TECTONIC SETTINGS AND TEMPORAL EVOLUTION OF OROGENIC GOLD DEPOSITS

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Summary

Orogenic gold deposits are characterized by a unique and consistent pattern through geologic time, with the more important deposits having formed at about 3.1 Ga, 2.7-2.5 Ga, 2.1-1.7 Ga, and <0.6 Ga. Age patterns for Precambrian gold deposits are remarkably similar to those of episodic growth of juvenile crust, both reflecting discrete periods of mantle overturning and extreme heating at the base of the lithosphere. Patterns subsequent to 1.7 Ga reflect the decreasing influence of such plume activity on plate tectonics and the increasing impact of modern-style plate tectonics on crustal evolution and ore deposition. Under the younger style of tectonic regime, gold ores were emplaced within thin orogenic belts along cratonic margins. Reworking of these margins has led to the total erosion of Mesoproterozoic and Paleoproterozoic gold lodes. Preserved gold systems that developed along cratonic margins are only preserved within the • 600 Ma Gondwana, Paleo-Tethys, and Circum-Pacific orogens.

Introduction

Orogenic gold deposits have formed over more than 3 b.y. of Earth history, episodically during the Middle Archean to younger Precambrian, and continuously throughout the Phanerozoic. This class of gold deposit is characteristically associated with deformed and metamorphosed mid-crustal blocks, particularly in spatial association with major crustal structures. A consistent spatial and temporal association with granitoids of a variety of compositions indicates that melts and fluids were both inherent products of thermal events during orogenesis. Including placer accumulations, which are commonly intimately associated with this mineral deposit type, recognized production and resources from economic Phanerozoic orogenic-gold deposits are estimated at just over one billion ounces gold. Exclusive of the still-controversial Witwatersrand ores, known Precambrian gold concentrations are about half this amount. The recent increased applicability of global paleo-reconstructions, coupled with improved geochronology from most of the world's major gold camps, allows for an improved understanding of the distribution pattern of orogenic gold in space and time.

Patterns of Gold Formation through the Precambrian

There are few well-preserved blocks of Middle Archean mid-crustal rocks with gold-favorable, high-strain shear zones in generally low-strain belts. The exception is the Kaapvaal craton where a number of large orogenic gold deposits are scattered through the Barberton greenstone belt. A few >3.0 Ga crustal fragments also contain smaller gold systems in the Ukrainian shield and the Pilbara craton. If the placer model is correct for the Witwatersrand goldfields, then it is possible that an exceptional Middle Archean orogenic-gold lode-system existed in the Kaapvaal craton at one time. The latter half of the Late Archean (ca. 2.8-2.55 Ga) was an extremely favorable period for orogenic gold-vein formation, and resulting ores preserved in mid-crustal rocks contain a high percentage of the world's gold resource. Preserved major goldfields occur in greenstone belts of the Yilgarn craton (e.g. Kalgoorlie), Superior Province (e.g. Timmins), Dharwar craton (e.g. Kolar), Zimbabwe craton, Slave craton (e.g. Yellowknife), Sao Francisco craton (e.g. Quadrilatero Ferrifero), and Tanzania craton, with smaller deposits exposed in the Wyoming craton and Fennoscandian shield. Some workers also suggest that the Witwatersrand ores were formed from hydrothermal fluids in this period.

The third global-wide episode of orogenic gold-vein formation occurred at ca. 2.1-1.8 Ga, as supracrustal sedimentary rock sequences became as significant hosts as greenstones for the gold ores. Greenstone-sedimentary rock sequences now exposed in interior Australia, northwestern Africa/northern South America, Svecofennia, and the Canadian shield were the focus of gold veining prior to final Paleoproterozoic cratonization. Many of these areas also contain passive margin sequences in which BIFs provided favorable chemical traps for later gold ores. Widespread gold-forming events included those of the Eburnean orogen in West Africa (e.g. Ashanti); Ubendian orogen in southwest Tanzania; Transamazonian orogen in the Rio Itapicuru greenstone belt of the Sao Francisco cratón, west Congo craton, and Guyana shield (e.g. Las Cristinas); Tapajos-Parima orogen on the western side of the Amazonian shield; Trans-Hudson orogen in North America (e.g. Homestake); and Svecofennian orogen on the southwestern side of the Karelian craton. Where Paleoproterozoic tectonism included deformation of older, intracratonic basins, the resulting ore fluids were anomalously saline and orogenic lodes are notably base metal-rich. Examples include ore-hosting strata of the Transvaal basin in the Kaapvaal craton and the Arunta, Tennant Creek, and Pine Creek inliers of northern Australia.

The Mesoproterozoic through Neoproterozoic (1.6 Ga-570 Ma) records almost 1 b.y. of Earth's history that lacks unequivocal evidence of significant gold-vein formation. To a large extent, the preserved geological record of this time indicates that this was a period of worldwide major extension, intracontinental rifting, and associated anorogenic magmatism. Some juvenile crust was, nevertheless, added to cratonic margins in this period, particularly during the growth of the Rodinian supercontinent at ca. 1.3-1.0 Ga. Some early Neoproterozoic dates are reported for important orogenic gold ores within the older mobile belts around the southern Siberian platform (e.g. Sukhoi Log), but it is uncertain whether these dates are correct or, in many cases, are ages of country rocks to the main lodes that may have formed later. Late Neoproterozoic collisions, which define the initial phases of Gondwana formation, mark the onset of the relatively continuous, orogenic gold-vein formation in accretionary terranes that has continued to the present day. Ore formation occurred during Pan-African events in the Arabian-Nubian shield, within the Trans-Saharan orogen of western Africa and extending into Brazil's Atlantic shield, within the Brasilia fold belt on the western side of the Sao Francisco craton, and within the Paterson orogen of northwestern Australia.

Phanerozoic Gold-Rich Orogens

Paleozoic gold formation, accompanying the evolution of Pangea, occurred along the margins of Gondwana and of the continental masses around the closing Paleo-Tethys Ocean. In the former example, orogenic lodes extend from the Tasman orogenic system of Australia (e.g. Bendigo-Ballarat), to Westland in New Zealand, through Victoria Land in Antarctica, and into southern South America. Early Paleozoic gold-forming Caledonian events in the latter example included those associated with amalgamation of the Kazakstania microcontinent (e.g.Vasil'kovsk) and closure of the Iapetus Ocean between Baltica, Laurentia and Avalonia (e.g. Meguma/Carolina Slate Belt/Peru). Variscan orogenic gold-forming events in the middle to late Paleozoic correlate with subduction-related tectonics along the western length of the Paleo-Tethys Ocean. Resulting gold ores extend from southern Europe (e.g. in the Iberian Massif, Massif Central; Bohemian Massif), through central Asia (e.g. Muruntau, Kumtor), and into northwest China (e.g. Wulashan). The simultaneous Kazakhstania-Euamerica collision led to gold vein emplacement within the Uralian orogen (e.g. Berezosk).

Mesozoic break-up of Pangea and development of the Pacific Ocean basin included the establishment of a vast series of circum-Pacific subduction systems. Within terranes on the eastern side of the basin, the subsequent Cordilleran orogen comprised a series of Middle Jurassic to mid-Cretaceous orogenic gold systems extending along the length of the continent (e.g. Mother Lode belt, Bridge River, Klondike, Fairbanks, Nome). A similar convergent tectonic regime across the basin was responsible for immense gold resources in the Russian Far East, mainly during the Early Cretaceous (e.g. Natalka, Bam). Simultaneously, important orogenic gold systems developed within uplifted basement blocks of the northern (e.g. Dongping), eastern (e.g. Jiaodong Peninsula), and southern (e.g. Qinling belt) margins of the Precambrian North China craton. Orogenic gold veining continued in the Alaskan part of the Cordilleran orogen (e.g. Juneau gold belt) through the early Tertiary, and was also associated with Alpine uplift in southern Europe, and strike-slip events during Indo-Asian collision in southeastern Asia, through the middle, and into the late, Tertiary.

Plate Tectonics, Crustal Growth, and Ore Formation

The important periods of Precambrian orogenic gold-deposit formation, at ca. 2.8-2.55 Ga and 2.1-1.8 Ga, correlate well with episodes of growth of juvenile continental crust. Similar characteristics of the Precambrian orogenic gold ores to those of Phanerozoic age have led to arguments that "Cordilleran-style" plate tectonics were also ultimately responsible for the older lodes. However, the episodic nature of ore formation prior to ca. 650 Ma also suggests significant differences in overall tectonic controls. The two broad episodes of Precambrian continental growth, and associated orogenic gold-veining, are presently best explained by major mantle overturning in the hotter early Earth, with associated plumes causing extreme heating at the base of the crust. This subsequently led to massive melting, granitoid emplacement, depleted lower crust and resultant extensive buoyant continental crust. Resulting Late Archean and Paleoproterozoic crustal blocks are large and relatively equi-dimensional stable continental masses that are thermally and geometrically most suitable for the long-term preservation of auriferous mid-crustal orogens, particularly distal to their margins.

More than fifty percent of the preserved Precambrian crust formed between 1.8 and 0.6 Ga, yet these rocks contain few orogenic gold deposits, therefore indicating that more than volume of preserved crust controls the distribution of these ores. Despite much of this appearing to have been a time of worldwide extension and anorogenic magmatism in cratonic interiors, significant continental growth was still occurring along cratonic margins (e.g. Albany-Fraser and Musgravian orogens in Australia, growth of North America on southern side of Hudsonian craton, collisions on southwestern margin of Amazonian craton, etc.), culminating with the formation of Rodinia by ca 1.0 Ga. Beginning at the end of the Paleoproterozoic, however, there was a change in crustal growth patterns, such that juvenile crust began to be added as long narrow microcontinents and accretionary complexes around the margins of older cratons. This probably reflects the gradual change from strongly plume-influenced plate tectonics to a less-episodic, more-continuous present-day style of slab subduction and plate tectonics as a more homogeneous mantle was evolved. The long and narrow strips of juvenile crust younger than 1.8 Ga would have been relatively susceptible to continual reactivation and reworking during Mesoproterozoic through Phanerozoic collisions, and the high metamorphic-grade of most 1.8-0.6 Ga crustal sequences indicates unroofing of core zones to the orogens. These schist and gneiss sequences would have been beneath the levels of most-productive orogenic gold-vein formation within most orogens.

The distribution of orogenic gold ores formed during the last 650 m.y. of Earth history is well-correlated with exposures of the greenschist-facies mobile belts surrounding 1.8 Ga cratonic masses. Reworking of cratonic margins has eroded away most indications of orogenic gold older than ca. 650 Ma in these crustal belts, whereas younger lode systems are preserved especially from the last 450 m.y. The immense circum-Pacific placer goldfields collectively suggest a short lifespan for many of the lode systems; veins are apparently recycled into the sedimentary rock reservoir within • 100-150 m.y. after their initial emplacement if continental margins remain active. Where continent-continent collisions preserved Phanerozoic orogens in a "craton-like" stable continental block (e.g. central Asia) during supercontinent growth, gold lodes (e.g. Muruntau) could be better preserved. The lack of any exposed, large orogenic gold-systems younger than about 55 Ma indicates that, typically, at least 50 m.y. are required before these mid-crustal ores are unroofed and exposed at the Earth's surface.

Conclusions

The pattern of gold ages through geologic time is not random; rather it broadly correlates with that of thermal events associated with the growth of new continental crust. Large-scale fluid migration along major, deeply-seated structures is inherent to most orogenies as moderate to high (e.g. • 400-500°C) crustal temperatures are reached. If there are syngenetic sulfide minerals disseminated in this new crust, such as is common in greenstones and marine sedimentary sequences, then such sulfur will be partly released into the hydrothermal fluid perhaps via prograde desulfidization reactions during crustal heating. If such sulfur-bearing hydrothermal fluids migrate through patterns of fracture networks as they approach major fault zones, then they are capable of transporting a significant amount of the leachable gold along the flow path. This gold is eventually deposited in secondary and tertiary fault systems, adjacent to the main fault at shallower crustal levels of the uplifting orogen. If temperatures exceed about 700°C in and below fluid source areas, both fluids and melts will migrate upward simultaneously. Hence, the ubiquitous spatial and temporal association between gold and granitoids in orogenic belts.

Areas of the Earth with oldest continental crust are dominated by Late Archean and Paleoproterozoic cratonic blocks. Where rocks of this age are well-exposed in the near-surface in these cratons, they almost always contain clusters of significant orogenic gold deposits (e.g. western Australia, north-central Australia, India, southern Africa, central Africa, western Africa, northern South America, and north-central North America). Where cratons of these ages are widely covered by younger sequences, they likely contain similar gold concentrations, but these are simply not exposed (e.g. Siberia, eastern Europe, Wyoming, China cratons, Greenland). Whether cratons are dominated by greenstone terranes (e.g. Yilgarn, Superior) or clastic metasedimentary rock sequences (e.g. Birimian, Northern Territory of Australia) appears irrelevant. Gold concentration was an inherent part of continental growth at 2.8-2.55 Ga and 2.1-1.8 Ga regardless of lithology. Recent geochronology indicates that, within a given craton, gold formation may be quite diachronous, as in many Phanerozoic orogenic belts, rather than a single craton-wide episode.

Phanerozoic orogens that developed during the last 600 m.y. around the margins of Gondwana and the Paleo-Tethys Ocean prior to final amalgamation of Pangea, and that surrounded much of the Pacific rim subsequent to the break up of Pangea, are the source for most of the Earth's other economic gold concentrations. However, where orogenesis was a low T-high P event, such as in formation of the Brooks Range in Alaska, the early Alps, and much of the Appalachians, gold veining was not an important part of orogenesis. Where high-T events do occur, but deep-seated structures are lacking, such as in relatively thin accretionary prisms on orogen margins, gold ores may still be relatively minor (e.g. Japanese Islands, Chugach terrane of Alaska). The lack of large gold provinces younger than ca. 50 Ma provides a threshold for approximating the minimum time required to unroof a major orogenic gold system. The fact that many of the Phanerozoic gold systems older than ca. 100 Ma are associated with large placer fields indicates the short-lived nature to this type of gold deposit, unless preserved for billions of years by the early Precambrian cratonization processes.

The style of plate tectonics need not be critical to the formation of orogenic gold deposits. Any thermal event within hydrous and S-bearing juvenile crust, whether it be initiated by Precambrian plume-like events, or younger, more-typical subduction/collision type processes, can form the same type of gold deposit. The lack of significant gold ores between ca. 1.8 and 0.6 Ga appears to be a function of changing patterns of continental growth, eventually linked to a shift in styles of plate dynamics on a cooling Earth. Beginning in the Mesoproterozoic, there was a diminishing impact of mantle plumes for forming large, regulary-shaped masses of juvenile crust with a high potential for cratonization and preservation of gold lodes. A more modern-day style of plate tectonics, which was associated with the growth of Rodinia, led to juvenile crust being added as irregular fragments around the margins of the older cratonic blocks for at least the last ca 1.5 b.y. Such long, thin blocks of new crust were particularly susceptible to reworking and erosion by subsequent orogenesis. Most exposures of Mesoproterozoic and Neoproterozoic mobile belts, therefore, are characterized by deep crustal orogenic root zones that were below gold-favorable parts of the crust.