerals, silver about 100 and gold only 25 (Table 1).

Native gold is by far the most common gold mineral. The five tellurides calaverite, krennerite, nagyagite, petzite, and sylvanite are the only other "common" gold minerals. Sacaramb (Nagyag), Romania; Cripple Creek, Colorado; and Kalgoorlie, Western Australia are classic localities for these species. Of the other 19 gold minerals only 3 are represented in the Harvard collection, which is one indication of their rarity. The rest of this presentation focuses on native gold.

Chemistry

Gold forms complete solid solution series with silver and copper in artificial experiments, but natural specimens are much more limited in composition. Solid solution with silver is common, but solution with copper is rare. Argentian gold was given the name electrum in antiquity and it is still used, but not as a species name. Increasing amounts of silver shift the color of gold from a rich golden yellow toward white. Silver-rich gold specimens can tarnish! It also reduces its bullion value, consequently miners and dealers are sensitive to composition. Other large, mostly platinum group elements sometimes alloy with gold, but these are rare.

Morphology

Gold crystallizes with the highest symmetry possible in crystals, making its forms elegant and easy to visualize. However, most specimens of crystallized gold consist of threads, wires, ribbons, leaves and arborescent forms. More or less ideal single crystals of gold are rare and never large. A palm-filling hopper octahedron from Venezuela 4 cm on an edge is the largest crystal I've seen. The following is summarized from Francis (2004) based on Goldschmidt's *Atlas der Krystallformen* and on the Harvard collection.

There are only seven kinds of forms that gold or any mineral crystallizing in the hexoctahedral class of the isometric crystal system can exhibit (Figure 2). The number of faces, their shape and symmetry, and their spatial relations to other forms are characteristic and aid in their recognition. The following discussion and accompanying table begin with the special forms and end with the general form.

The cube *a*{001}is a common form either alone or in combination with other forms, especially the octahedron. The classic European source for crystallized gold is the mining district in the Apuseni Mountains of western Transylvania (formerly known by its German name "Siebenbürgen"), Romania . Cubes are common but many other forms have been observed there as well. A small but fine example of a cube with its corners truncated by octahedral faces from Brad, Romania, is in the collection of the University of Bonn (Burchard and Bode 1986, p. 131). The Lena River in Yakutsk, Russia is another source of cubic crystals from which contemporary specimens have been available. The Dilz mine near Mariposa recently produced groups of rather rough cubes, a real rarity for California (Leicht 1987).
The octahedron *o*{111} is by far the most common crystal form of gold. However, undistorted crystals are extremely rare. Single crystals are typically skeletal. Leaves, which are greatly flattened octahedral crystals, are often decorated with trigonal growth hillocks and sometimes fully three-dimensional crystals.

The dodecahedron *d*{011}is well known on garnets and a variety of other species including gold. Small dodecahedral gold crystals are probably best known from central Victoria, Australia. A dodecahedron modified by the octahedron and cube from Nordmark, Sweden, is figured in Goldschmidt.

Tetrahexahedra are forms with indices of the type {*0kl*}, where *k* and *l* are not equal. Goldschmidt lists four: *e*{012}, *f*{013}, *h*{014}, and *k*{025}. Only *e*{012} is common. Although tetrahexahedra are generally unfamiliar, they are common forms on gold, and silver and copper as well. Goldschmidt depicts Brazilian and Russian crystals. The Zapata Mine 25 miles south-southwest of Santa Elena de Vairen in Bolivar province in southeastern Venezuela is a spectacular new locality for gold crystals, notably fine single and twinned tetrahexahedra .

Trapezohedra are 24-sided forms with indices of the type {*hhl*}, where *h* is a smaller number than *l*. Goldschmidt lists five: *m*{113}, *n* {112}, *μ*{114}, {118}, and {223}. The trapezohedron so common on garnets is *n*{112}, but *m*{113} is the only trapezohedron common on gold. It is observed on specimens from Rosia Montana, Romania and one extraordinary 2 - 3 cm crystal from the Zapata mine. In a short note on the morphology of gold "threads" from the White Bull mine in Oregon Dana (1886) showed that these elongated crystals are *m*{113} trapezohedra grown along the [111] direction.

Well known as a dominant form on diamond, the hexoctahedron {*hkl*}only occurs as a modifying form on gold crystals, typically as tiny triangular faces. Goldschmidt lists four hexoctahedra: *s*{123}, *t*{124}, *x*{1.10.18}, and *z*{345} found on complex crystals from Beresov in the Ural Mountains of Russia, Brazil, and California. Blake (1885) identified and figured hexoctahedra on small crystals from the Princeton mine on the Mariposas Estate, Mariposa County, California, but without reporting measurements or assigning Miller indices. Dana (1886) identified *t*{124} and *x*{1.10.18} on crystals from Tuolumne County. He was especially careful to establish the later, which has improbably high indices. After examining specimens in the Bement collection, Dana concluded that *x* is fairly common on California gold crystals. An excellent and beautifully illustrated study of the morphology of contemporary specimens from the Colorado quartz mine near Mariposa by Kampf and Keller (1982) identified the same two hexoctahedra.

In summary, (1) sharp single crystals of gold are small and rare and (2) only five of the sixteen different crystal forms that have been identified on gold crystals are common. They are: *a*{001}, *o*{111}, *d*{011}, *m*{113}, and *x*{1.10.18}.

In contrast to crystals that resemble drawings in textbooks, the gold crystals most frequently encountered are skeletal octahedra. More typical yet are grossly distorted crystals. These may be elongated into ribbons or wires, form reticulated or arborescent groups, or be flattened into leaves. Parallel growth and twinning on (111) are a common complication. Better understanding of these beautiful specimens requires studying the conditions and mechanisms of their growth. Petrovskaya (1970) reported that morphology is correlated with depth of formation. Crystals formed deeper have simpler morphology.

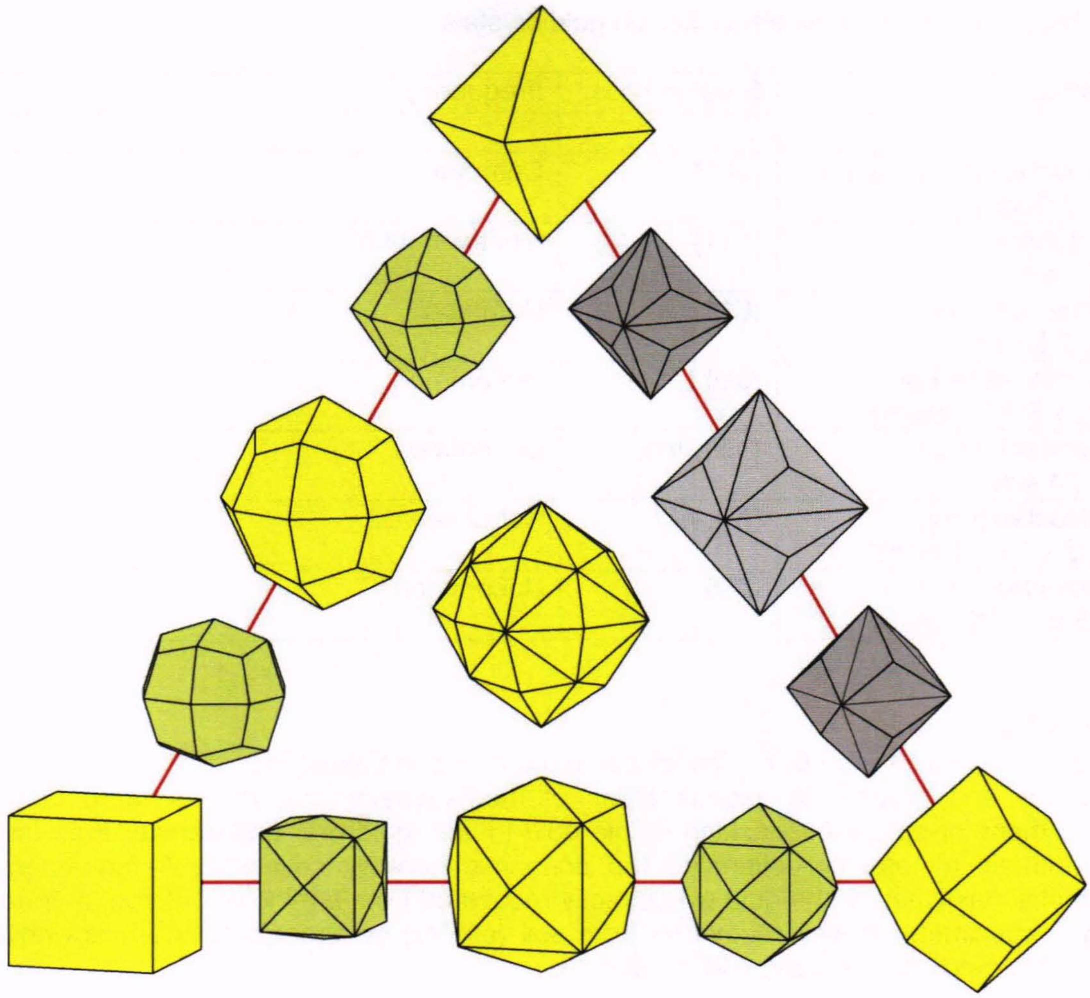

Figure 2. Triangular diagram portraying the geometrical relations between the seven distinct types of forms in the cubic crystal system. The corners are defined by forms with fixed Miller indices and fixed shapes. At the apex is the octahedron, {111}. The cube, {001} is at the lower left corner and the dodecahedron, {011}, is at the lower right. The edges and interior represent forms with variable indices and shapes. Trapezohedra lie along the left edge between the octahedron and cube. The trapezohedra depicted (top to bottom) are {334}, {112}, and {113}. Trisoctahedra lie along the right edge between the octahedron and dodecahedron. The forms depicted (top to bottom) are {344}, {122}, and {144}. Tetrahexahedra lie along the bottom edge between the cube and dodecahedron. The tetrahexahedra depicted (right to left) are {034}, {012}, and {014}. Hexoctahedra ({123} depicted) occupy the interior of the figure. Forms colored yellow are observed on gold crystals; gray forms (trisoctahedra only) have not been reported on gold crystals. Notice that the variable forms look more and more like the fixed form at the apex as you move from the midpoint of an edge toward that apex. Diagram by R. Peter Richards.

Table 2. Forms and their frequency on gold crystals.

Forms	Miller indices	Frequency
Hexahedron (or cube) (6 sides)	{001}	Common
Octahedron (8 sides)	{111}	Most common
Dodecahedron (12 sides)	{011}	Common
Tetrahexahedron (4 x 6 = 24 sides)	{0*kl*}	Uncommon
Trapezohedron (24 sides)	{*hhl*}, *h<l*	Uncommon
Trisoctahedron (3 x 8 = 24 sides)	{*hll*}, *h<l*	Not observed
Hexoctahedron (6 x 8 = 48 sides)	{*hkl*}	Uncommon

Specimen types

Gold specimens range from vials of panned grains and flakes, to nuggets, to isolated crystals and groups, to various types of matrix specimens, rich or lean. Lean specimens or specimens lacking visible gold I label "gold ore" and transfer from the systematic mineral collections to the economic geology collection. A fundament distinction is whether the gold was directly recovered from a mine or outcrop, a "lode gold" specimen, or was recovered from soil (eluvial) or streams (alluvial) downhill from the outcrop, a "placer gold" specimen.

Placer gold

Placer deposits are formed by differential transport of minerals of varying specific gravity. Heavy minerals stay behind while light minerals are washed or blown away. Alluvial gold is recovered by panning, sluicing, or dredging the sediment in stream bottoms. The conventional scientific view is that gold-bearing rock exposed at the surface breaks away from the outcrop by, for example, freeze-thaw action and that the resulting boulders, cobbles and pebbles, typically of vein quartz, that contain gold are the normal products of erosion. With increasing distance from the source the quartz, which is brittle, is broken away liberating the gold. The gold, which is malleable, is beaten and abraded by tumbling in a stream during flood season into rounded nuggets, the definition of which is simply lumps of precious metal. The size of gold particles decreases with distance from the source. Surprisingly, there are serious proposals that nuggets grow in streams by chemical precipitation and by the mashing of nuggets together! While some evidence supports the contention, recent investigation (Hough et al., 2007) favors the erosional (hypogene) origin rather than the growth in sediments (supergene) model.

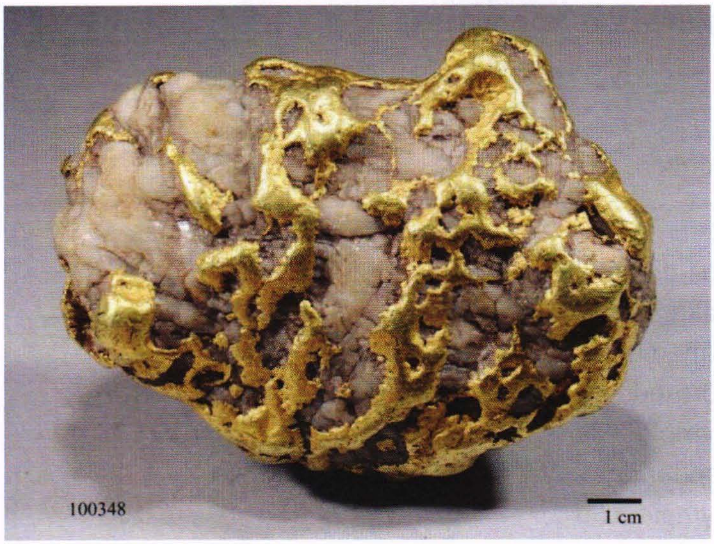

Figure 2. Matrix nugget of gold in quartz, CA.

Figure 3. Very rounded gold nugget from France.

Because gold nuggets connote value and sometimes instant wealth, they are of perennial interest to the general public as well as the mineral collecting community. Typically large nuggets are quickly melted to realize their bullion value; hence few large gold nuggets (Tables 3) are preserved. Probably the oldest surviving is Russia's largest nugget, the 1161 Troy ounce "Golden Triangle" discovered in 1836 and preserved in the Diamond Fund in Moscow. Nuggets are found worldwide but some regions are famous for them. Victoria in southeast Australia holds the record for the largest and the most really large nuggets. Reviewing Australian gold Dermot & Birch (2003) coined the colorful term "meganuggets" for them! In contrast to Victoria, the fabulously productive Witswatersrand goldfields of South Africa does not yield nuggets. The development since about 1980 of metal detectors specially tuned for gold has lead to an electronic gold rush (Coogan & Cook, 2003) with impressive results (Table 4). Most of the contemporary nuggets are used in jewelery; only a fraction are sold as specimens.

Table 3. Historic large nuggets (mass in Troy ounces).

Victoria

mass	*identification*	*location*	*year*
2316	Welcome Stranger	Bull-dog Gully, Moliagul	1869
2206	Welcome	Bakery Hill, Ballarat	1858
1616	Leg of Mutton	Canadian Gully, Ballarat	1854
1286		Burrandong, NSW	1858
906	Curtis	Gympie, Qld	
850		Londonderry, WA	1894
804		Gympie, Qld	
800		Coolgardie, WA	1894
400		Snowy River, Kiandra, NSW	1860
350	Maitland Bar	Hargraves	1887
338	Little Hero	Coongan River, Pilbara, WA	1890

Russia

1161	Big Triangle	Miass	1842
325	Udav		
299	Camel	Kolyma	1947
196	Kaltsytovyi		
108	Rabbit's Ears	South Urals	
97	Bolshoi Drychatyi		

California

648	Willard	Magalia district	1859
600		Knapp's Ranch, Columbia district	1850s
532		French Ravine, Sierra County	1855
426		French Ravine, Sierra County	1851
426		Pilot Hill, El Dorado County	1867
408		Sullivan Creek, Columbia district	1849
360		Gold Hill, Columbia district	1850s
336	Holden Chiaspa	Sonora district	1850s?
300		Mokelumne River, Amador County	1848
300		Downieville, Sierra County	1850
266		Minnesota, Alleghany district	1850s?
250		Spring Gulch, Columbia district	1850s

Table 4. Contemporary large nuggets (mass in Troy ounces).

Victoria

mass	*identification*	*location*	*year*
874	Hand of Faith	Kingower, Vic.	1980
819	Normandy	Eastern Goldfiels, WA	1995
520	Evening Star	Ora Banda, WA	
317		Inglewood, Vic.	1995
268	Golden Aussie	Feysville, WA	1980
256	Pride of Australia	Wedderburn, Vic.	1980
50	Bunyip	Bridgewater, Vic.	1975

Alaska

294.1	Alaska Centennial Nugget	near Ruby	1998
182	Anvil Nugget	Anvil Creek near Nome	1903
146		Hammond River near Wiseman	
137		Hammond River near Wiseman	
122	Ganes Nugget	Ganes Creek	1985
107		Anvil Creek near Nome	
97		Anvil Creek near Nome	
95		Anvil Creek near Nome	
92	Heart of Gold	Glacier Creek near Kantishna	1984
84		Anvil Creek near Nome	

California

156	Mohave	Mohave County	

Mexico

389	Boot of Cortez	Caborca Mountains, Sonora	1989

Lode gold

Typical matrix or "lode" gold specimens are quartz from hydrothermal veins, but primary or hypogene gold can be found in a variety of rock types. Gold is also found in the supergene (weathering) environment where it precipitates from ground water solutions and may be of high fineness.

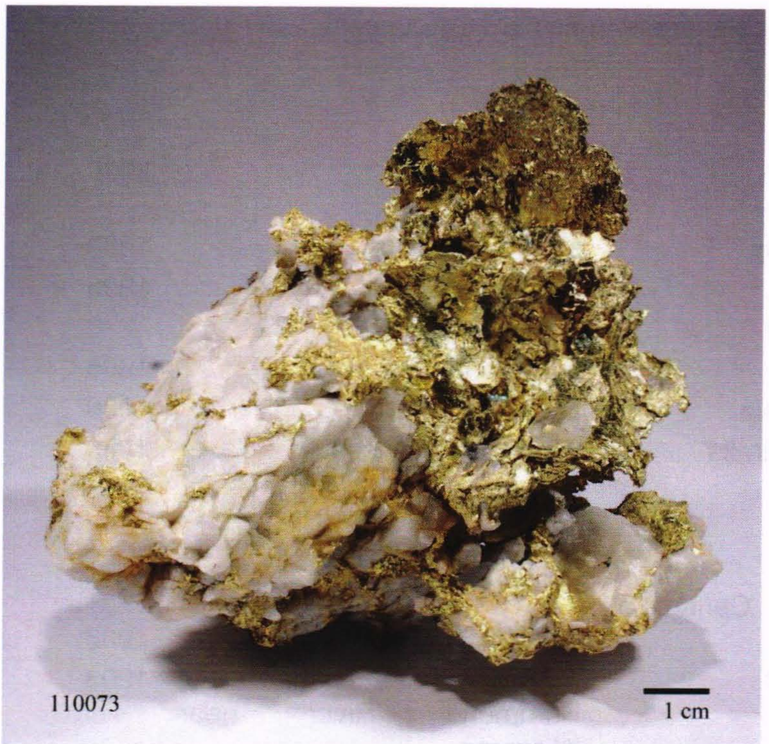

Figure 4. Gold leaves in quartz Grass Valley, CA.

Gold deposits

Gold is found in a variety of kinds of mineral deposits besides the familiar hydrothermal quartz veins such as those in the famous Mother Lode belt of California or Russia's equivalent, the Beryozovskoe gold field in the Ural Mountains. Epithermal deposits are associated with volcanic centers and geologically young. They were emplaced at shallow depths and often provide well crystallized specimens. The famous Rosia Montana deposit in Romania's golden quadrilateral is the classic European locality for small but fine gold crystals on quartz druses. Round Mountain in Nye Co., Nevada is new world-class specimens of crystallized gold. Other types of gold deposits do not produce collector grade specimens at all. In fact, some produce invisible gold – the particles are so small that they are never seen. The Witwatersrand goldfields are paleoplacer systems noted for its richness but the gold grains are minute. The rare showy Witwatersrand specimens were formed by remobilization of gold during a later metamorphic event. Carlin-type deposits, which are extensively developed in Nevada, are also invisible gold are deposits. R.W. Boyle's *Gold, History and Genesis of Deposits* (1987) and Guilbert and Park's *The Geology of Ore Deposits* (1986) are excellent introductions to the geology of gold deposits and their study.

Rarity

Gold is valuable because it is beautiful, useful and rare. How rare is gold? Estimating the abundances of the elements in the universe, Earth, crust, etc is one of the great achievements of 20th century geochemistry. Much of that work was done by V. M. Goldschmidt in Olso! The average abundance of gold in the crust is 0.005 ppm (or grams per ton), which places it along with the platinum group elements among the very rarest of elements.

Why is it so rare? Elements are made in stars by successive fusion of nuclei culminating with iron. Heavy elements are formed by supernova explosions of stars. The amount of gold in the Earth was fixed when the Earth formed from the protoplanetary disc of gas and dust rotating about the sun at 4.567 billion years ago. The planets are assumed to have initially been homogeneous. Shortly thereafter, however, the Earth melted with consequent massive redistribution of the elements forming an iron-rich core and a silicate-rich mantle. From this mantle the overlying crust, hydrosphere and atmosphere formed. Goldschmidt also introduced the terms siderophile, chalcophile, and lithophile to describe elements with preferential affinity for metallic iron, sulfur and silicate. During differentiation gold, being a siderophile element was concentrated in the core leaving little in the mantle to be later moved into the crust where it can be found by Man.

The Specimen Market

Gold is a collecting specialty pursued by many who have little interest in minerals other than gold. In the mid twentieth century fine specimens of gold and especially crystallized specimens were very difficult to obtain. Gold specimens are now readily available due to several factors: (1) The development of effective metal detectors has rejuvenated prospecting for gold. (2) The rise in the price of gold from the standard of $35/Troy ounce maintained by the US government until 1971 has made prospecting for nuggets far more attractive. (3) The spectacular rise in the prices paid for mineral specimens has promoted mining for mineral specimens rather than specimens being solely a byproduct of mining for commodities like metals or industrial minerals. The Eagle's Nest mine, Placer County, and the Colorado Quartz and adjacent mines, Mariposa County, California have been sporadically producing large numbers of crystallized specimens. Many dealers carry gold specimens and some specialize in gold. Nuggets from Alaska, Australia and elsewhere are offered regularly at the Denver and Tucson shows. See Cook (2004) for an excellent review of the gold specimen market over the last three decades.

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