Gold is where you find it.
—Anonymous

Chapter V. Prospecting for gold deposits

Introduction

Gold is won from deposits specifically mined for the metal and from a great variety of polymetallic deposits in which it is a minor byproduct. Gold is, therefore, a suitable indicator not only of its own deposits but frequently also of a large number of other types, particularly those carrying copper, silver, lead and zinc. The converse of the old Chilean prospecting proverb, "If thou findest copper thou hast gold" is true for many metals with which gold is associated. In the following we shall deal principally with methods applicable to those deposits in which gold is an important constituent and only briefly with deposits in which the element is a byproduct.

Selection of areas

Those searching for gold-bearing deposits should study carefully the types of deposits and their geological setting as outlined in Chapter III. Particular note should also be taken of the modes of oxidation of the various types of gold deposits as discussed in Chapter IV. Since gold and silver usually occur together the chapter on prospecting in the writer's monograph on silver (Boyle, 1968*b*) will complement parts of the present chapter.

There are no known bodies of granitic, intermediate or basic rocks, pegmatites or porphyries where indigenous (syngenetic) amounts of gold and silver are enriched in sufficient quantities to constitute orebodies. A few granitic and intermediate stocks and quartz-feldspar porphyry bodies are known, however, in which higher than average amounts of gold and silver are present. Most of these are greatly enriched in indigenous pyrite with which the gold and silver are associated. Conceivably, bodies such as these could exist that have commercial quantities of indigenous gold and silver. They should be sought in volcanic terranes, particularly those with abundant tuffs and interbedded pyritic sediments, and in sedimentary belts rich in pyritic schists, slates and argillites. The smaller granitic, dacitic and quartz-feldspar porphyry, stocks, irregular bodies and their associated dykes appear to be the most favourable for primary enrichments of gold and silver. Such rocks are also frequently marked by higher than average contents of Cu, Mo, As and Sb.

Bodies of igneous rocks ranging from parts of batholiths to dykes are frequently the hosts for gold deposits. In these the gold is epigenetic, that is introduced into favourable structural sites such as fractures, faults and shear zones. These types of deposits are considered subsequently.

Gold-bearing skarn and contact metamorphic deposits require little comment. They occur mainly in the contact aureoles of granitic and allied rocks and in medium- and high-grade metamorphic terranes. In these environments nearly all deposits are developed in limestones, dolomites, calcareous sandstones or calcareous shales. Metamorphosed sedimentary piles of argillites, black schists and the various calcareous rocks seem to be particularly favourable as do piles containing metavolcanic rocks, tuffs and calcareous rocks. The thought should be kept in mind that the pyritiferous black shales and argillites and the volcanic rocks may be the source of the gold and silver and other elements, and that these were mobilized during metamorphism and granitization and chemically trapped in the calcareous rocks where suitable primary (porosity) and secondary structural conditions prevailed.

A great many of the metamorphic and granitized terranes in Canada are susceptible to mineralization of the skarn and contact metamorphic types. The metamorphic terranes of the Appalachian Belt, the Grenville, the vast metamorphic terranes of the Canadian Shield and the numerous metamorphic belts and contact zones of the western Cordillera are examples of broad select areas in which to prospect for gold-bearing deposits of the skarn type. The Grenville rocks of Ontario and Quebec should receive more attention than they have as favourable sites for the deposition of gold-silver deposits.

Among the various vein, lode, stockwork and disseminated types of deposits categorized in Chapter III there are two general types – the gold-quartz type in which gold is the principal economic constituent and the polymetallic type containing lead, zinc, copper and other base metals with gold and silver as valuable and sometimes indispensable byproducts. There appear to be no general rules governing the localization of these deposits, a feature that should be kept in mind by the prospector. There are, however, certain patterns of occurrence that seem worthy of note.

On a statistical basis the gold-quartz and gold-bearing polymetallic veins and lodes show two characteristic modes of occurrence with respect to the various types of country rocks. A large number of these types of deposits occur in volcanic piles especially those containing abundant interbedded tuffs and pyritiferous sediments. The second greatest concentration of these deposits is in metamorphosed sedimentary piles, especially those containing greywackes, quartzites and pyritiferous argillites and slates. Neither of these modes of occurrence are at all new to the seasoned prospector – the greenstones and propylites of many mineral belts and the greywacke-slate assemblages with their abundant quartz bodies have long been known as favourable auriferous areas. The philosophy of prospecting in these two environments has, however, been that the metals were derived from local granites or some other suitable igneous rock. Perhaps we should take a more careful look at the country rocks themselves as the source of the metals. There is abundant geochemical evidence to suggest that the pyritiferous schists, slates, iron-formations and tuffaceous rocks intercalated with the older greenstones, or in the case of Tertiary volcanic piles lying below them, may be the source of the gold and silver, and that the andesites, basalts, trachytes, etc. as well as the intrusive porphyries may also have made their contributions. Likewise, it is also highly probable that sulphide-bearing black slates, schists, phyllites, etc. are the source of the noble metals in the deposits localized in the greywacke-slate assemblages. As these various rocks were structurally deformed and metamorphosed, numerous dilatant zones were formed along faults, shear zones, sheared beds and on the crests of anticlines. These low pressure zones became the depositional sites for the more mobile constituents from the rocks, including quartz, the components of pyrite and arsenopyrite, gold and silver and other constituents. (*See also* the last section of Chapter III.)

The philosophy in prospecting for these two types of gold-silver deposits should be to seek out areas containing the favourable rocks mentioned above, paying particular attention to sulphide-bearing sediments. From this point careful attention should be directed to areas that were structurally deformed during the metamorphic history of the favourable areas. It should be mentioned that the black pyritiferous schists, phyllites and argillites are usually incompetent rocks and do not generally contain the deposits. They probably provided the elements to the deposits; more competent rocks such as the greywackes, greenstones and local intrusive stocks and dykes are generally the sites of the structural traps.

The old volcanic belts (greenstones) of Precambrian to Mesozoic age inclusive are generally folded, faulted and extensively sheared. The gold-quartz and auriferous polymetallic deposits in these belts tend to favour the lower grade epidote amphibolite and greenschists facies, but this is not an invariable rule. Numerous deposits are known in the high grade amphibolite facies, in batholithic granitic bodies near their contact with the greenstones or in stocks, plugs, dykes and sills of various igneous rock types in the higher grade metamorphic facies. Many deposits are in great carbonated shear zones or in subsidiary structures. During shearing, chloritization, hydration and carbonatization of the shear zones, SiO_2, various metals, sulphur, arsenic and antimony were released and migrated into dilatant zones as outlined in the last section of Chapter III. A number of auriferous deposits in greenstone belts are in tuffs or iron-formations, and others are disseminations and stockworks in quartz-feldspar porphyry, dacite and diorite dykes or stocks that frequently carry much pyrite and pyrrhotite. These types of deposits are mentioned later.

In some of the old volcanic (greenstone) belts the gold deposits may show a preference for certain rock sequences. In the Birch Lake–Uchi Lake area of Ontario Goodwin (1965*b*) found by detailed stratigraphic studies that the volcanic components are arranged in superimposed sequences or cycles. Each cycle exhibits a progression from predominantly mafic effusives below to predominantly felsic extrusives above. Sedimentary rocks are preferentially associated with the felsic extrusives. Two volcanic cycles are represented, and the gold occurrences are preferentially distributed with respect to them. Of 50 recorded occurrences, 39 are located in the upper felsic division of the Lower volcanic cycle and 40 are associated with closely interbanded dacite-rhyolite pyroclastic rocks, andesitic lavas and siliceous sediments. The gold-bearing quartz veins either lie at the contacts of enclosing lithologic units or occupy crosscutting fractures in one or more adjacent units.

No preferential distribution of gold deposits within the volcanic sequence is present in the Yellowknife Greenstone Belt nor is any immediately obvious in the Red Lake district. At Timmins, however, there is a slight tendency for the deposits to lie within certain stratigraphic members. The story of the relationships of gold deposits in the old greenstone belts is, therefore, complex. The often repeated assertion that gold (and sulphide) deposits exhibit a relationship to felsic volcanic members may reflect structural rather than volcanogenic conditions. In volcanic sequences the rhyolites, trachytes and dacites appear to fail structurally more readily than basalts and andesites. Failure of the felsic members is also commonly by brittle fracture, whereas the mafic members shear or form schist zones. Rocks that fail by brittle fracture seem also to be more susceptible to mineralization in some belts compared with those that shear or form schist.

In the recent literature some stress has been placed on the association of gold deposits and ultramafic rocks, these rocks being considered as possible sources for the gold. Viljoen *et al.* (1969,1970) noted a possible relationship between ultramafics and gold deposits in the Barberton Mountain Land, South Africa, and Pyke (1976) has drawn attention to a similar relationship in the Timmins area of northeastern Ontario. The latter author also pointed to the coincidence of ultramafics and gold deposits in other Archean greenstone belts, including the Holtyre area, Kirkland Lake–Larder Lake area and the Val d'Or area, all in the Abitibi Greenstone Belt. Gold deposits are also commonly concentrated in or near ultramafic bodies in a number of other places in the writer's experience. Examples are widespread in the Mother Lode System of California (Knopf, 1929) where the system cuts serpentinites, in the Bridge River area of British Columbia and in a number of greenstone belts in Western Australia, particularly Coolgardie (McMath *et al.*, 1953) where the relationships of many of the veins, including Bayley's Reward, and ultrabasic rocks (flows and/or sills) are well displayed. McMath *et al.* underline the fact that "ultrabasic rocks are the most favoured host rocks of the Coolgardie district."

The reasons for the association of gold deposits and ultrabasic rocks are not entirely clear. Some investigators consider the rocks to be the source of the gold; others think that structural considerations are more important. Probably both are responsible agents. As noted in Chapter III carbonatization and hydration during shearing and faulting of ultrabasic rocks may deliver large amounts of gold and other elements to migrating solutions (Table 73) that ultimately deposit these in suitable dilatant zones such as fissures and faults. Ultrabasic rocks, as is well known, are particularly susceptible to hydration and carbonatization and probably release of gold. Not all ultrabasic rocks are enriched in gold as shown by the researches of Anhaeusser *et al.* (1975) and the compilation recorded in Table 13. One must conclude from these facts that both source and tectonic effects are important considerations.

It bears emphasizing that the old greenstone belts as well as many of the younger volcanic terranes, and also certain sedimentary sequences, are marked by extensive developments of carbonatization and hydration (chloritization, sericitization, etc.). These are manifest in some terranes by random and irregular zones comprising large volumes of rock; more generally, however, the zones are linear or anastomosing and follow lines of extensive faulting, shearing, crushing and drag folding. Gold may have been released from such zones as noted in Chapter III and quantified in Table 73. Examples are numerous of the close association of gold deposits and extensive zones of hydration and carbonatization (Boyle, 1976). Prospectors finding such zones should consider them particularly favourable indicators and should search diligently for nearby dilatant zones (open fissures, faults, shear zones, drag folds, etc.) in which the gold and gangue elements have been concentrated.

At this point it should be mentioned that Ridler (1976) has also emphasized the relationship of many gold deposits in Archean rocks to extensive carbonate zones. His interpretation of these zones differs, however, from that of the author; he considers these zones, e.g., the so-called Larder Lake Break, to be carbonate exhalites associated with the volcanism of the greenstone belts.

From the above discussion it follows that those searching for auriferous deposits in old volcanic belts should seek out favourable source rocks such as interbedded pyritiferous sediments, tuffs, iron-formation, pyritic porphyries and zones of extensive carbonatization and hydration in the vicinity of favourable structures such as faults, fracture zones, schist zones, shear zones, breccia pipes, drag folds, etc. Frequently these structures are marked by depressions or ridges depending on their weathering characteristics and are often revealed by lineaments, circular and S-shaped lakes, marshes and bogs and irregular topographically high or low features. In the Canadian Shield and elsewhere many favourable gold-bearing structures are marked by lineaments on the ground and on air photos. Such lineaments mark depressions and are produced mainly by the differential weathering of shear zones, faults, dykes, tuff beds, etc. that have been highly carbonated and pyritized. Many of these features have been accentuated by the abraiding action of glaciation. An excellent example of the use of lineaments in prospecting for gold deposits is afforded by the Yellowknife Greenstone Belt. In this gold belt there are three types of lineaments. One type marks diabase dykes, another late Proterozoic faults, and the third, and most important, marks the carbonated chlorite schist zones in which the gold-quartz veins and lodes occur (Fig. 17). During early exploration in this belt the late Dr. A.S. Dadson of Ventures recognized the significance of the latter type of lineament in prospecting, and his recommendations for diamond drilling along one of the prominent linear valleys of the area led directly to the discovery of the great orebodies of the Giant Mine. It should be pointed out that not all gold-bearing structures are marked by depression features. On the contrary, in some volcanic belts the mineralized zones may be heavily silicified and may weather as linear, curved or irregular ridges.

With regard to prospecting in old Precambrian shield areas (Canadian Shield, Indian Shield, African Shield, Australian Shield, etc.), Emmons (1932) laid great stress on the relationship of auriferous deposits to granitic intrusions and classified their position with respect to these intrusions as follows, the least productive first:

1. Granite areas 1 mi or more from a contact with invaded (greenstone, sedimentary) rocks. Lodes are numerous but generally not workable. Few deposits are productive.

2. Granite areas less than 1 mi from their contact with greenstones or sediments. A few valuable lodes have been worked in these areas, but most are small and only moderately productive compared with the lodes of the next two groups.

3. Invaded (greenstones, sediments) rocks of the 'island' or 'roof pendant' areas. These contain numerous deposits, many of which have been profitably mined.

4. Areas of the invaded (greenstones, sediments) rocks near small stocklike intrusives. These contain most of the largest gold lode mining districts in the shields.

The flows, tuffs and associated sediments in young (Tertiary) volcanic belts are usually relatively flat-lying but are generally extensively faulted. Great volumes of these rocks are highly propylitized (basic rocks) or sericitized (rhyolites) often on a regional scale. Silicification and argillization are two other effects that are often widespread, and in some districts the rocks may be alunitized. The mineralized zones commonly show little direct relationship to these alteration effects, although most occur within the general confines of the regionally altered zones. In a few regions irregular belts or bands of propylitic, sericitic, silicic or argillic alteration flank the mineralized belts and are fairly reliable indicators. Similarly, bands, belts and patches of alunitization may also indicate the presence of veins within, flanking or underlying the belts and patches. An example of this type of relationship is shown in Figures 32 and 33.

Most of the gold-quartz veins and gold-bearing polymetallic deposits in the young volcanic belts occur in faults or in brecciated zones. These cut all types of rocks but are commonly concentrated in linear belts or in curved patterns in the peripheral zones of rhyolite or dacite necks, dykes or sills. Some of the faults are marked by pronounced scarps or lineaments. Particularly favourable loci for the occurrence of auriferous deposits in the young volcanic belts are where andesites, rhyolites, etc. overlie pyritiferous sediments and volcanics of older vintage, the young andesites and other volcanics being the receptacle rocks and the older sediments, volcanics, etc. the source of the gold and other metals (*see* Fig. 92).

Deposits in sedimentary belts are commonly concentrated in greywacke-quartzite-slate assemblages; also in argillite-shale-sandstone-black schist piles containing limestone, limy shale or limy sandstone members. Particularly favourable are greywacke-slate assemblages isoclinally folded and then cross-folded with the formation of abundant pitching folds. The structural traps in these piles of rock are provided by dilation zones along the crests of folds (saddle reefs), along bedding planes (bedded-veins) and in the myriad small faults, drag folds and contorted zones that result from the folding and faulting of the rocks. Chemical traps are provided by the fractured and contorted carbonate rocks. The source of the gold and its accompanying elements, including silicon (quartz), is probably the sedimentary pile, particularly the pyritiferous argillites, slates and schists. The migration of the elements was promoted in part by dilation of the various structures, but also by the thermal fronts associated with regional metamorphism, granitization and granitic injection. In this respect, most of the deposits appear to have been controlled by the thermal fronts since they occur predominantly in the low-grade (relatively unmetamorphosed) facies. This is well marked in Nova Scotia (Newhouse, 1936) and at Yellowknife (Boyle, 1961*a*). A few are clustered along the isograd line between the relatively unmetamorphosed greywackes, slates and argillites and their metamorphic equivalents the knotted (andalusite, garnet, cordierite) quartz-mica schists. Where structures are the controlling features and are formed late in the metamorphic history of a sedimentary belt, deposits may occur in the high-grade facies and in any enclosed granitic bodies. Gold and polymetallic deposits localized in the carbonate members of sedimentary piles show no particular relationship to metamorphic facies; some, usually the skarn-type deposit, are formed in the high-grade facies whereas others, the highly silicified types, are localized mainly in the low-grade facies.

Disseminated and stockwork types of gold deposits in igneous dykes, sills and small stocks should be sought in both volcanic and sedimentary terranes, generally though not always in the higher grade metamorphic facies. In the younger volcanic terranes the intrusive host rocks of these types of deposits are often highly sericitized or propylitized. All dykes, sills and small stocks that contain pyrite and/or stockworks of quartz or carbonate veinlets should be carefully analyzed for gold (and silver). Similarly, all igneous bodies of this nature that exhibit alteration effects such as chloritization, sericitization, carbonatization, alunitization, etc. should be analyzed for gold. Even those surface zones that report only trace amounts of the metal should be considered favourable since they may be the upward extension of bonanzas at depth. Where this is suspected deep vertical holes should be drilled to investigate the conditions at depth in the stocks, sills and dykes.

Disseminated gold deposits in sedimentary and volcaniclastic beds are of two general types as mentioned in Chapter III – those in tuffs and associated iron-formations and those in carbonate-bearing beds (Carlin type). The former are restricted mainly to volcanic belts and are usually in tuffs and iron-formations interbedded with andesites, basalts, etc. (greenstones), although a few occur in sedimentary belts. Most are marked by abundant developments of pyrrhotite, pyrite and often arsenopyrite; others contain these minerals in addition to abundant quartz and carbonates in veinlets or disseminated throughout the tuffs and iron-formations. The sulphides tend to weather readily, and the bands, belts and zones that are gold-bearing frequently weather low and form marked linear depressions. Others, commonly the highly silicified types, weather high and form prominent ridges. Nearly all are heavily iron stained, and some have marked gossans. The disseminated gold deposits in carbonate-bearing beds (Carlin type) seem to occur mainly in sedimentary belts, although there is no reason to assume that they should not also occur in volcanic belts. There are few criteria to distinguish their precise localization judging from the occurrence of those that are known in United States and U.S.S.R. Most of these deposits seem, however, to be localized in tectonically disturbed zones near regional faults of some magnitude. Most of these deposits are easily located by geochemical methods utilizing rocks, stream sediments and soils as the sampling media.

The presence of certain dyke rocks and stocklike bodies generally of igneous origin within volcanic and sedimentary belts has long been considered a favourable indicator of the possible occurrence of gold (and certain types of sulphide) deposits. Here the author may mention quartz-feldspar porphyries that occur frequently in the Precambrian gold belts of the world, porphyritic dacites that are common in most Tertiary gold belts, and various albite aplites and porphyries (keratophyres, albitites, alaskites) that occur in gold belts of various ages. There appears to be some prospecting value in these observations especially where the various types of porphyries are enriched in pyrite. The reason for the association of gold with quartz-feldspar and albite porphyries and dacites may be one of source as mentioned in Chapter III, it may be one of structural competency to hold fractures, or it may be the result of both these factors.

The association of gold deposits with albite porphyry dykes and stocks variously named keratophyres, albitites and alaskites has been noticed by Gallagher (1940) and Ward (1958). The latter detailed the types of deposits genetically related to the albite porphyries as follows: (1) auriferous silicified albite porphyries; (2) auriferous quartz veins in albite porphyries; (3) auriferous quartz veins in the country rocks in the vicinity of the porphyries; and, (4) auriferous sulphide lodes in the country rocks in the vicinity of the porphyries.

These deposits are said to be characterized by a high Au/Ag ratio (generally more than 9) and a simple mineral association comprising gold, pyrite, pyrrhotite, arsenopyrite, chalcopyrite, sphalerite, galena, and small amounts of scheelite and gold tellurides.

Ward (1958) hypothesized that a simple mineral association and a high Au/Ag ratio point to a genetic association with albite porphyries. Once this relationship is established the possibility of the four different types of gold ore deposits stated above can be suspected to occur in a district. In alluvial gold areas, exposures of albite porphyries similarly advise the search for more than one type of gold ore deposit.

Bilibin (1947) considers that many auriferous deposits are associated with small diorite intrusives that are the precursors of batholithic bodies in some gold belts (Kolyma region of U.S.S.R.). In other belts he noted that many gold deposits are confined to zones marked by small postbatholithic intrusives as in northern Kazakhstan, the Kalba and Kuznetsk Alatau regions and elsewhere. Other Soviet geologists have also noted the association of auriferous deposits with small intrusives particularly in the Urals and eastern Transbaikal. Ivankin and Rabinovich (1972) review the evidence for the association of gold deposits with small intrusives and list the following combination of factors, which they think leads to the formation of granitic magmatic systems that yield auriferous solutions in the early magmatic stage, during the formation of the batholiths proper and during the postbatholithic stage.

1. High basicity of the palingenic magma, whose composition is shifted from predominantly granodioritic toward dioritic and gabbro-dioritic due to the magmatic replacement of different iron-magnesian sedimentary-volcanogenic and

other rocks – all products of the basaltic magmas of previous cycles.

2. Complete differentiation of these specific magmas with the appearance of contrasting petrographic types of rocks, such as gabbros and plagioclase granites, diorites, syenites, etc.

3. Considerable upward movement of the magmas in the mesobyssal and hypabyssal zones of the earth's crust, facilitated by the segregation of volatile components and differentiation of the magmas. This is followed by the accumulation of mineralizing agents in the outer (frontal) parts of the magmatic columns and by the divergence at different levels and convergence of the hydrothermal solutions. Immobile magmas even with a high primary gold content evidently do not give rise to ore-magmatic systems.

4. The assimilation of carbonate rocks by the magma as one of the causes of its differentiation.

5. The interaction of the mobile structural-tectonic elements with the magmas during the period of the latter's formation, migration and differentiation. In many respects this determines the morphology of the frontal zones of the plutons and the development of the ore-magmatic systems.

Borodaevskaya and Rozhkov (1974) remark on the paragenetic link between minor intrusions and gold deposits in numerous auriferous regions. They distinguish the most common minor intrusions with which gold deposits are associated as follows: (1) minor intrusions of the middle stages of orogenic development of an area, and (2) minor intrusions of the late orogenic stage and of activation zones in regions where the folding has been completed. They point out that a characteristic feature of the interrelationship of minor intrusions and auriferous mineralization is the frequent occurrence of deposits in the intervals between injection of igneous rocks of different ages – a feature that they think emphasizes the close link between ore- and magma-generating sources.

Certain unusual rocks have often been thought to be signs of the presence of auriferous deposits. There is an adage among some gold prospectors that lamprophyres are good indicators of the presence of gold deposits. Such seems to be the case in some belts (McLennan, 1915), but in others there is no relationship whatsoever in the writer's opinion. The possibility of a genetic connection should, however, be kept in mind in further research work in gold belts.

It bears repeating that all regional and local zones and patches of propylitization, alunitization, pyritization, arsenopyritization, carbonatization, chloritization, sericitization and silicification in all ages and types of rocks should be carefully scrutinized for enrichments of gold and silver. Such zones are often revealed by a bleached appearance on the weathered surface; some are reddish due to heavy iron staining, and others are black due to the presence of manganese oxides. All such zones should be analyzed for gold and silver and their indicator elements such as arsenic. Even where the surface zones are relatively low in these elements, the thought should always be entertained that such zones are the upward manifestations of deeper bonanzas. Where this is suspected deep drilling is suggested utilizing the concepts of primary halos as outlined subsequently.

Those seeking areas containing modern (nonlithified) gold placers should be guided by the principles discussed in the section on placers in Chapter III and should consult the references given in that section, particularly the works by Gardner and Johnson (1934–1935), Jenkins (1946), West (1971) and Wells (1973). In applying the basic principles governing the formation of placers it must be constantly kept in mind that the climatic and geomorphological conditions when the placers were formed in any particular area were in most cases much different than those that obtain today.

One must think and construct models in terms of paleoclimatic and paleogeomorphic conditions and reconstruct the history of erosion and deposition of the auriferous sediments. This will be appreciated by examining Figure 72 where it will be seen that the old stream and placer deposits bear no particular relationship to the present day topographic or drainage patterns.

The occurrence of gold placers in an area is dependent on four general conditions – a source for the gold, a mechanism for the release of the metal from its source, a concentration mechanism and favourable conditions for preservation of the deposits. Each of these conditions need only be reviewed briefly here since the details are given in Chapter III.

The source of the gold may be one or more of the following: epigenetic gold-quartz deposits; auriferous disseminated and massive sulphide bodies; auriferous polymetallic deposits, slightly auriferous quartz stringers, blows and veins in schists, gneisses and various other rocks; various slightly auriferous minerals such as pyrite and other sulphides in graphitic schists and other rocks; slightly auriferous conglomerates, quartzites and other rocks; and old placers. Intermediate sources such as the last two in the system – primary source–alluvial placer – must always be kept in mind as reiterated in Chapter III.

Weathering is the principal method of release of gold from its deposits, although glacial action may be effective in glacial terrains. The erosive action of wind is an important method of liberation of gold in some desert regions.

Concentration of gold in placers is accomplished mainly by physical means, but chemical processes also play a large part in some cases as outlined in Chapter III. The principal concentrating agents are: gravity (eluvial placers), water (gulch, stream, river, flood plain, delta and beach placers), wind (eolian placers) and glaciers (glacial placers).

The favourable conditions for preservation of gold placers are: abandonment of stream and river courses containing pay streaks as a result of change of course or rapid downward cutting by streams and rivers; regional uplift, which mainly affects alluvial deposits especially marine placers raising them above the active surf; and burial, which may be by landslide materials, glacial materials, flood plain gravels, alluvial fans, desert outwash detritus, or volcanic flows and tuffs.

Throughout the world areas containing modern placers are generally marked by a 'kindly' terrain that is characterized by a subdued topography marked by broad, often terraced intrenched valleys and rounded deeply weathered hills commonly with nearly accordant summit levels. The paleogradients have usually been relatively low, approximately 30 ft/mi. Few extensive placers were formed in terrains marked by sharp alpine features and high gradient V-shaped valleys; similarly excessively flat terrains far from mountain systems and their foothills have yielded few productive placers. The rocks in placer districts are invariably metamorphosed, and there has usually been considerable igneous activity both extrusive and intrusive. Deep secular weathering is a feature of all placer areas.

Fossil placers occur predominantly in sedimentary terranes generally in conglomerates or quartzites or sequences of both these rocks. Occurrences in greywackes are not common, and there are no known occurrences of fossil placers in shales and limestones. Conglomerates are of many origins including marine, lacustrine, estuarine, fluviatile (fanglomerate) and glacial. Sandstones have similar origins. Both types of rocks generally mark periods of deep secular weathering that is favourable for the production of gold placers.

It is not possible *a priori* to determine where fossil placers are likely to occur. As noted above sedimentary belts should be sought out and the various conglomerates, quartzites and sedimentary breccias examined carefully with the pan or by chemical or fire assay analyses for gold. Zones in sandstones and conglomerates containing magnetite or ilmenite should receive particular care in sampling. Likewise, all conglomerates and sandstones, in fact any sedimentary rock or tuff carrying pyrite, pyrrhotite and/or arsenopyrite, should be carefully tested for gold, platinum, uranium, rare earths and base metals.

The location of fossil auriferous conglomerates and quartzites in sedimentary sequences is difficult to predict. Many lie near the base of the sequences, but others lie well above the base in some districts. Those seeking such conglomerates and quartzites should carefully study the sections in Chapter III, dealing with fossil (lithified) placers and auriferous quartz-pebble conglomerates. Sufficient examples are given there to illustrate practically all possible occurrences of these types of gold deposits. Surface indications of auriferous conglomerates and quartzites are commonly present in regions containing these deposits, being often manifest by large amounts of pyrite in the rocks; excess quantities of quartz pebbles or sands in streams and soils; large concentrations of SO_4 in ground and surface waters due to the oxidation of pyrite; abundant iron staining and gossans, both residual and transported; anomalous radioactivity in the rocks, soils and waters; and the presence in the environment of solid hydrocarbons enriched in one or more of Th, U, rare earths and Au.

The report of the working group on uranium in quartz-pebble conglomerates (International Atomic Energy Agency, Vienna, 1974; Formation of uranium ore deposits; Proceed. Symp. Athens, p. 707) is of interest in prospecting for auriferous deposits in the quartz-pebble conglomerates. They state:

> Uranium-bearing, oligomictic, quartz-pebble conglomerates are epicontinental sediments laid down in Precambrian intracratonic basins. Most of these conglomerates are found in the sedimentary section prior to the development of the first limestones. None have been found of age younger than the first red beds and we believe that none younger will be found. We suggest that reports of young conglomerates of this type, such as a Cambrian conglomerate described in Soviet literature, are in error.
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> The deposition of uranium-bearing minerals in the known conglomerates appears closely related to sedimentary features. This is particularly true in the Witwatersrand and at Elliot Lake, where the presence of uranium in young, cross-cutting conglomerate beds clearly relates to scour of older beds.
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> Where the uraniferous mineral is structurally ordered thorian uraninite, we believe it to be of detrital origin. However, pitchblende occurs in some of the conglomerates and, in our opinion, this must have been deposited from solution even though the uranium has not moved far in dissolved form. In the main, such pitchblende is associated with carbonaceous material normally referred to as thucholite. The available evidence suggests that this material is of organic origin.
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> The conglomerates do not normally contain magnetite or ilmenite. On the other hand they always contain abundant pyrite. We are forced to believe that most pyrite originates by sulphidization of detrital magnetite and ilmenite. The sulphur originated from volcanogenic processes, active at the early stages of crustal evolution, which pertain to the time of deposition of the conglomerates. Some of the pyrite so formed may have entered the conglomerates in detrital form.
>
> Conglomerates and contained minerals ultimately formed by collection, concentration and distribution of detritus by major stream systems.
>
> The formation of an economic deposit relates both to material available at source and to the degree to which the sorting and cleaning process produces a heavy mineral concentrate in the ultimate conglomerate. Known conglomerates differ widely in this regard so that uraniferous conglomerates may contain a variety of other valuable minerals. At present, gold is the significant example of this.
>
> Age determinations suggest that the conglomerates form between about 2800 m.y. and 2200 m.y. As noted earlier, this is prior to the development of the first red beds of the sedimentary section. Prospection for such ores should utilize this as a working hypothesis.
>
> In the opinion of the Working Group, those encountering conglomerates of this kind should prepare heavy mineral concentrates from reasonable rock volumes to facilitate study and understanding of the origin of uranium-bearing minerals and other heavy minerals in the rocks. Except for South Africa, where extensive work of this kind has been done, there is regrettably little data available. The Working Group recommends radiometric logging of all drill holes as the Rand-type thin conglomerates can easily be missed if core recovery is poor.

The writer would urge caution with respect to the conclusions drawn about the age of the quartz-pebble conglomerates. There may well be much younger representatives than those now known. Finally, the statement about magnetite and ilmenite may not be valid as regards the auriferous types, as the Tarkwa deposits in Ghana so clearly testify. The statements that the conglomerates formed earlier than the first limestones is questionable. Archean rocks on which the productive quartz-pebble conglomerates were laid down contain notable amounts of sedimentary carbonates (limestones in places) (Boyle, 1976*a*).

Mordvin *et al.* (1973) have investigated the specific characteristics of auriferous Precambrian conglomerates in eastern Siberia and have concluded the following, which is of interest in prospecting for these deposits: (1) the auriferous conglomerates are confined to the margins of ancient shields; (2) most are restricted to Precambrian rocks formed in depressions that underwent slow subsidence; (3) all are only gently folded and metamorphosed; (4) the ore minerals are confined to the cement of monomictic quartzites or oligomictic conglomerates with well packed average size pebbles; (5) auriferous sections have large intervals of sedimentary hiatus; (6) the stratification in the auriferous conglomerates is better developed than that in basal conglomerates, indicating their formation as quartzose terrigenous rocks which were products of deep chemical weathering; (7) auriferous conglomerates occur in regions marked by preexisting epigenetic gold deposits; and (8) many of the auriferous conglomerates occur in strata enriched in iron.

To conclude this section it is worth mentioning that the prospector should prospect in old geological reports, ancient treatises and the narratives of explorers. Gold has been sought by man for thousands of years, and he has documented its occurrence since the invention of writing. Old gold workings, prospects and chance occurrences of the precious metal are described in the most ancient writings, some now long forgotten. Perusal of these descriptions is often valuable in selecting auriferous areas for further work not only in the search for gold but also for silver, copper and other base metals with which gold is commonly associated. As an example one can point to the Pontic goldfield in Turkey, mentioned in ancient Greek and Roman writings and then largely forgotten. Today this field (Trabzon) is one of Turkey's important sources of copper, lead, zinc and silver.

> To properly prospect for gold deposits one must have a knowledge of the geochemistry of the primary and secondary processes of concentration of the precious metal.
>
> —A.E. Fersman, 1939

Geochemical methods

General

Gold has not been used extensively as an indicator element in geochemical surveys mainly because of difficulties in its estimation in field laboratories. It is, however, a very valuable indicator of various types of deposits as will be shown presently and for this reason should be employed more frequently. In addition to indicating deposits in which it is a major constituent, gold is also useful in detecting various types of silver deposits, polymetallic lead-zinc-copper deposits and certain types of copper deposits.

Indicator elements

In its deposits gold is associated with a large number of elements as detailed in Chapter III and discussed in another publication by the writer (Boyle, 1974*a*). Most epigenetic auriferous deposits contain essentially the same suite of elements, but the contents range widely from mere traces to minor amounts. The gold-bearing quartz-pebble conglomerates contain a suite of elements that differ only slightly from other types of gold deposits, and there are some differences in the elemental associates of gold in modern and fossil placers.

The elements greatly enriched in epigenetic gold deposits such as skarns, veins and stockworks include Al, Ca, Mg, Fe, Mn, Na, K and B and those bound in the quartz, carbonate and sulphide gangue minerals. In addition there are a large number of other elements that exhibit enrichments, being present either in the gangue minerals, the accompanying metallic minerals, sulphides, sulphosalts, etc., or in the native gold and various other gold minerals. These include: Li, Rb, Cs, Cu, Ag, Sr, Ba, Zn, Cd, Hg, B, Ga, In, Tl, Sc, Y, La, rare earths, Th, U, Ge, Sn, Pb, Ti, P, As, Sb, Bi, V, Se, Te, Cr, Mo, W, F, Re, Co, Ni and the Pt metals. Most of these elements are useful only as general indicators of the presence of gold and should be only considered as such in all types of geochemical surveys. Some such as Li, K, Rb, Cs, Ti, V and Cr are useful indicators principally in geochemical surveys utilizing rocks (primary halos) as a sampling medium. The elements most commonly accompanying gold in epigenetic deposits and those with the highest specificity as indicators include the following in their approximate order of importance: Si(SiO_2, quartz), S (FeS_2, pyrite), Ag, As, Sb, Te, B, Bi, Hg, Mo, W, Cu, Zn, Pb, Cd, Tl, Ba, Sr, Mn, Se, F, Cl, U and Th. Silver, arsenic and antimony are nearly universally enriched in all types and ages of epigenetic deposits. Tellurium and selenium enrichments are usually restricted to specific mineral belts and where found may serve usefully in geochemical surveys. Selenium tends to be enriched mainly in Tertiary deposits. Boron is characteristic of epigenetic gold deposits in sedimentary piles but may also be enriched in various types of auriferous deposits in volcanic terranes. Boron is more characteristic of older deposits than those in Tertiary and younger rocks. Bismuth is enriched in a number of epigenetic gold deposits of various ages and types. Mercury exhibits the highest enrichments in the young deposits, falling off generally in amount with increasing age of the deposits. Other factors than age, however, appear to control the enrichment of mercury in some deposits. Thus, veins and lodes that are enriched in sphalerite, stibnite, tetrahedrite and other sulphosalts are usually, likewise, high in mercury content regardless of their age. This is emphasized by certain oreshoots in the Precambrian Yellowknife Greenstone Belt that contain nearly as much mercury as Tertiary deposits in Japan and New Zealand. Molybdenum is common in many types of epigenetic gold deposits but rarely in significant amounts to be useful as an indicator in geochemical surveys except in certain belts. Tungsten is a frequent element in relatively deep-seated epigenetic gold deposits and occurs in some of the younger shallower veins as well. The significance of tungsten as an indicator for epigenetic gold deposits is largely unknown. Because of its low abundance its appearance in higher than average amounts in soils, stream sediments and vegetation may signal the presence of auriferous mineralization. Copper, zinc, lead, cadmium and barium are useful but not specific indicators of epigenetic gold-bearing deposits. They tend to signal the presence of polymetallic deposits, although lead and barium are frequently useful in soil analyses and stream sediment surveys for gold deposits because of their low mobility and their tendency to be concentrated in these media near the deposits. Manganese is particularly abundant in Tertiary deposits in certain regions. Its presence in anomalous amounts in water, soils, stream sediments and vegetation may be a general indicator of both gold and polymetallic deposits of this age, as well as those of older vintage, in an area. Fluorine is particularly characteristic of certain Tertiary deposits (e.g., Cripple Creek) and should be a good indicator of these deposits under most conditions. The element is present only in small amounts in Precambrian, Paleozoic and Mesozoic deposits. In these deposits the efficacy of fluorine as an indicator is limited except where extensive developments of sericite, other micas, tourmaline or minerals such as topaz are present. Chlorine may be enriched in the oxidized zones of certain auriferous deposits, the element being bound mainly in silver and copper halides such as chlorargyrite and boleite.

Thallium is enriched in some of the younger auriferous deposits, particularly those of Tertiary age; its effectiveness as an indicator in geochemical prospecting is unknown. Rubidium and cesium are enriched in certain wall-rock alteration zones associated with auriferous deposits as mentioned in Chapter III. At the Ogofau Gold Mine in southern Wales Al-Atia and Barnes (1974) found a well-developed primary rubidium halo in the shaly country rocks enclosing the auriferous veins and lodes. The rubidium aureoles were better developed than those for Pb, Zn, Cu and Hg. Uranium and thorium occur in various types of auriferous skarns, veins and lodes but generally only within specific mineral belts characterized metallogenetically by these two elements. Uranium, in particular, may be a good indicator of gold-bearing deposits in such belts.

In the quartz-pebble conglomerate type of auriferous deposits the elements greatly enriched include those bound in the gangue minerals, particularly Si(SiO_2), Al, Fe and S. In addition there are a large number of others that exhibit enrichments, often only to a slight degree. These elements occur in the gangue elements, in various metallic minerals, in oxides and complex substances such as uraninite and thucholite, or in the native gold. These include Ag, U, Th, rare-earths, As, Cu, Pb, Zn, Hg, Co, Ni and platinoids. Some deposits (e.g., Tarkwa) are essentially devoid of U, Th, rare-earths and the base metals. Of the elements associated with gold in the quartz-pebble conglomerates the most indicative of the precious metals would appear to be Ag and As as well as U, Th, rare-earths, Hg and the base metals in particular areas.

The heavy minerals associated with gold in eluvial and alluvial placers are familiar and need not be considered in any detail here. The most frequent associated heavy minerals are magnetite, hematite, ilmenite, pyrite, arsenopyrite, garnet, zircon and monazite; in addition cassiterite, platinoids, native bismuth, amalgam, native copper, cinnabar, scheelite, wolframite, barite, galena, stibnite and sulphosalts are present in some areas. None of these minerals are specific indicators of gold, but some, such as arsenopyrite, native bismuth, scheelite, stibnite, sulphosalts and platinoids, are suggestive of the presence of the precious metal.

The elements in the heavy concentrates from stream sediments, soils, eluvial placers, etc., most indicative of gold, are Ag, Pt metals, Te, As, Sb, Bi, W, B, Ba, Hg, Cu, Zn, Cd, Pb, Tl, Se, Sn, Ni, Co, U, Th, rare-earths, Zr and P in about that order of specificity.

Gold differs in its chemistry and the resistate character of its minerals from most of its indicator elements (*See* the section on associated elements in Chapter III.) Consequently, the relationship of the primary and secondary halos and dispersion trains of gold and those of its indicator elements is complex. In some terranes and surficial environments the halos and dispersion trains and fans of both gold and its indicators are coincident; in others the halos and dispersion trains and fans of the indicators may be displaced with respect to those of gold. From this it follows that each gold belt is more or less individual, and pilot studies to determine the exact nature and relationship of the gold halos and dispersion trains and fans and those of its indicators should precede detailed surveys. This applies particularly to surveys utilizing surficial materials (water, soils, vegetation, etc.); less so to lithogeochemical surveys.

Lithogeochemical methods

Relatively little detailed work has been done using the gold or indicator element content of fresh unsheared and unaltered country rocks to outline geochemical or metallogenic provinces containing gold deposits; hence our knowledge of this aspect of broad regional geochemical prospecting for gold is rather limited. Judging from the trace element studies done by the writer at Yellowknife (Boyle, 1961*a*), Keno Hill (Boyle, 1965*a*), and in the Bathurst-Newcastle district of New Brunswick there are no definite elemental patterns in the unaltered and unsheared country rocks that would suggest the presence of gold (and silver) deposits in these areas. Certain of the rocks, especially the pyritic black schists, pyritic tuffs and iron-formation in these areas contain higher than normal amounts of gold (and silver), but this seems to be true also of areas where no gold (and silver) deposits are known. No particular patterns in the gold content of the various granitic intrusives in these districts were noted; all were very low in gold content (<0.005 ppm). Some quartz-feldspar porphyries in the Yellowknife Greenstone Belt were found to be somewhat enriched in what is thought to be indigenous gold (0.10 ppm). Most of these are spatially related to the gold deposits.

Seeland (1973*a,b*) carried out a broad scale reconnaissance for gold in the sedimentary and metamorphic rocks of the United States south of the Great Lakes region, the aim being to discover fossil placers in clastic rocks on the southward dipping paleoslope draining the auriferous areas in the Canadian Shield north of the Great Lakes. In 799 samples gold was detected in only 36. Four samples yielded 0.1 to 0.4 ppm Au. Seeland (1973*a,b*) concluded from the data that the frequency with which gold was detected in the rocks of the region suggested the possibility that certain undetermined syngenetic chemical processes have concentrated anomalous amounts of gold in rocks of chemical origin (Grenville marble, glauconitic sandstone, gypsum, etc.). He thought that these chemical processes may be more effective concentrators of gold than the expected placer-forming physical processes, even in a region relatively close to a source of clastic gold. In addition he speculated that the general lack of gold and the small grain size of the gold that was found (less than 5% of the hydraulic equivalent size in the nonglauconitic sandstone-quartzite category) are results of postdepositional leaching.

Finally, he postulated that the apparent abundance of chemically or biochemically precipitated gold and the relative lack of clastic gold in a region close to a major gold source could also be explained by the presence of an east-west late Precambrian–early Paleozoic continental divide just north of the Great Lakes separating a known south- and southeast-trending paleocurrent system from a probably north-trending system. Thus, he concluded that most Canadian Shield gold deposits would lie north of this divide, and the logical place to look for fossil placers would then be in the basal Paleozoic clastic rocks near James Bay.

Wrücke and Armbrustmacher (1973) determined the gold contents of bedrock samples collected during a geochemical reconnaissance in the Gold Acres–Tenabo areas, northern Shoshone Range, Nevada. Included in this report are also analytical data for 30 other elements. No conclusions were drawn from the data.

Roslyakova and Roslyakov (1975) found complex patterns in the regional gold and indicator element halos associated with auriferous fields in U.S.S.R. Their research is summarized at the end of this section.

Summarizing we can say that much more research comparing the trace element content of fresh rocks in mineralized belts with those in barren areas is necessary before an answer to the problem of whether or not the unsheared and altered country rocks reflect definite geochemical gold provinces or belts in which it is more probable to find gold deposits.

On a more limited scale, however, considerable data are now available on the distribution of gold and its indicator elements in the country rocks, mainly intrusives, in the vicinity of gold deposits. Many years ago Emmons (1937) emphasized the intimate relationship of some gold deposits to the apices of granitic stocks and small batholiths, the philosophy being that as the differentiated metal-bearing hydrothermal solutions streamed out of the crystallizing magma they would concentrate in the fractures and faults in the country rocks around the apices and apophyses of the stocks. Gross (1950) tested this general philosophy in his study of the spatial relation of gold deposits to intrusive bodies in Manitoba and northwestern Ontario. He used indicators that he considered to be late crystallization products of the intrusives, namely silica, zircon, uranium and thorium. Four intrusives, the Dome and McKenzie–Gold Eagle stocks of Red Lake, Ontario; part of a batholith in the Rice Lake district of Manitoba; and the Froghead Bay stock in the Eagle Lake district of Ontario were investigated. The first three have associated gold deposits; the fourth has no known associated gold deposits. In the first three the concentrations of the indicators increased in the direction of the gold deposits; in the fourth there was no pattern. This was said to indicate a migration of the late solutions towards the known ore deposits. It is obvious that such patterns could be particularly useful in prospecting for gold deposits in the vicinity of stocks and small batholiths.

A number of investigations of the gold content of stocks and small batholiths in gold belts have now been completed and attempts have been made to relate the data obtained to the presence or absence of associated gold deposits. The results have been mixed to say the least. Some investigators find that intrusives in the vicinity of gold-bearing deposits exhibit enrichments of gold; others have found no such relationships. The various investigations dealing with this feature of geochemical prospecting that have come to the notice of the writer are summarized in Chapter II and need not be repeated here. The writer's experience in the matter of intrusives in gold belts is that some small stocks and irregular porphyry bodies, usually enriched in indigenous pyrite or pyrrhotite, often contain higher than normal amounts of gold in the vicinity of gold deposits. This is true in the greenstone belts at Yellowknife, at Matachewan, at Timmins and elsewhere. Moorhouse (1942) has commented on the common occurrence of auriferous albitite dykes and albite porphyries in the Canadian Shield and elsewhere. He gave evidence that he thought pointed to the magmatic differentiation origin for the gold. Others have considered that the higher than normal content of gold is due to secondary processes attendant upon fracturing or shearing. This is certainly true in many cases; in others the gold enrichments appear to be primary.

Wolfe (1975) gives interesting data in this respect from six Early Precambrian felsic intrusions in Ontario. These range in size from 4 to 88 km². Four (Dome stock, Red Lake area; Larder Lake stock; Lebel stock, Kirkland Lake area; and Cairo stock, Matachewan area) have associated gold deposits and two (Kabenung Lake and Coyle Lake) are barren. Wolfe observed that the gold levels in unmineralized stocks are consistently below the 5 ppb detection limit of the analytical method used. In contrast, analyses of samples from stocks with associated gold mines within their borders and in nearby metavolcanic-metasedimentary host rocks show a strongly skewed trace element gold population with a substantial percentage of gold values exceeding 5 ppb and ranging as high as 320 ppb. From these data he hypothesized that (1) orestage hydrothermal metasomatism has produced widespread gold enrichment in Precambrian intrusions that host epigenetic vein-type gold deposits, and (2) geochemical gold analysis of samples collected from 30 to 50 randomly distributed sites can be used to estimate the gold exploration potential of stock-sized bodies and to outline internal patterns of gold variation that may be useful in directing exploration to particular contacts or portions of a stock. He cautioned that his results *do not* conclusively indicate that the presence of auriferous deposits is signalled by unusually high gold contents in primary unaltered igneous rocks.

When relating gold deposits to igneous rock bodies such as dykes, stocks and small batholiths one must be certain that the igneous bodies are either older than or coeval with the gold mineralization. In the first case the mineralization may be associated as a result of metamorphic secretion processes; in the second the mineralization may be related genetically via differentiation processes.

The concentration of certain indicator elements in intrusive stocks and small batholiths may signal the presence of auriferous deposits in some districts. In this respect Garrett (1974) has shown from extensive data on the mean mercury content of granitoid plutons in the McQuesten area of the central Yukon that a positive correlation exists between plutons with a high mercury content and the presence of gold deposits.

Dvornikov (1964) working in the southeastern Donets Basin of the U.S.S.R. also noted a regional relationship between the mercury content of the rocks and the presence of gold deposits. He found mercury dispersion aureoles in the country rock, and in soils and alluvial deposits. Two types were distinguished (a) primary, formed in sandstones, clay shales, limestones and coal simultaneously with the lead-zinc and gold deposits and occurrences, and (b) secondary, formed in soils, loose alluvial deposits and waters subsequent to the formation of the deposits.

Both types of mercury dispersion aureoles fringe the districts of lead-zinc and gold deposits of the Nagol'nyy Range. The mercury dispersion aureoles were found to be usually several times as wide as the zones of mineralization, deposits and ore-bearing belts. The mercury content of the rock within the contours of the dispersion aureoles was determined to be tens of times higher than the geochemical background.

Cornwall *et al.* (1967) examined the Ag, Hg and Au contents of residual soil, rock from mine workings and bedrock over a large area in Nevada marked by two bonanza silver-gold districts (Comstock and Tonopah). They observed that geochemical anomalies for silver clearly delineate areas of principal silver mines in both districts, and mercury anomalies show the same pattern at Tonopah. In the Comstock district, however, mercury values were found to be highest outside the main silver-gold mining area a feature that they thought suggested horizontal zoning from a central silver-gold area outward to a mercury area. They speculated that if similar zoning occurs in the vertical plane, several mercury anomalies in the districts may be underlain by silver-gold mineralization.

Analyses of mineral separates in the country rocks may be used to indicate the presence of gold deposits. The best mineral separates for this type of work in our experience appear to be pyrite and arsenopyrite, particularly the latter. Pyrite and arsenopyrite isolated from the greywacke and slate wall rocks adjacent to gold-quartz veins in the Meguma Group of Nova Scotia are invariably enriched in gold (and silver) compared with these minerals taken from rocks distant from the veins. Similar relationships were noted at Keno Hill in Yukon. Not enough work was done, however, to establish if there is a gradual increase in gold content towards the veins. This approach should be tried on long drill cores where they are available. Magnetite appears to concentrate gold in some rocks as noted in Chapter II; it could be a useful mineral in studies of this type.

With respect to pyrite, Sher and Demchenko (1962) comment on the use of the mineral as a guide to concentrations of gold and remark on the frequent enrichment of pyrite in and near gold-bearing deposits. In the Lena Gold Belt, U.S.S.R., they noted two distinct types of pyritization, the gold mineralization being associated with late pyritization characterized by a major development of pentagonal dodecahedral crystals. In the Philippines, Santos and Walters (1971) found that pyrite, chalcopyrite and sphalerite in deposits and prospects of various types were gold collectors and noted that these minerals were consistently high in the precious metal in auriferous districts. On this basis they concluded that the three sulphides are useful in evaluating prospective gold-bearing belts. They considered that a lower threshold limit of 1 ppm gold distinguished gold-productive belts from those containing essentially base metal deposits.

Vakrushev and Tsimbalist (1967) examined the gold content of sulphide minerals in a number of gold-bearing skarns, gold-quartz deposits and nongold-bearing skarn in the Altai-Sayan, U.S.S.R. All sulphides, particularly pyrite, were enriched in gold in the first two types of deposits; in the last the sulphides were characterized by minimal gold contents. From these data they concluded that the gold content of pyrite gives a direct indication of commercial gold mineralization in evaluating skarn deposits.

In a similar study on auriferous and barren skarns in the Kommunarovsk and Ulen-Tuimsk regions of the Altai-Sayan, Okhapkin and Bozin (1971) found that the ore magnetites contain lower amounts of Ti, V and Cr than the accessory (barren) magnetites. The authors considered that the low content of Cr in the auriferous region could be used as a prospecting criterion.

Many types of gold deposits are enveloped by primary halos of various types, involving both major and trace elements. Some of the halos are of the additive type[32], that is they exhibit an increase in the content of particular constituents as the veins are approached; others are of subtractive nature and show depletion or decrease of a particular constituent as the veins are approached.

The major constituents that seem to be of the greatest use in geochemical prospecting for gold using primary halos appear to be SiO_2, K, Na, CO_2, S and H_2O. The behaviour of these constituents during wall-rock alteration processes and the mineralization of most types of gold deposits is outlined in Chapter III and need not be repeated in any detail here.

Silica exhibits major decreases as gold-quartz veins and lodes are approached particularly in ultrabasic, basic and intermediate volcanic and intrusive host rocks. The effect is not marked in most acidic host rocks and sediments of the greywacke-slate type and their metamorphic equivalents. Silicification, or increase in silica content as the veins and lodes are approached, is a feature mainly of limy host rocks, certain acidic rocks and occasionally sediments of the greywacke-slate type and their metamorphic equivalents. Silica profiles may be of interest in locating gold-quartz deposits in sheared greenstones and in the various other types of rocks mentioned above. The method is probably best used on drill core although grids of surface rock samples may also be employed. It is imperative to ascertain the exact nature of the profiles to be expected before employing the method; in this respect one or more pilot profiles across known gold deposits will give the required information as to whether subtractive, additive or uniform profiles prevail for the types of deposits sought. The effectiveness of using silica profiles alone in prospecting for gold deposits is relatively unknown. Probably decreases or increases in silica content provide no more than general information that mineralization processes have been active in the particular shear zone, fault or bed. Combined with information on the distribution of other major and trace elements in halos about gold deposits, silica profiles, however, provide another arrow in the quiver of the ore hunter.

[32]The terms additive and subtractive are meant only in a descriptive sense. They are not intended to infer that the constituents were added to the wall rocks from the vein channels (fractures, faults, etc.) or similarly removed from the wall rock to the vein channels. Primary halos are usually complex and difficult to analyze with respect to the original direction of flow of constituents. In homogeneous, unfractured wall rocks an increase in a constituent toward a vein site may indicate movement of constituents from the vein channels into the wall rocks; or alternatively it may indicate the frozen profile of a smooth buildup of diffusing ions at a precipitation front. Where the wall rocks are extensively fractured an increase in constituents may indicate an increase in the number of small fractures as the vein site (the main locus of fracturing) is approached. In this case again the constituents may have migrated from the main channel into all the subsidiary channels; or alternatively diffusion of constituents toward and into the vein site may have resulted in the filling of the principal fractures as well as all of the small subsidiary ones. The subtractive halos may indicate that constituents moved toward and into the vein sites; or alternatively that they were widely dispersed into the wall rock beyond the halo. The genesis of halos is really not the problem in geochemical prospecting, although it is advantageous to have an idea as to how each halo was produced if possible. Empirically it is known that certain gold deposits have particular types of halos, whereas others have different types. *See also* the discussion on wall-rock alteration on Chapter III and the outline of the origin of epigenetic gold deposits in the same chapter.

Potash and soda commonly show an antithetical arrangement in alteration profiles as gold-quartz and other auriferous deposits are approached (*see* Tables 45 to 59). This relationship is also reflected in their ratios. Thus, as the deposits are approached potash commonly increases consistently whereas there is a simultaneous decrease in soda; the K_2O/Na_2O ratio, therefore, generally increases as the veins are approached. This is of considerable importance in surveys utilizing drill core or grids of surface rock samples, since if a progressive increase in the ratio K_2O/Na_2O is observed, the indication is that gold mineralization is being approached (Boyle, 1974*b*). Similar phenomena have been observed by the writer around polymetallic deposits of various types. Actually the phenomena is only a reflection of potash metasomatism associated with mineralization. The use of the ratio K_2O/Na_2O is, however, more sensitive and indicative.

Borcos and Stanciu (1974) observed a genetic relationship between the gold-silver mineralization and the wall-rock alteration effects, manifested principally by intense sericitization of the host Tertiary andesites, in the Hanes deposit in the metalliferous mountains of Romania. When the K_2O content of the alteration zones exceeds 3 per cent proximity to economic orebodies is indicated.

Carbon dioxide (carbonate) is particularly indicative of gold-quartz mineralization, since nearly all types of host rocks exhibit an increase in CO_2 as the auriferous deposits are approached. In skarn and silicified bodies in limy rocks the reverse is true; there is a major decrease in CO_2 due to skarnification or silicification. It is imperative, therefore, to ascertain the types of profiles to be expected in an area before detailed prospecting using this constituent is attempted. In this respect a study of Tables 45 to 59 is instructive. In the aureoles of most gold-quartz deposits CO_2 is introduced into the wall rocks concomitant with removal of SiO_2. The ratio SiO_2/CO_2, therefore, decreases as mineralization is approached in most cases. In limy rocks that are skarnified or silicified, on the other hand, the ratio SiO_2/CO_2 usually increases consistently toward the ore zones. Analyses for CO_2 and SiO_2 of drill cores or of rock samples on grids should be useful in assessing an approach to gold orebodies, but it must be stressed that careful scrutiny of the results and a knowledge of the profiles to be expected in an area are necessary for success. Keyed with trace elemental surveys of the same rock samples the information obtained from SiO_2/CO_2 ratios may be invaluable.

Fakhry (1974) has shown that infrared spectroscopy is a useful means for evaluating the ratio of carbonate to silicate minerals in rock samples from the alteration zones of gold deposits, particularly at the Fawakhir Mine, eastern desert, Egypt. The ratio of absorbance of the C-O vibration absorption band of carbonates and the Si-O vibration absorption band of silicates (C-O/Si-O) defines a characteristic parameter (δ) that ranges from 0 in rocks with no carbonate to some high positive value where carbonatization is marked. This ratio, therefore, increases with carbonatization, that is toward auriferous veins, where this type of alteration prevails.

Barkhudaryan and Grebenchikov (1974) described a method utilizing infrared spectroscopy for evaluating the gold content in auriferous quartz veins.

Konstantinova *et al.* (1973) state that the composition of carbonates may be used as an indicator of the intensity of hydrothermal gold mineralization in the Sukholozhsky prospect in the Lena region of U.S.S.R. Thus, superore zones are characterized by carbonates with high contents of Ca and Sr, and there is a general increase in these elements and an increase in Fe and Mg in the carbonates with depth, that is toward and into the auriferous ore zones. Gormasheva *et al.* (1973) by approximate extraction methods of the components of carbonates with acetic acid have been able to differentiate auriferous propylite zones from those that are barren in the Evensky Gold Belt, U.S.S.R. The auriferous variety associated with the gold deposits is characterized by the presence of Fe-Mn carbonates whereas the barren ones contain mainly calcite and dolomite.

Sulphur commonly increases in the host rocks of gold deposits as the ores are approached. All profiles studied by the writer in nearly all types of gold deposits show this effect except those in sulphide-rich iron-formations and certain pyrite-rich rocks such as pyritiferous shales and porphyries. In these any pattern is usually swamped by the large amount of sulphur present in indigenous pyrite and pyrrhotite. Combined with studies of the distribution of heavy metals and especially of the semimetals As, Sb, Se and Te, the distribution of sulphur may be particularly useful in exploration work involving drill cores and surface rock samples on grids.

The water content of host rocks due to hydration processes adjacent to gold-quartz and other types of gold-bearing deposits is commonly erratic and dependent upon certain equilibrium relationships inherent in the formation of chlorite, sericite, clay minerals and other hydrous minerals. These relationships are commonly difficult to ascertain without detailed petrographic work. The water content of rocks is, therefore, not particularly useful in geochemical surveys using primary halos. A more useful index is the ratio $SiO_2/(CO_2+H_2O+S)$. In most types of gold deposits, excepting skarn and silicified deposits, this ratio consistently decreases as the orebodies are approached. This is easily understood from the fact that as the silicates are carbonated, hydrated or sulphidized, silica is released and this usually migrates into the dilatant zones to form quartz.

$$\text{(Ca,Fe,MG) silicates} + CO_2 \rightarrow \text{(Ca,Mg,Fe,)}CO_3 \text{ (ankerite)} + SiO_2$$
$$\text{Mg-Fe-silicate} + H_2O \rightarrow \text{chlorite} + SiO_2$$
$$\text{Fe-silicate} + S \rightarrow \text{pyrite} + SiO_2$$

Where arsenic and boron occur in quantity in the alteration halos these elements should be added to the total of the volatiles.

Gold is associated with a large number of trace elements that can serve under particular conditions as indicators in geochemical prospecting surveys using grids of surface rock samples and drill cores. The chemistry of these elements and their relationships to gold in hypogene deposits and their wall-rock alteration zones are discussed in detail in the sections in Chapter III on associated elements and wall-rock alteration phenomena. The elements that should serve as the best indicators in lithogeochemical work include Rb, Cs, Cu, Ag, Ba, Zn, Hg, B, U, Pb, As, Sb, Bi, Se, Te, Tl, Cr, Mo, W, Mn, Co and Ni. Of these the most specific indicators are Cu, Ag, Zn, Hg, B, As, Sb, Bi and Te. As, Sb and Te are nearly universally present in hypogene gold deposits. Of these three, As is the best indicator; Sb and Te are normally very low in content in many gold deposits, and hence if they are found in amounts higher than their normal abundance (Sb–0.7 ppm; Te–0.05 ppm) this should signal the probable presence of gold (and silver) mineralization. Fluorine may be useful in certain types of deposits where tourmalinization is well developed or where fluorite is a gangue mineral as in some Tertiary deposits (e.g., Cripple Creek). The efficiency of chlorine, bromine and iodine as indicators of gold deposits in lithogeochemical surveys is relatively unknown. Judging from the general erratic behaviour of chlorine in some of the alteration halos examined by the writer it would appear that these elements have only a limited usefulness under the most favourable conditions.

Many of the indicator elements of gold exhibit a much smoother behaviour in their distribution compared with the precious metal. This is often manifested in both regional profiles and in those across primary halos associated with auriferous deposits. The elements most often exhibiting this desirable behaviour include As, Sb, B and Zn. Many factors influence the zoning of indicator elements associated with the focus of auriferous mineralization, particularly the lithology, degrees of porosity and permeability of the host rocks (principally the amount of fracturing, shearing and contortion to which the rocks have been subjected; also the initial porous and permeable character of the rock), and the penetrative nature (gas, liquid) of the mineralizing medium. From my general observations I conclude that the mobility of the indicator elements with respect to gold and silver in primary halos follows the general sequences:

Gangue elements:

$$Si > B > K > Na > Ca = Mn > Mg > Co > Fe = Ni > Al$$

Gaseous compounds:

$$CO_2 = S = Se > As > Sb > Te$$

Base metals:

$$Hg > Zn > Cd > Cu > Pb > Mo = Bi = Sn = W$$

Precious metals:

$$Ag > Au > Pt$$

In primary and leakage halos, therefore, one tends to find that compounds such as CO_2, Hg, B, S, As, etc. have travelled far from the focus of Au-Ag mineralization. They commonly occur in greater concentrations well up-dip from the auriferous orebodies and generally have broad lateral halos, whereas the other constituents such as Cu, Pb, Mo, Bi, Ag and Au have relatively few up-dip manifestations and restricted lateral halos.

A number of investigations utilizing gold and its indicator elements in geochemical surveys using rocks to locate gold-bearing deposits are described in the literature. Most of these are based on trace elements in primary halos.

Goloubinoff (1937) seems to have been one of the first to suggest the use of rock samples in prospecting for gold deposits. He noted that rocks in gold-bearing districts have a higher than average gold content (clarke). He gave as the average clarke for gold a value of 0.10 ppm, and found a micronorite from Haut Tonkin to be eight times the clarke, a pegmatite from Annam 25 times, and a diabase from the Belgian Congo (Zaire) and a norite from French Guinea (Guinea) to be 10 times, all in auriferous areas.

Sokoloff (1950) carried out geochemical surveys utilizing rock and drill cores in the vicinity of the gold deposits of Kalgoorlie, Western Australia. The greenstones showed a number of gold positive bands that the author interpreted as trace analogues of economic lodes, localized by microstructures in the country rock. These appeared to bear no particular relationship to the main lodes. On continuous gold halos around the lodes the author commented as follows: "Diffusion of traces of gold into walls of the lode channel would result in a reasonably continuous anomaly in the rock that could be termed a gold halo. Suggestions of such diffusion are indeed present locally. The linear extent of the diffusion is very small, however. Some lodes are entirely devoid of the halos. Rock within a few inches of the lode may be gold-negative."

In an abstract Robertson (1955) mentions the interesting fact that geological structures can be traced by geochemical means in some places. At Maryville, Montana, a contact of granodiorite with hornfelsed Belt sediments is conspicuously marked by concentrations of Au and Ag in the granodiorite.

In recent years a considerable number of investigations have been carried out on primary trace element halos associated with gold deposits in an effort to use the data obtained as a guide to the location of the deposits, especially those that are blind or deeply buried. Those noticed in this compilation deal mainly with vein, lode and replacement type gold-bearing deposits and include investigations by Kutyukhin (1960), Boyle, (1961*a*), Khramyshkin (1962), Kvyatkovskii (1963), Mukanov and Romashin (1964), Rakhmatullaev and Gamaleev (1964), Mazzucchelli (1965), Fakhry (1965), Polikarpochkin *et al.* (1965), Palei *et al.* (1967), Mahrholz and Slaughter (1967), Gapontsev and Polikarpochkin (1969), Kitaev *et al.* (1968), Khramyshkin (1968), Potapenko *et al.* (1968), Grigor'ev (1968), Eleyeva and Rusinova (1969), Bezirganov (1969), Baumshtein and Grigor'ev (1969), Zashchinskii *et al.* (1969), Obraztsov (1969), Stevens *et al.* (1969), Kitaev *et al.* (1970*a,b,c*), Mel'nikov and Mel'nikova (1970), Roslyakova *et al.* (1970), Laipanov and Sher (1971), Grigoryan and Zubov (1971), Wilson (1971), Ovchinnikov and Grigoryan (1971), Sears (1971), Bolter and Al-Shaieb (1971), Gapontsev (1971), Voin (1971), Orazbekov (1971), Polikarpochkin and Kitaev (1971), Bowen (1972), Prosnyakov *et al.* (1972), Atabek'yants (1972), Obrazbekov (1972), Mercer and Crocket (1972), Ovchinnikov *et al.* (1972), Aristov *et al.* (1972), Al-Shaieb (1972), Jae (1973), Kitaev and Chumakin (1973), Chibisov *et al.* (1973), Korobeinikov (1974*a*), Gustavson and Neathery (1975) and Steed *et al.* (1976).

The results and conclusions drawn from these investigations have been varied and are not readily systematized. In a general way it can be said that the primary trace element halos associated with most types of gold veins, lodes and replacement bodies are marked. Widths, extents and up-dip projections vary widely depending upon the types of host rocks, localizing structures, degree of wall-rock alteration, post-mineralization fracturing and other geological factors. Each gold belt and commonly each deposit has its individual characteristics. The most satisfactory indicators for use in primary halo surveys in the search for gold deposits appear to be Au, Ag, As, Sb and Hg. Other elements such as Zn, Pb, Cu, B, Ba and W are applicable in certain belts. All investigators agree that As and Sb, particularly the former, are the best universal indicators. At Yellowknife, enrichments of these two elements in the shear zones can be noticed hundreds of feet up-dip from underlying orebodies. Laterally, the schist and weakly mineralized material in shears and fractures are enriched in both elements up to distances of 500 ft or more from known orebodies. At Norseman in central Western Australia, Mazzucchelli (1965) noted strong leakage halos of arsenic above lenticular gold-quartz reefs in inclined zones of reverse shearing. These persisted up the shear zones as much as 2000 ft up-dip from blind orebodies and could be detected in soils over the barren suboutcrops of the ore-bearing structures.

The details of the dispersion of various trace elements including gold in primary halos associated with auriferous mineralization are complex. Some observers find the lateral dispersion limited to a few feet and even to a few inches in some gold districts; in others the lateral dispersion may exceed 300 ft. The vertical dispersion, up-dip of orebodies in shear zones, fracture zones or replaced beds is commonly much greater than the lateral dispersion for reasons of permeability and porosity. In most districts the leakage halos can be detected at distances measured in hundreds and in places in a few thousands of feet above blind orebodies. Multiple element analyses of primary halos have been done in a number of gold districts in U.S.S.R. especially at the Baleisky and Onokhovsky gold deposits in Transbaikal and the Belaya Gora deposit in the Far East (Polikarpochkin *et al.*, 1965; Polikarpochkin and Kitaev, 1971). These deposits are clusters of epithermal gold-quartz veins in a variety of sediments and volcanics that exhibit marked chloritized, silicified, kaolinized and pyritized zones adjacent to and between the veins. The minerals in the chalcedonic quartz veins are essentially native gold of low fineness, stibnite, pyrite and arsenopyrite with varying amounts of pyrargyrite, galena, sphalerite, chalcopyrite, cinnabar, fluorite, realgar and orpiment. The details of the elemental distributions in the halos of the various deposits are complex and should be sought in the original works. In general it can be stated that the halos have a multicomponent nature exhibiting enrichments of Au, Ag, As, Sb, Cu, Pb, Zn and Hg. Normally the halos are narrow (30 m) near the roots of the deposits, widen out (in places to 300 m) in the rocks flanking the productive parts of the deposits and continue so for distances up to 300 m above the orebodies. A vertical zonation of elements in the halos is also apparent; maxima for Au and Ag occur adjacent to the zones of productive mineralization whereas the maxima for As, Sb and Hg are displaced higher up the structures. The Au/Ag ratios also show vertical variations, the zones of maximum mineralization (maximum gold deposition) being distinguished by a maximal value of the ratio, whereas the halos above and below are characterized by decreased values of the ratio.

Polikarpochkin and Kiteav (1971) conclude from their research on the primary halos associated with epithermal gold deposits that:

> The marked lateral extent of the halos aids in the lateral search for orebodies, and the projection of the halos upward above the orebodies for a considerable distance is particularly helpful in locating blind orebodies. In the latter respect, the search for deep orebodies is best done by using the halos for arsenic, antimony, mercury, and copper. The halos for gold and silver, on the other hand, are restricted in their vertical extent and are thus not particularly useful.
>
> Prospecting for blind orebodies can be guided by the elemental composition of the halos and the nature of the change of the concentration of the elements with depth. If the halos exhibit high concentrations of only arsenic, mercury, and antimony without high concentrations of gold and silver, this indicates that one is high above the zone of optimal gold mineralization. Copper concentrations in the halos decrease markedly as one approaches this zone of optimal mineralization. The presence of high contents of gold and silver indicates a near approach to the zone of maximal mineralization, especially when a decrease in the Ag/Au ratio is apparent. The vertical interval over which these elemental variations are manifest is equivalent to the vertical range of the supra-ore halos and is approximately 200 to 300 meters. A decrease in the content of gold and silver with depth and an increase in the Ag/Au ratio means that the zone of optimal mineralization is higher than the level of sampling or that it has been eroded. The identification of sub-ore halos is particularly important in prospecting. They can generally be recognized by their narrow width and a progressive decrease in their content of gold with depth. The silver contents in these halos are frequently high, and there may also be higher lead contents in places.

Much more work is required on the distribution of gold and silver in primary halos associated with gold deposits to define their exact nature. This is especially true where gold-quartz veins and lodes occur in wide schist zones as at Yellowknife and elsewhere. In such zones the wide shear (schist) zones of chlorite schist appear in places to be depleted in gold and silver with respect to the country rocks, the two metals being probably added to the quartz veins and their adjacent intensely altered carbonate-sericite schist zones (Boyle, 1961*a*). Others have noted this phenomenon (*see* the section on origin of gold deposits in Chapter III). In particular, Roslyakova *et al.* (1970) remark on negative gold halos associated with the Darasun gold deposits in eastern Transbaikal and the Berikul' deposit in the Kuznetskii Alatau Mountains, both deposits being steeply dipping quartz veins, the former in granodiorite and the latter in plagioclase hornblende porphyries and tuffs respectively. The negative gold halos correspond to the zones where the most intense wall-rock alteration effects are manifest, in granodiorite they may be up to 2 m wide adjacent to the narrow veins. Roslyakova *et al.* (1970) conclude that the gold (and other elements such as Ag, As, Pb, Zn, Cu, Ni, Co, etc.) were transferred to the vein sites from the wall rocks. Bolter and Al-Shaieb (1971) have also noticed negative anomalies in gold and other metals in the immediate vicinity of veins in andesites in the Searchlight district of Nevada. In general, it appears that gold and silver tend to show a regular increase in quantity towards deposits in some places, whereas in others the general increase in the concentration curve may be interrupted by negative (i.e., leached out) sections (Fig. 98).

Leakage halos associated with gold mineralization and manifest by pervasive alteration of country rocks (propylitization, pyritization, arsenopyritization, silicification, alunitization, etc.) within mineral belts or between vein systems; weakly mineralized schist, mylonite, gouge, etc. in satellite and subsidiary shears, fractures and faults; patches and linear streaks of silicified rock; and rocks exhibiting other evidence of epigenetic introduction of elements such as silicification of limestones, development of skarn and impregnation of rocks by pyrite and arsenopyrite are considerable aids in the location of gold deposits buried deep within rocks or hidden

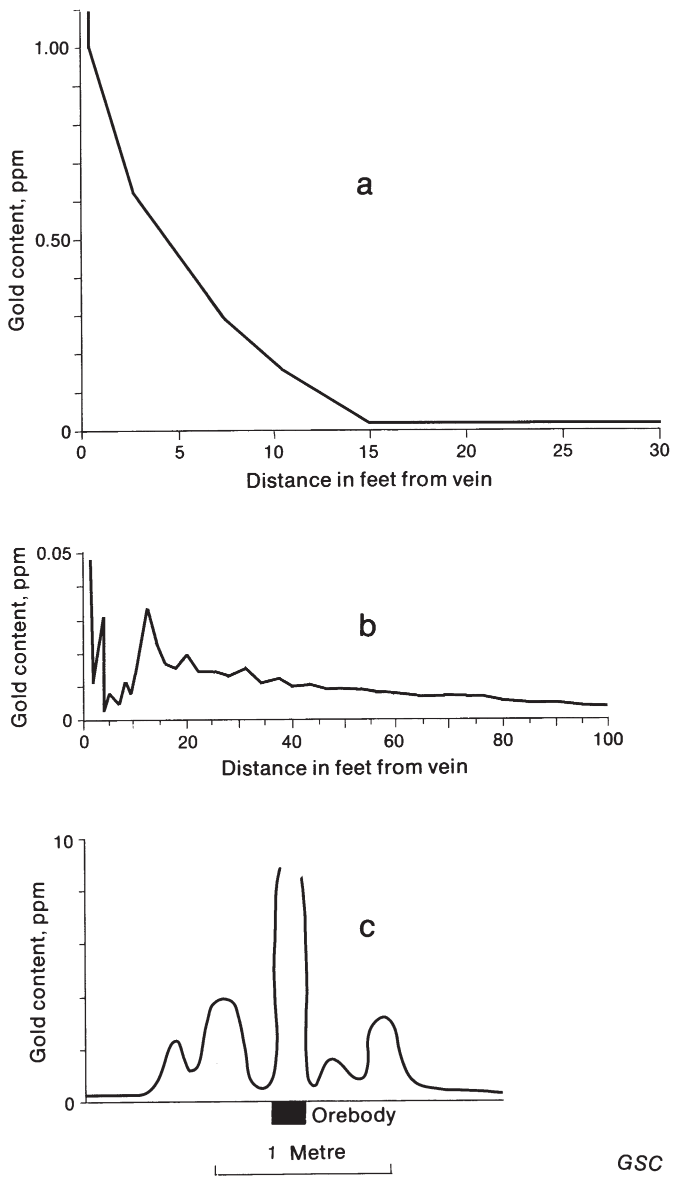

Figure 98. Positive and negative primary profiles in auriferous deposits. (a) General distribution of gold in the primary halos at Yellowknife, N.W.T. (b) Distribution of gold at the Chief of the Hill Mine, Searchlight district, Nevada (after Bolter and Al-Shaieb, 1971). (c) Distribution of gold at one of the Klyuchi orebodies, eastern Transbaikal, U.S.S.R. (after Roslyakova and Roslyakov, 1975).

by overburden especially in valleys. Analyses of the above materials for gold and silver and their indicator elements, particularly As, Sb, Te, Hg, etc. when plotted on geological maps of an area and analyzed in three dimensions may indicate the presence of various types of gold deposits. Thus, the large gold-quartz lodes of the Yellowknife area, Northwest Territories, most of which lie in drift-filled valleys, are clearly indicated by satellitic and subsidiary shears and fractures weakly mineralized with Au, Ag, As and Sb in the rocks flanking the valleys. Similar conditions exist in the Red Lake Camp and elsewhere in the Canadian Shield according to the writer's observations. Disseminated deposits of the Carlin, Nevada type are particularly susceptible to discovery by surveys utilizing analyses of the materials of narrow quartz veins, calcite veins and shear zones in partially silicified limestone for As, Sb, W, Hg, Au, etc. Thus, the anomaly in the Cortez district of Nevada outlined by Erickson *et al.* (1966) led directly to the discovery of over 3 million tons of open pit gold ore averaging 0.3 oz Au/ton (U.S. Geol. Surv. Circ. 560, 1968, p. 1).

The use of analyses of the materials of leakage halos and of pervasive alteration zones cannot be over-emphasized in prospecting for covered and deeply buried, blind gold-bearing orebodies. When carrying out a lithogeochemical survey based on leakage halos or pervasive mineralization effects using either rock samples or drill cores the following points should be kept in mind. In addition to analyzing the rock and core samples, all shear zones, fractures, contorted zones and altered zones should, likewise, be sampled and analyzed for gold and its indicator elements. A detailed geological map showing all these features as well as any small veins, no matter what size, should be plotted and the gold and indicator element values entered at the appropriate sites. Where drilling is done, sections with all of this detail should also be prepared. Only in this way is it possible to observe patterns in the primary gold dispersion in the rocks and from these patterns to predict the locus of large deposits. It should be constantly borne in mind that most large deposits have a halo of smaller satellites developed in subsidiary or parallel fráctures or in favourable sites in porous, permeable and chemically replaceable rocks. Trace-element work on small shear zones, fractures, etc. increases our ability to differentiate smaller and smaller satellites. It may well be that the data when plotted will show an increase in the gold or indicator element content of alteration zones in a certain direction or that the number of gold-bearing fractures, etc. increases toward a certain valley or draw beneath which lies a major shear or fault zone containing deposits. It is also advisable to contour the results since this method often brings out zones that should be trenched or drilled.

Palei *et al.* (1967) have investigated the geochemistry of gold and some of its indicator elements in alteration zones in the vicinity of the Sultanuizdag deposit in Uzbekistan, U.S.S.R. Some of their observations are of interest. They found that the nearby Dzhamansai intrusion is the most enriched in gold (0.066 ppm Au) in the area. Among the various alterations in the intrusive rocks only sericitization and silicification displayed a direct connection between the degree of alteration and gold content. A direct positive correlation was observed between the concentrations of Au and Ba. The relation between Au and Pb or Ga was inverse. In the Aktausk intrusion a direct relation was noticed between the Au concentration and the degree of muscovitization and silicification and a direct relation was traceable between the concentrations of Au and Ba. For Au and Cu an inverse ratio obtained. Mica-plagioclase-quartz schists form a hydrothermally but slightly affected belt at a distance of 1 to 2 km from the Au-bearing zone. The Au concentration of the belt averages 0.0036 ppm. As the mining area is approached hydrothermal alterations intensify, Au concentrations rise to 0.009 ppm, and within 10 to 20 m from the orebodies, to some tenths of a ppm. In order to determine the relationships between Au and the accessory elements the correlation ratios were calculated. The results showed that the Ba, Mn, As and Be concentrations rise in direct proportion to that of Au. The reverse applies for Pb. A marked relationship prevails also between Au and the elements Ga, Zr and Y. There was no observed correlation between Au and Cu or Zn. The main amount of Au was deposited during the post-magmatic stage and is due to epigenetic processes.

Geochemical surveys utilizing leakage halos and zones characterized by pervasive mineralization effects associated with gold-bearing deposits have been carried out by the United States Geological Survey for a number of years mainly in the western States, but also in Alaska and elsewhere. Investigations noticed during this completion include those by Erickson *et al.* (1964, 1966), Gott and McCarthy (1966), Gott *et al.* (1969), Drewes (1967), Cornwall *et al.* (1967), Lovering *et al.* (1968), Wrücke *et al.* (1968), Elliott and Wells (1968), Whitebread and Hoover (1968), MacKevett and Smith (1968), Gott and Zablocki (1968), McCarthy *et al.* (1969*a*), Akright *et al.* (1969), Wells and Elliott (1971), Chaffee (1972), Bailey and Williams (1975), Ashley and Albers (1975) and Ashley and Keith (1976). In the areas in Nevada containing disseminated gold deposits in limestone (e.g., Carlin, Cortez, Getchell, Gold Acres), oxidized materials along fractures, small quartz and calcite veins, silicified zones, mineralized material in shear zones and breccia zones, altered rocks, gossanous materials and jasperoid[33] have proven to be excellent sampling materials. In these Au, As, Sb, Hg, W, Ag and Bi appear to be the best indicators of gold mineralization. A number of other elements including B, Ni, Cu, La, Y, Ga, Sc, Pb, Mo, Sn, Zn, Cu and Te are also present in anomalous amounts in the sampling materials and in the known orebodies. In the Drum Mountains, Utah, jasperoid is gold bearing and commonly contains anomalous amounts of Ag, Bi, As, Sb, Sn, Pb, Cu, Hg and Y. Silver in altered rocks and other materials clearly marks the gold-silver-bearing lodes and zones in the Comstock Lode and Tonopah areas, Nevada, and mercury appears to be particularly useful for indicating gold-silver mineralization at depth in both areas. In the southern Santa Rita Mountains, Arizona, sampling of altered rock revealed large zones of granitic rocks enriched in Cu, Pb, Zn, Ag and Au. At Cripple Creek the volcanic rocks between the productive veins contain an average of about 0.6 ppm Au, and a large area of rocks marked by a gold anomaly averaging 2.5 ppm Au was located near the Cresson Mine. This anomaly also contains enriched amounts of Ag, Te and Hg. In the Ely porphyry copper district of Nevada, jasperoid, gossanous material, silicified fracture fillings and dolomites exhibiting silica boxworks were found to be good sampling materials. Gold, silver, tellurium and mercury in these materials are distributed in zones clearly related to centres of alteration that are in turn related to the major copper deposits. The four elements form halos around a copper-rich core. The Ely district as a whole is greatly enriched in tellurium, large volumes of rock containing of the order of 100 ppm Te (2000 times the average abundance of Te in igneous rocks). Tellurium and mercury are also enriched in certain jasperoid samples (Lovering *et al.* 1966). They found that the 'favourable type' of jasperoid commonly associated with metalliferous ores generally contained >1 ppm Te and >5 ppm Hg, whereas the 'unfavourable type' found in barren zones contained only low amounts of these elements.

In the Taylor Mining District and vicinity near Ely, Nevada, Lovering and Heyl (1974) found analyses of jasperoid to be particularly indicative of precious metal mineralization. They observed certain characteristics of the jasperoid which appear to be most useful as guides to the focus of silver-gold mineralization as follows: (1) a change from dominantly brown to dominantly grey to dark grey or nearly black, (2) a coarsening in texture of the matrix jasperoid, (3) an increase in the number of vugs and (4) an increase in the ratio of copper to chromium. They noted that all the metals including silver and gold, that have been produced from the Taylor district exhibit strong anomalies in jasperoid samples from the central part of the district – in fact, the ores are actually mineralized jasperoid – but the metals show no consistent zonal distribution relative to each other. They also observed that the metals tend to vary considerably in concentration among samples from the same locality and tend to increase and decrease simultaneously as shown by samples collected across a mineralized body. However, they found a variety of patterns in the regional anomalies of the metals that are detailed in the original paper.

Two recent studies in the Goldfield area of Nevada, one on the silicified rocks of the district (Ashley and Keith, 1976) and the other on the distribution of gold near orebodies in the oxidized zone (Ashley and Albers, 1975) are of interest in the problems related to prospecting for these deposits. Briefly two correlations of elements were noted in the silicified rocks – the first Au, Ag, Pb, Bi, As and Cu represents a relict hypogene association preserved in spite of oxidation, and the second As, Cu, Mo and Fe is a supergene association produced during oxidation when varying amounts of these elements were mobilized and precipitated with limonite. For the second investigation 278 samples of argillized and silicified dacite were collected in 1966 from excavations at the Combination and January mines, which once yielded gold in commercial quantities. Semiquantitative analyses show that Au, Ag, Pb, B, Hg and As are notably enriched in rocks of the cuts. All these elements except lead and mercury formed conspicuous ore minerals. Geochemical maps and one geochemical profile across strike show that relatively high concentrations of all these elements are restricted to silicified zones. This low-tenor metallization dispersed through silicified zones does not extend into adjacent clay-bearing rocks. During oxidation, arsenic, copper, molybdenum and zinc were

[33] Jasperoid refers to an epigenetic rock body formed mainly by fine-grained, chertlike siliceous replacement of a pre-existing rock. Most jasperoid bodies range in size from small pods to masses more than 1000 ft wide. Most are structurally controlled and occur along fault and fracture systems; some are chemically controlled by the presence of limy rocks, the silica replacing the carbonates over large volumes or along specific linear zones probably marked by faults and other porous zones. Many of the individual masses of jasperoid are brecciated, the fragments being cemented by younger quartz or less frequently by coarse calcite. The jasperoid rock is generally aphanitic to very fine grained and exhibits a variety of colours including shades of grey-black, grey, greyish brown, light brown, yellowish brown and reddish brown. Much jasperoid is marked by micro vugs, especially in the highly mineralized belts. In most mineralized belts the ore metals, the jasperoid and certain rhyolite porphyry dykes all appear to be genetically related. The ore metals appear to have been introduced penecontemporaneously with the late stages of the silicificiation that gave rise to the jasperoid bodies, by solutions moving upward along fault and fracture systems.

leached from the silicified zones and the orebodies within them, but these metals did not form distinct supergene halos in the surrounding argillized rocks. From the semiquantitative data available, the average amount of gold in silicified vein material was calculated to be between 2 and 4 ppm.

The mineralogical and chemical criteria for assessing what may happen to the precious metal values in auriferous deposits with depth has intrigued geologists and mining engineers for centuries. In the writer's opinion there are few sure and certain criteria that can be considered as signals that the values will continue unchanged, increase or peter out with depth. The changes with depth manifest in horizontal and vertical trace element halos and their relationship to continuance of gold values are discussed above, and the essentials of vertical elemental and mineral zoning in auriferous deposits are discussed in the last part of Chapter III and need not be repeated. A discussion of the use of the Au/Ag ratio in predicting conditions at depth in auriferous deposits is also given in Chapter III and the effect of supergene enrichment, one of the factors in the variation of gold values with depth, is outlined in Chapter IV. In many auriferous areas the persistence of the structural elements localizing the orebodies is an important consideration in the depthwise continuation of gold values, although it is well known that in many belts the structures may continue to depth, but the gold content may diminish or cut-off abruptly. To generalize, one can say that in the shallow, commonly Tertiary, deposits the precious metal values tend to diminish with depth. Few such deposits are productive of gold below 2000 ft. On the other hand the deep-seated, generally older than Tertiary deposits, may extend to depths greater than 10 000 ft (e.g., Kolar).

Anderson (1935) gave a number of geological guides that he considered could be helpful in examining gold-quartz mines with respect to depth continuation and other matters in the North American Cordilleran region. Indications of petering out of gold-quartz orebodies considered were: (1) persistent increase in the base metals. This may be gradual or abrupt; (2) marked decrease in the fineness of gold. This indicates an approach to the bottom of the ore zone; (3) presence of a dyke (the most acidic dyke in the particular igneous assemblage of rocks in the district) from which the gold-quartz orebodies segregated. The dyke(s) can often be recognized by the presence of finely disseminated primary pyrite; and (4) presence or association of pegmatite or feldspar with the gold-quartz veins. The last two criteria are based on Anderson's (1935) idea that gold-quartz veins differentiate directly from the most acid dykes of any igneous assemblage. Hence, when the gold-quartz veins pass into the dykes they have reached their source and must terminate. These ideas have been criticized by Dougherty (1936) who pointed out that in many areas gold-quartz orebodies continue downward to considerable depth in, along or near the most felsic (acidic) dykes in the belt, such as dykes of alaskite, albitite, quartz porphyry and feldspar porphyry.

The recent book by Roslyakova and Roslyakov (1975) on the subject of the endogenic (primary) halos of gold deposits merits close attention since it embraces a large amount of very careful work. Only a brief summary can be given here; the details should be sought in the original publication, a translation of which is available from the Geological Survey of Canada library.

Roslyakova and Roslyakov review past work on endogenic halos associated with gold deposits and give brief descriptions of the types of gold deposits covered by their investigations. These include mainly quartz vein and disseminated types, auriferous sulphide bodies and auriferous skarns. The deposits include the Darasun, Klyuchi, Natilii, Muruntau and many others that are described in the present volume. The narrative continues with a discussion of the background contents of gold in the rocks (sedimentary, igneous, metamorphic) in the various regions studied. Samples were taken of fresh rock well removed from the mineralized centres (50–80 km). The general averages obtained in ppm were as follows: sedimentary–0.003, with values up to 0.0065 for conglomerates and sulphidic sediments; volcanics – 0.0005–0.005 with values up to 0.010, the basic varieties being highest in gold; acidic intrusive igneous rocks – 0.001–0.005; basic intrusive igneous rocks – 0.001–0.006; metamorphic rocks – 0.001–0.0054. From their data Roslyakova and Roslyakov (1975) concluded that each region in the U.S.S.R. has its own characteristic regional gold background, determined mainly by the development of specific rock types. On the whole they concluded that for most regions the background (in the rocks) ranged from 0.0018 to 0.0034 ppm and the distribution generally follows the lognormal law. They found no particular correlation of gold with other elements in the rocks, although in sediments and their metamorphic equivalents they detected a correlation between the abundance of the precious metal and organic matter in certain regions only. (Compare the data and discussion on gold in rocks given in Chapter II.)

The characteristics of endogenic halos associated with the various types of auriferous deposits follow. This section is preceded by a general summary that can be paraphrased as follows:

Anomalous concentrations of gold and its associated elements are distributed unevenly as distance increases from individual orebodies and then as distance increases from the auriferous ore zones. There is, however, a definite pattern common to all the ore fields, auriferous ore zones and individual orebodies.

At a distance of 10 km or more from the auriferous ore zones anomalous contents of gold, and in certain cases also of arsenic, lead, molybdenum and copper, are encountered in restricted zones. Anomalies of this kind are not strongly marked, either in terms of gold content or of its dispersion. These anomalies are caused by the deviation from the norm to a greater or lesser extent of the contents of carbonaceous matter, dark-coloured minerals and accessory magnetite and sulphides in the country rock.

The gold contents begin to vary more and more on approaching the auriferous ore zones and then on approaching individual orebodies; their average values also increase. Several zones, i.e., halos, can be identified by reference to the content of gold and the nature of its distribution, its concentrator minerals and correlations with other elements. At the present stage of research, halos of three orders can be distinguished with confidence; (1) ore field halos; (2) ore zone halos; and (3) individual orebody halos.

The endogenic ore field halos are in reality local sectors of the earth's crust with anomalous amounts of gold as compared with the background or clarke of a large region. Most of these halos are extensive according to the authors, the area of the Tertiary Oganchensk Goldfield in Kamchatka being about 50 km^2. The ratio of its width to its length is approximately 1:2. The halo conforms with the orientation of the main tectonic structures of the goldfield, i.e., with the great zones of fracturing and brecciation. Compared with the regional background the gold content in the ore field halo is some 4 times higher in amount. The fluctuation in particular precious metal values is within 2 to 3 orders of magnitude, whereas the fluctuation in the regional background is within one order of magnitude.

Similar features were noted in the other goldfields studied by Roslyakova and Roslyakov (1975). The endogenic ore field halo of the Kozlovskoe field is irregular in shape but some 150 km^2 in area; that for the Klyuchi field more than 12 km^2 in area; and that for the Darasun field about 600 km^2 in area. Gold values in these various halos exceed at least twice the regional averages. Summarizing, the authors make the following statements with respect to ore field halos:

1. The ore field halo serves as the local background to the auriferous zones; the larger these zones, the larger the scales and the higher the average contents and dispersion of gold in the ore field halo. The halos of large ore fields are hundreds of square kilometres in area, those of comparatively small fields cover tens of square kilometres, and those of individual gold occurrences extend to a few kilometers only.

2. The ore field halos have a complex morphology, which is dependent on the basic structures of the region. Their average gold contents are three or more times greater than the regional background. Their particular values vary within 3 to 4 orders of magnitude, and often, especially in the vicinity of deposits, the gold contents are one order of magnitude lower than the regional background. It is, therefore, vital when defining ore field halos to show both the increased and the reduced gold contents as well as the nature of the gold distribution in sectors of the ore field that differ in their composition and in the extent of their alteration.

3. Disseminated sulphides, accessory magnetite, light-coloured minerals and micas are the gold concentrators in ore field endogenic halos. There is no reliable correlation between the gold in the halos and other primary ore elements. In places the gold is directly correlated with barium and copper.

4. Increased gold concentrations (tens of parts per billion) and a distinct irregularity in the gold distribution over large areas are vital geochemical prospecting criteria for gold mineralization. The presence of anomalously low gold contents against an increased background may be a reliable sign of the near approach to a deposit.

Extensive data for auriferous ore zone halos are given in the following section, and these are discussed in great detail. It is stated that these halos are in general complex, gold and other associated elements being often distributed in an irregular and often erratic manner. Ore zone halos are usually revealed against the local background by a large spread of from four to five orders of magnitude in the gold contents, and copper, lead, zinc, arsenic and other chalcophile elements are found in increased amounts. Both positive and negative (leached out) gold halos occur, and these vary in size according to the scale of the mineralization. In some ore zones the gold contents in the halos equal the regional background. Pyrite and arsenopyrite and certain skarn minerals are the principal gold carriers in ore zone halos. Gold correlates with numerous elements within the halos, but the patterns are often complex, and each ore zone has its own characteristics. The most common correlations of gold are with copper, lead, zinc, silver, cobalt, nickel, barium and arsenic.

Individual orebody halos are described at great length and discussed in the light of wall-rock alteration effects. Most orebody halos are complex and each vein, impregnated zone, sulphide lens, etc. has its own characteristics, although within an ore zone there is much regularity. Individual orebody halos may be marked by positive or negative halos or combinations of these. The main concentrator mineral of gold in positive halos is generally pyrite.

Much detail is given with respect to the zonality and correlation of the various chalcophile and other elements with gold in individual orebody halos. Only a brief summary can be attempted here as follows:

The horizontal distribution of trace elements in altered rocks near auriferous veins such as Ag, Pb, Zn, Bi, Mo, Y, Sc and Hg has much in common with the distribution of gold. Ni, Co, Sn, Cr, Zr and V behave differently. All these elements may, however, form positive, external negative and exocontact negative halos near the orebodies. The positive halo maxima and the negative halo minima for the various elements often fail to coincide. The discrepancy with the gold halo maximum and minimum is particularly great in the case of Ni, Co, Sn, Cr, Zr and V halos, which are considerably more extensive. Anomalously high arsenic and antimony contents can be detected only in the vicinity of the ores, encompassing both the positive and negative halos of Au, Ag, Pb and the other associated elements. All these factors make the correlation between gold and trace elements in the country rocks in the vicinity of the orebodies extremely complicated. Calculation of the coefficients of correlation between the contents of elements and distances from the orebodies commonly reveals a low inverse relationship between them. This situation is thought to be due to the alteration of negative and positive halos, and especially by the presence of exocontact negative halos.

Despite the complexity of the relationship between elements in hydrothermally altered rocks horizontally outward from auriferous orebodies, the elements are commonly distributed according to their concentration maxima as follows: As, Sb-Au, Ag, Pb, Zn, Cu, Bi, Mo, Hg-Ni, Co, Sn, V. Variations in this sequence are normal in some auriferous deposits, especially those with very rich ore shoots.

Vertical zonality in the distribution of elements in halos is apparent from the occurrence of the highest concentrations of certain halo elements in the upper parts of some orebodies, of others in the central parts, and of yet others in the deep parts. In particular, for the Darasun deposit, the following vertical zonality is normal: Pb, Zn, As, Ag and Sb are concentrated in the halos of the upper parts of orebodies, and Cu, Bi, and more rarely Cr, Ni and Co, concentrate in the lower parts. The vertical zonality in the Muruntau deposit exhibits a predominance of Ag, Pb and Cu in the rocks above the ore and of Au, Co, Mo and W in the lower parts of the ore zone. These examples indicate that there is no universal vertical zonality in the halos associated with auriferous deposits.

Regarding changes in the width of gold halos with depth, it can be said in some cases that there is no change, in others an increase and in yet other cases a decrease. Some investigators have established that endogenic gold halos are most marked in the vicinity of the zone of optimum gold mineralization, and that all other conditions being equal the width and productivity (an index of the nearness to ore shoots) of gold halos decrease as the distance increases from the ore shoots upward and downward along the dip.

In the last section of the book on prospecting for gold deposits using endogenic halos the authors emphasize the high cost incurred in prospecting for auriferous deposits using endogenic halos, a feature that makes it imperative to have criteria that can be used to concentrate attention on a limited number of promising sectors. Prior to the development of highly sensitive methods for the estimation of gold, indicator elements (Cu, Pb, As. etc.) have been employed extensively in geochemical prospecting for gold. Roslyakova and Roslyakov think a change in this approach is necessary. They advocate the use of gold directly as an indicator now that the analytical methods are available for its precise determination. They point out that while arsenic is a good pathfinder for gold, it is not infallible and mention a number of deposits where the element is ineffective. They further consider that even the Muruntau deposit, which was found by using arsenic, could have been better and faster located by using gold directly as an indicator. Mercury is, likewise, not always a good indicator of gold deposits as shown by the Darasun Goldfield. Here again gold is the better indicator. Their final statement is worthy of quotation.

"Our observations indicate that gold should be determined at each stage of the geochemical investigations. Gold deposits should be sought in terms of gold. Only this approach permits a correct assessment of the potential of an area and the discovery within it of blind deposits at least cost."

Within the confines of auriferous deposits in shear zones, faults, stockworks, other dilatant zones and chemically favourable rocks a number of geochemical techniques can be utilized to determine the trend and location of the pathways of mineralization, to outline the zonation of the mineralization, to predict the possible continuation of known ore on the strike and pitch of the oreshoots, to predict the vertical extent of mineralization and to determine a variety of other features useful in the development and mining of orebodies. This is a large subject that lies outside the scope of this bulletin, and only a brief listing of the methods can be considered here. These include:

1. Plotting single metal values, the sum of metal values and/or metal ratios on plans and sections, particularly on longitudinal sections, of the deposits and their associated primary halos. Such plots permit various comparisons, indicate which metals are associated, the probable pathways of mineralization, changes of mineralization with type of wall rock, zonation parameters, the extent of secondary enrichment or depletion due to oxidation and reduction processes, the nature of the primary halos and the possible vertical extent of primary mineralization. The Au/Ag ratio of native gold and of the ore shoots as a whole in auriferous deposits is of considerable use in this type of work. (*See* the section on Au/Ag ratios of deposits in Chapter III.)

2. Plotting of mineralogical data, including mineral types, asymmetric growth banding of crystals and textures of mineral intergrowths in the ore. Such data may indicate the direction and extent of pathways of mineralization ('the plumbing system') and may give information on zoning. In a number of deposits, particularly those of Tertiary age (epithermal deposits), there is a consistent mineralogical zonation as discussed at length in the last part of Chapter III. In these deposits the precious metals are enriched near the surface with base metals at depth. Deep seated deposits do not generally exhibit this type of zonation, although in some auriferous districts there may be consistent changes in the type and texture of the ore and gangue minerals that are significant.

3. Plotting data obtained from liquid inclusions and from various mineralogical geothermometers and geobarometers on plans and sections of the deposits. The methods and some of the results of these techniques are discussed in a subsequent section.

4. Plotting isotopic data on ore and gangue elements on plans and sections of the deposits. Such data may indicate pathways of mineralization and may give information on zoning (*see further* the section on other methods in this chapter).

Further details on some of the techniques mentioned above with appropriate bibliographies are given by McKinstry (1948) and Goodell and Petersen (1974) and in various papers recorded in the Selected bibliography.

Pedogeochemical methods

The materials used in pedogeochemical surveys include soils, weathered residuum, calcrete, silcrete, ferricrete, and various glacial materials including till, sand, gravel, etc. These materials may be analyzed directly for gold and its indicator elements; alternatively samples of the materials can be panned and a heavy (or light) concentrate obtained for mineralogical and/or chemical analyses. The latter method is particularly effective since gold tends to collect as the metal in soils, weathered debris and glacial materials in the vicinity of its deposits. The halos and trains developed in soils, tills and allied materials are of a chemical (hydromorphic) and/or resistate (mechanical) nature. Total analyses of soils and allied materials for gold will outline the combined chemical and resistate halos and trains; selective extraction techniques generally outline only the chemical halos and trains; and heavy and light concentrates the resistate halos and trains.

Pedogeochemical surveys should be conducted on a closely spaced grid (25 to 50 ft centres) because of the relatively narrow width of most types of gold-bearing deposits. For deposits of the quartz-pebble conglomerate, stockwork, mineralized pipes and disseminated types the spacing can be increased to 100 ft centres or more in most cases.

Gold may be the best indicator of its deposits in some districts whereas some of its associated elements may be more effective in others. The selection of the best indicator(s) will depend on the type of deposit and the conditions of oxidation, soil formation, glaciation, etc. Those contemplating work in glaciated terrains should read the papers by Forgeron (1971) and Nichol and Bjorkland (1973). Pilot studies should be carried out if possible before conducting extensive surveys. During the pilot stage the elements associated with gold in the types of deposits in the district should be ascertained, as should also the effectiveness of these elements as indicators in the soils, tills, etc. In our experience, and judging from the investigations of others, the best indicators of gold deposits utilizing soils, weathered residuum and glacial materials are Au, Ag, Hg, Sb and As, particularly the last element. In some districts Mo, W, Cu, Pb, Zn, Cd and U may be useful if these elements accompany gold in its deposits; Te, Se, Bi, Ba, Ni, Co, Sn, F and B appear to have only a restricted use in districts where the primary deposits are enriched in these elements. For surveys based on analyses of heavy mineral separates of soils, weathered residuum and glacial materials Au and Ag are generally the best indicators; others include As, Sb, W, Mo, Cu, Pb, Zn, Hg, Cd, platinoids, Te, Bi, Sn, Tl, Ba, Sr, Ni, Co, U, V, Cr, Sc, rare-earths and B. Pilot studies to determine which of the latter indicators are effective should be carried out before embarking on extensive surveys.

Selecting the horizon or horizons from which to obtain the soil samples, weathered residuum or glacial materials usually requires some knowledge of the soils and their parentage or of the glaciation in the area in which the survey is to be carried out. Here again pilot studies should indicate the best horizons to sample and in addition give information on the backgrounds of the various indicator elements in the different horizons. Generally the B horizon is the best for sampling, although the A horizon may be effective in some areas. The latter often exhibits an enrichment in gold, silver, arsenic, antimony and other indicator elements, and the anomalies may have greater contrast than those in other horizons. In some areas only the C horizon close to bedrock gives satisfactory results. This is especially true when the weathered residuum or glacial deposits are thick. Heavy and light mineral surveys are best carried out by using materials as close to the bedrock as possible, although in some places near surface samples of soils, tills, etc. may be satisfactory.

Deciding what are anomalous gold contents in soils, weathered residuum and glacial materials depends on the district and should be determined by preliminary surveys. The normal gold content of soils is usually less than 0.005 ppm and the normal silver content ranges from 0.1 to 0.5 ppm (Table 19). The range for the other two common indicators of gold in background soils, weathered residuum and glacial materials is As – 7 ppm; Sb – 0.7 ppm. Means for some other indicators in normal soils, weathered residuum and glacial materials are as follows: Hg – 0.06; Mo – 2; B – 8; W – <4; Cu – 20; Pb – 15; Zn – 75; Cd – 0.2; Te – 0.01; Se – <0.2; U – 1.0; Bi – <0.5; Sn – 2; Tl – 0.1; Ba – 400; Sr – 100; Ni – 15; Co – 5; and F – 250; all in parts per million. The writer has found that values above 0.01 ppm Au and 0.7 ppm Ag are generally anomalous and should prompt the prospector to investigate the cause. Anomalous values of the indicator elements cannot be stated with any assurance since the dispersion and enrichment characteristics of the various elements vary so widely. However, consistent values 2 or 3 times the average abundance of the figures given above should receive attention.

A number of geochemical prospecting investigations utilizing soils, weathered residuum and glacial materials have been described in the literature. Those noticed in this compilation, and dealing specifically with the detection of gold deposits, include the following:

In Canada the first attempt to use geochemical methods for tracing gold mineralization through glacial overburden is that described by Chisholm (1950). He was able to successfully trace a gold-bearing zone in the Kenora district of Ontario under glacial overburden ranging from a few inches to 5 ft in depth by utilizing copper, lead and zinc as indicators.

Sokoloff (1950) found that analyses of mature residual soils in Western Autralia showed a correlation between gold anomalies in the soil and known lodes. He cautioned that soil anomalies are difficult to interpret and cannot distinguish between a large underlying deposit or one where only the remnants remain after deep erosion. In this situation the level of erosion with respect to the potential target is important to determine where possible. In Japan, Shima (1953*a,b*) used copper and zinc successfully as indicator elements in soil surveys carried out to locate gold-silver veins. James (1957) investigated the metal dispersion patterns in soils over arsenical and antimonial gold deposits in three Rhodesian areas. The results showed that anomalous arsenic values are commonly found in all depths of the soil in the immediate vicinity of mineralization. Anomalous quantities of antimony also occurred, but copper and zinc showed no increase in content. The retention of As and Sb in soils was highest in Fe-rich soils. Narayanaswami (1960) found arsenic to be a particularly good indicator in soil surveys for locating arsenopyrite-bearing gold lodes in the Kolar Goldfields, India. Martinet (1959) also found that the arsenic content of soils was a good indicator of gold deposits in French West Africa. The gold and arsenic anomalies shown on the profiles are mainly coincident. Webb (1958) and Mather (1959) also report that arsenic (and antimony) are good pathfinder (indicator) elements for locating gold deposits utilizing soil surveys in Rhodesia and Sierra Leone. Webb makes reference to the common observation that arsenic is strongly retained in Fe-rich soils. He also notes that there is relatively restricted leaching of arsenic during weathering where such soils are formed, and such lateral dispersion as does take place is probably largely mechanical.

Chapman (1959) found that anomalous amounts of arsenic and/or lead in the soil, particularly in the C horizon are the best indicators of gold- and silver-bearing galena veins in the Kantishna area of Alaska. Zinc was also found in anomalous amounts at some sites, but copper rarely showed more than a background amount. Similar results were found by Boyle (1965*a*) in the Keno Hill–Galena Hill–Dublin Gulch area of Yukon. There, arsenic is a particularly good indicator in residual soils for detecting quartz-pyrite-arsenopyrite-gold-silver veins. Over or slightly downhill from these veins marked arsenic anomalies with a high contrast were obtained; a similar phenomenon was noted for antimony. In areas covered by glacial materials deep sampling near the bedrock is the only satisfactory way of using pedogeochemical methods.

Cu, Pb, Zn, Hg and As have been favoured indicators utilizing pedogeochemical methods in a variety of terrains, throughout the world. Bayley and Janes (1961) found arsenic to be a suitable indicator in the Atlantic district of Wyoming, and Brotzen and Obial (1963) found that Cu, Zn and Pb were suitable indicators for a number of types of deposits, including those carrying gold, in the Philippines. Granier *et al.* (1963) noted a parallelism between the contents of Cu and Au in deeply weathered lateritic layers overlying metadiorite on Mount Flotouo (Ivory Coast). The gold content fluctuated from 1 to 8 ppm and the copper content from 400 to 1500 ppm. In Japan, Kishimoto *et al.* (1963) found mercury to be an excellent indicator of Tertiary (Neogene) Au-Ag quartz veins of the epithermal type. An intimate relationship between the mercury dispersion in the soil profiles and underlying hypogene gold-silver deposits was found.

Arsenic in soils has proven to be an excellent indicator of gold deposits in the Basin and Range Province of the western United States according to Cavender (1963). Near the Getchell Gold Mine in northern Nevada soils samples were collected along 50 profiles across potentially gold-bearing structures and areas, and the arsenic concentrations were statistically evaluated. The results were as follows: (1) arsenic anomalies in residual soils showed a direct relation to gold-arsenic mineralization and potential gold-bearing areas were delineated, (2) unknown and mineralized high-angle faults were uncovered, (3) arsenic mineralization was found in low-angle thrusts – structures previously considered unmineralized, and (4) the recognition and interpretation of local fault structures was augmented.

Dvornikov *et al.* (1963) observed that dispersion aureoles of mercury in the A horizon of the soils in the Nagol'nyi Range coincide with a belt of polymetallic and gold deposits and with fault zones, crests of anticlines and zones of quartz veins. The broadest and most strongly enriched aureoles were located over sulphide and quartz veins. The mercury was found to occur as soluble (chloride), oxide, sulphide, metallic and metal-organic compounds. The clay fraction was relatively richer in mercury than the bulk composition or the coarse fraction. The investigators considered that the high concentrations form as a result of the mechanical decomposition of orebodies and by the accumulation of mercury in the A horizon by the decay of plants whose roots tapped mercury-bearing soil solutions. They concluded that high mercury concentrations in the A soil horizon are an important prospecting clue for new mineralization zones.

An extensive integrated geochemical survey involving analyses of plants, soils and waters has been carried out by Razin and Rozhkov (1963) over the Kuranakh type gold deposits in the permafrost region of the Aldan Shield, Yakutia, U.S.S.R. These deposits are developed in a karst terrane in a mountainous taiga environment and are described in some detail in the section on placers. The soils are mainly soddy-forest loams. The gold content overlying the mineralized zones ranged from 0.1 to 5.7 ppm and increased down the soil profile, the largest amount being present in the C horizon. The highest gold content in the true soils (up to 2.8 ppm Au) was recorded in the B_1 horizon. Enrichments of gold were found only in the humic horizons of podzols in amounts ranging from 0.1 to 5.5 ppm. A clear relationship between the gold and Fe_2O_3 contents was noted in the soils and a less definite relationship between the gold and Al_2O_3 contents. Increased contents of Fe_2O_3 were usually marked by an enhancement of gold, especially in podzols. Razin and Rozhkov (1963) concluded that pedogeochemical methods were effective for locating gold deposits in permafrost regions.

Baxter and Poet (1964) found that Cu, Pb, Zn and As in soils gave a negative response over veins in the Cripple Creek area of Colorado, although they concluded that anomalous amounts of these elements may indicate favourable zones for general exploration. Tellurium was found to be more effective as an indicator of the veins and mineralized zones. The tellurium contents of the soil ranged from 0.25 to 12.5 ppm, the higher values being associated with veins and zones mineralized with gold tellurides.

Hawkes (1965) carried out a geochemical survey using arsenic as indicator for gold mineralization in the Marudi Mountain area, Guyana. The gold occurs as eluvial and alluvial deposits and also in arsenical quartz veins. Two hundred and fourteen soil samples from a depth of 2 ft were analyzed for their arsenic content. The results showed a high frequency of samples containing between 0 and 39 ppm arsenic. The mean of these values, which is 10 ppm, was taken as the regional background. The value for the threshold (130 ppm) was calculated using the mean (background) plus twice the standard deviation. A maximum to background ratio of 30:1 represented the greatest contrast recorded in the area. Five main and six smaller areas of anomalous arsenic values were located, and in two instances these apparently marked the extension of known gold veins.

Mazzucchelli (1965) and Mazzucchelli and James (1966) examined both the primary and secondary dispersion of arsenic and other elements related to gold mineralization in a belt of auriferous rocks, some 300 mi in length, in central Western Australia (Coolgardie-Kalgoorlie districts of the Australian Precambrian Shield. They observed that anomalies related to arsenical gold mineralization are detectable in the various types of residual soils occurring in the area studied, including relict lateritic soils. Arsenic was found to be concentrated mainly in secondary iron oxides in the coarse (+80 mesh) sand and silt fractions of the soils. Appreciable concentrations of arsenic were also found to be associated with the clays, particularly in the alkaline near-surface horizon of the solonized brown soils. The distribution of arsenic in the soil profile appeared to be dependent on pH and the abundance of secondary iron oxides. Lateral dispersion processes under the present semiarid climatic conditions were found to be dominantly mechanical, although appreciable hydromorphic dispersion of arsenic apparently took place during the development of the lateritic soils in the Pliocene.

Bateson (1965) emphasizes the point that in Guyana gold is a particularly good pathfinder for base metals. There, despite intense weathering and leaching, gold is relatively immobile and stable remaining behind in the residual clays and soils. The presence of gold in the weathered residuum, therefore, indicates mineralized zones which may contain base metals. The prospecting procedure employed is to identify the gold-bearing areas and follow this by soil surveys using Cu, Pb and Zn as indicators in the search for base metal mineralization.

Since 1965 there has been a general increase in the use of soils and allied materials on prospecting for gold throughout the world. Komov (1966) describes extensive aurimetric surveys using soils in the Yenisei Range, U.S.S.R. where the deposits are mainly gold-quartz veins. Both gold and arsenic proved useful as indicators. Gold exhibited the least migration and hence marked the location of the deposits most accurately. The zones mineralized with gold were indicated by dispersion halos in the soils with a gold content of 0.05 ppm or higher. Kurbanayev (1966) found that the content of thallium in the secondary dispersion aureoles in eluvium, alluvium and weathered materials of the Maykain gold-barite-polymetallic deposit (northern Kazakhstan) is a clue to the existence of sericitized rocks beneath the surface. Such rocks, containing thallium as a primary constituent, are often indicative of hydrothermal gold mineralization. In places fivefold enrichments of thallium in the eluvium, alluvium and weathered materials were found when compared with the bedrock (1.0 ppm Tl compared to 0.2 ppm respectively).

Anthony (1967) relates the history of the discovery of the Keystone Gold Mine, Cleary Hill area, Fairbanks district, Alaska by geochemical soil methods. The C horizon just above the uppermost stone stripe layer was sampled at a depth of about 33 in. Dithizone analyses for total soluble Cu, Pb and Zn were done on the spot, and the results plotted. The geochemical anomaly revealed as the result of the work marked a high grade gold-quartz vein some 2 ft in width and more than 2000 ft in length.

In the Tavua Basin, Fiji, Johnson (1967) found that arsenic was the most satisfactory pathfinder for gold in soils. There, the deposits are epithermal, occurring in shears and fractures that are associated with a Tertiary caldera (*see also* Chapter III).

A number of investigations have been carried out in recent years in various parts of the world mainly to determine the applicability and efficiency of soil sampling methods in prospecting for gold deposits of various types. Those noticed in the literature include investigations by Kurbanaev and Atchibaev (1968), Nason *et al.* (1968), Potapenko *et al.* (1968), Obraztsov (1969), Banister (1970), Reed and Miller (1971), Evangulov *et al.* (1971), Kartsov (1971), Watson (1972), Leonard (1973), Belogolova and Shibanov (1974), Lakin *et al.* (1974), Pasquali and Bisque (1975), Gustavson and Neathery (1975), Rosylakov (1976), Nestorenko *et al.* (1976), Watterson *et al.* (1976), and Kokkola and Pehkonen (1976). In these investigations the best indicator elements for gold-bearing deposits have proved to be Au, Ag, As, Sb, Pb, Cu, Zn, Ni, Co, Bi and Mo, particularly the first four. Hg has proved useful in some districts and Te in others. Kurbanayev (1966) found thallium to be enriched in the soils and eluvium overlying the auriferous polymetallic-barite Maikain deposit, U.S.S.R. and concluded that it was a useful pathfinder for such deposits. Steed *et al.* (1976) observed that anomalous arsenic and rubidium contents in soils best outlined the ore zones at the Ogofau gold mines, Dyfed, Wales.

In the West End Creek area, Yellow Pine district, Valley County, Idaho, Leonard (1973) found a gold anomaly near the Yellow Pine Mine by soil sampling. The gold anomaly is accompanied by a silver anomaly and by conspicuous though minor mercury, antimony, arsenic and tungsten anomalies. The gold content of 128 soil samples ranged from <0.05 to 8 ppm, the median value being 0.70 ppm. The Tertiary mineralization at the Yellow Pine Mine (Stibnite area) consists of disseminated bodies associated with faults and shear zones and containing essentially auriferous pyrite and arsenopyrite, gold, scheelite and stibnite, in a gangue of quartz, feldspar, sericite and carbonate. There are mercury prospects and mines in the area; these contain cinnabar as the principal mercury mineral.

Watson (1972) and others (*in* the Chamber of Mines Journal, Rhodesia, 1968, 1969*a,b*) describe an interesting gold anomaly in Kalahari sand associated with termite mounds in Rhodesia. He concluded that the enriched amounts of gold (0.05 ppm) (background 0.02 ppm) in the soil and termite mounds may have been carried up by termites from gold-bearing fissures in the Basement Complex to their mounds. Repeated erosion of the termite mounds probably dispersed the gold in the surrounding soil, thus producing an anomaly that has a width of 100 m or more in places. (*See also* the discussion on termite mounds in the section on Biogeochemistry in Chapter II and in the subsequent section on Biogeochemical methods.)

Humus-rich forest soil (mull) as a sampling medium in geochemical exploration for gold has been fairly extensively employed in the western United States. In the Empire district, Clear Creek County, Colorado, Curtin *et al.* (1968) and Lakin *et al.* (1974) found that the gold content of pine and aspen mulls is more representative of gold deposits in bedrock beneath colluvial and glacial cover than is the gold content in float pebbles, cobbles and soil below the mull. Similarly, in the Orogrande district, Idaho, the gold and silver contents of ashed samples of conifer needle humus samples were successfully used to outline a low-grade gold prospect (Rice, 1970). Using the same technique several gold-antimony anomalies were outlined near Stibnite, Idaho by Banister (1970). In a later publication Curtin *et al.* (1971) state that in the Empire district, gold deposits in bedrock beneath the colluvial and glacial cover are best delineated by the gold and, to a lesser extent, by the copper and bismuth contents of the mull ash. The distribution of anomalously high amounts of the last two metals in the soil below the mull corresponds to the gold deposits in bedrock only in places, and many of the high anomalies in soil probably reflect the inclusion of vein material in otherwise barren colluvial or morainal cover. They consider that the results obtained in the Empire district indicate that mull may be an effective geochemical sampling medium for gold, silver, bismuth, lead and zinc in forested areas blanketed by colluvium or glacial drift where the transported material offers no clue to the nature of the underlying bedrock. In a final summary of their work on mull Lakin *et al.* (1974) indicate the usefulness of the mull horizon (A or humic horizon) in prospecting for gold deposits in the western United States because of the general enrichment of gold in this horizon near auriferous deposits. They also note that the gold content of soil profiles in some areas increases near the bottoms of the profiles at or near bedrock. They suggest that this may be due to the release of gold from disintegrating fragments of vein material and/or to the downward migration of gold particles within the soil profiles during downslope creep of the soil.

Aferov *et al.* (1968) noted that the subhorizon A_0 of soils in the vicinity of the Darasun deposits is enriched in gold, and Talipov (1972) observed that the A (humus) horizon of the soils over auriferous deposits containing abundant arsenopyrite in central Kyzl-kum, U.S.S.R. is rich in arsenic. C.F. Gleeson (pers. commun., 1974) states that the samples from the A (humus) horizon developed on till in the Duparquet area of Quebec are much more useful than those from other horizons in prospecting for gold-quartz deposits. The contrast of the gold anomalies compared with the background is marked.

There are few published investigations dealing with prospecting for auriferous conglomerates utilizing soils or weathered residuum as a sampling medium. Zagoskin and Zagoskina (1971) state that the Khuzhir occurrence of auriferous conglomerates in a taiga-forest environment is indicated by a dispersion halo of gold in soils some 60 to 200 m wide. The halos are apparently complex due to the wide disperson of gold in soils near the conglomerates.

The gold content of soils and weathered residuum has been used effectively in the search for porphyry-type deposits. In Yukon, Canada, Archer and Main (1971) relate the history of the discovery of the Casino copper-molybdenum porphyry deposit by stream sediment geochemistry and the outlining of the principal mineralized zones by soil geochemistry, utilizing in both types of surveys Cu, Mo, Pb, W, Au and Ag as indicators. Over the deposit the gold content of the soils (B+C horizons) exceeded 0.5 ppm in places compared with a background of 0.05 ppm or less. Learned and Boissen (1973) also found gold to be a useful pathfinder element in the search for porphyry copper deposits in the Rio Vivi copper district of Puerto Rico. There, many of the deposits in the copper belt are characterized by intensely leached cappings and covered by residual soils and weathered residuum. Within the copper belt the residual soils overlying five major deposits were found to contain strongly anomalous amounts of gold. The gold content of the soils was uniform from deposit to deposit and was about equivalent to the gold content of the primary deposits (0.20 ppm). The general background content of gold in the soils remote from the deposits was generally less than 0.02 ppm.

The calcium carbonate (calcite) content of soils as determined by a gas-volumetric method was applied in prospecting for gold deposits in the Aldan mining district (Koltykan deposits) by Borovitskii and Shemyakin (1965). The Koltykon deposits are in fault, fracture and crushed zones that cut Archean gneisses, schists and marbles overlain by Cambrian dolomites, limestones, marly shales and sandstones all intruded by Cimmerian (Mesozoic) granitic and porphyritic bodies. The gold deposits are post-Cimmerian and consist of veins and lenses of pyrite, quartz, ankerite and Cu-Pb-Zn sulphides. The ores are deeply oxidized and converted to a loose argillo-limonitic mass containing fine-grained gold in amounts up to 300 ppm. The drift cover is some 10 to 15 m thick.

The reason given for applying the carbonate survey in the Koltykon field was that late calcite terminated the deposition of the ores. Soil samples taken at 15 cm depth and analyzed for $CaCO_3$ (calcite) showed marked anomalies over the known deposits, even though the overburden was 15 m thick. Borovitskii and Shemyakin (1965) admit that the mechanism of enrichment of calcium carbonate in soils over dislocations that control the gold mineralization is obscure, but stress that this circumstance is a fact regardless of the presence of carbonate host rocks in the surveyed area.

The writer suggests that Borovitskii and Shemyakin (1965) appear to have found salt halos in the soils overlying the faults and fractures. These halos are probably due to the fixation of calcium in the soils by carbon dioxide that has risen along the fracture system from depth. Another possible mechanism is the fixation of calcium (or elements such as Mg, Fe, Mn) in the soil by carbon dioxide derived from the (bacterial) oxidation of methane which has migrated up faults from depth. Another mineral that is commonly found in soils above fractures and faults is gypsum; derived by the fixation of the available calcium in the soil by SO_4 resulting from the (bacterial) oxidation of hydrogen sulphide that has risen along the fractures. Carbon dioxide, methane and hydrogen sulphide are common gaseous constituents of fault systems, some containing gold deposits, even in the Precambrian (Boyle, 1961*a*). Salt halos in soils over mineralized fault and fracture zones, marked by the presence of minerals such as calcite, gypsum, marcasite, etc., should receive much more detailed attention from those doing research in geochemical prospecting methods.

Analyses of heavy mineral concentrates obtained from soils, weathered residuum or glacial materials by panning, rocking, sluicing or other methods are a most effective method of outlining secondary dispersion trains and halos related to gold deposits. Several techniques can be applied in heavy concentrate studies, including: (1) the heavy concentrates can be studied mineralogically and the frequency of gold colours, pyrite, arsenopyrite, native bismuth, barite, limonite and other heavy mineral associates of gold determined and plotted; (2) the whole sample of heavy concentrates or separated fractions such as the magnetic and/or nonmagnetic fractions can be assayed or analyzed for gold (and silver) and the results plotted; or (3) the heavy concentrates or separate mineral fractions such as pyrite, magnetite and limonite can be analyzed for gold and the elemental indicators of the element such as As, Sb, Bi, Te, Zn, Cu, Pb, Ba, etc., and the results plotted. In all of these techniques the sampling media can be collected on a grid or on lines as the terrain dictates. The work should be quantitative – a standard quantity of soil, glacial materials, etc. should be collected from which all of the heavy minerals are separated and the whole or an aliquot analyzed. The mineralogical and chemical results on the heavy concentrates should then be uniform, but if different samples sizes are used in the survey the mineralogical and chemical results should be calculated to a standard sample size. In practice, the sample size for obtaining the optimum amount of heavy concentrates for mineralogical and chemical work has to be determined in the field since the content of heavy minerals varies widely in soil, eluvium, and glacial materials. Any of the horizons of the soil can be chosen for sampling, but generally the B and C horizons are the best. In glacial terrains samples taken near the bedrock (in the basal till, sand, gravel, etc.) are generally the most effective in outlining dispersion trains and fans.

It should be emphasized that if the soil or glacial materials are sieved before panning for heavy minerals or gold the best sieve size must be ascertained to give the optimum contrasting anomalies for the heavy minerals employed. This can only be done by pilot surveys in an area. This feature is critical for gold particles since in any given area these tend to a relatively uniform size. If too small a sieve size is used, the majority of the gold particles may be screened out with the result that the analytical results will show spotty and often spurious anomalies that have no bearing on the actual occurrence of gold.

Crude panning methods are effective if gold mineralization alone is sought. One simply pans the soil, eluvium, weathered residuum and glacial materials on a grid or on lines as dictated by the geology and the terrain. The colours of gold are counted and recorded on a plan of the grid or lines. Increase in the number of colours in a dispersion train or fan heralds the approach to the primary sources. It need not be emphasized that this method has led to the discovery of countless gold deposits throughout the world, especially in countries that are covered by thick residual deposits. With the advent of more sophisticated analytical methods of geochemical prospecting the gold pan has been somewhat neglected, a circumstance that is unfortunate because there is no better instrument for tracing fans and trains of heavy minerals (gold, cinnabar, barite, cassiterite, platinum, etc.) in soils, eluvium, weathered residuum and stream sediments as emphasized by Mertie (1954), Theobald (1957) and Wells (1973). In glacial terrains the use of the pan is somewhat restricted when applying pedogeochemical methods except for materials on or near the bedrock.

Light mineral associates of gold obtained from soils, eluvium and glacial materials can also be used in tracing secondary dispersion trains and fans related to primary gold deposits. Particularly applicable in this respect is the presence of vein quartz in the soils and drift. By plotting the frequency of vein quartz nodules and particles it is sometimes possible to locate the source of the veins. Many gold deposits were found by the old prospectors using this technique. Lee (1963) provides a modern example by utilizing vein quartz, chloritic fragments and other vein materials as indicators in glacial fans at Kirkland Lake, Ontario. Other minerals such as ankerite, limonite, wad and fuchsite can also be used as indicators. Before attempting work on light minerals, however, it is desirable to study the nature of the vein quartz, carbonates and other associated light vein minerals in the known gold veins of a district in order that proper comparisons can be made between the minerals in the primary deposits and those in the secondary dispersion trains and fans.

Only a few investigations of heavy minerals in soils in the secondary dispersion trains and fans associated with gold deposits have been published. Those noticed in this review include papers by Dvornikov *et al.* (1964) and Bolotnikova (1969). In the soils and friable bedrocks of the Nagol'nyi Ridge the first investigators found native Au, an Ag-Hg alloy and native Pb, Zn and Cu near zones of Pb-Zn and Au mineralization. Native lead was exceptionally abundant. These native metals and alloys are considered to be good indicators of the deposits on the ridge. Bolotnikova deals mainly with the particle size distribution of gold in the secondary dispersion halos over the gold-sulphide deposits in the Maikainsk district. She recommended that the fractions -0.5 to $+0.1$ mm of the residual materials should be used as the initial sampling media during prospecting for gold-sulphide deposits in the district.

Gurev (1970) describes mineralogical-geochemical heavy concentrate surveys carried out in the Kyzyl-kum gold province. There, as a result of oxidation processes part of the gold is fixed in the iron hydroxides (limonite), which is pseudomorphous after the pyrite. Analyses of these hydroxides separated from the heavy concentrates of soils, residual materials, etc., in conjunction with other chemical and mineralized work, have proved useful in the metallometric surveys.

Certain auriferous porphyry copper deposits in Melanesia contain abundant rutile in the ore zones, five times more than in the host rocks (L.J. Lawrence, pers. commun., 1975). On weathering, this rutile may be contributed to the soils and ultimately to the stream sediments and alluvium. Excess amounts of rutile in the heavy separates of these materials could be a valuable indicator of these types of auriferous porphyries.

Analyses for gold, silver and other common associated elements in sulphide, gossan and vein quartz boulders in glacial materials may be a useful approach for outlining secondary dispersion trains and fans related to gold-bearing deposits in the glaciated regions of Canada and other countries. The method is an old one and was generally referred to as tracing float by the old prospectors. An early reference to this type of prospecting is found in the paper by Moore (1925), who relates the presence of highly auriferous quartzite boulders north of Goudreau Lake in Ontario, the source of which had not yet been found at his time of writing. Float tracing, or boulder tracing as it is now called, has been used successfully in Sweden and Finland (Grip 1953; Okko and Peltola, 1958; Hyvärinen *et al.*, 1973). Similar studies have been carried out by Lee (1963, 1965), Cachau-Herreillat and La Salle (1971) and Shilts (1973, 1974) using vein quartz fragments, chloritic fragments, trace elements and heavy minerals including gold in the glacial materials of basal tills, eskers, frost boils and buried valleys in the vicinity of the Kirkland Lake gold-silver deposits, in the auriferous belts of Quebec and in mineralized belts of Northwest Territories. Boulder tracing and closely allied methods involve a close study of the glacial features followed by the plotting of the location of the boulders and chemical analyses on geological maps in order to discover the apex or source of the fan or train that marks the outcrop sites. Details of sampling and concentrating equipment are discussed at length in the papers by Lee and Shilts. Lee (1971) reviews progress in float and boulder tracing in the Canadian Shield in Canada and notes that the discovery of some seven major gold deposits in this geological terrane was assisted by float and heavy clast surveys.

In recent years overburden drilling has been employed extensively in the search for gold and many other types of mineral deposits. The techniques are discussed at length by Van Tassel (1969), Gleeson and Cormier (1971) and Wennervirta *et al.* (1971) and are particularly applicable to permafrost terrains, deeply covered glacial terranes, lateritic terranes, filled valleys and buried eluvial and alluvial placer fields. Overburden surveys are conducted on grids or selected lines or traverses in a manner similar to that employed in pedogeochemical surveys. Samples for analyses may be collected from any level but in general are usually obtained from the zone immediately above bedrock. It is advisable, particularly in placer fields, to sample the near-surface bedrock as well.

Geochemical prospecting for auriferous deposits in deserts and other arid terrains where much of the cover consists of wind-blown materials presents a number of unique problems that have been discussed by Bugrov (1974) and Bugrov and Shalaby (1975). They found that sieving-out of the –0.25 mm fraction to eliminate the dilution effect of aeolian sands enhanced anomaly contrasts in surveys utilizing eluvium and colluvium. Other details are given in the original papers.

Hydrogeochemical methods

The hydrogeochemical methods discussed include those based on ground and surface waters, precipitates at springs and in water courses, stream, river and lake sediments and heavy mineral concentrates in spring, stream, river and lake sediments as sampling media. In practice, surveys may utilize only one of the media, but generally two or more are often used. For thorough work all media should be employed, especially where the geology and types of mineralization are poorly known.

The normal content of gold in natural waters is very low (of the order of 0.00003 ppm [0.03 ppb] or less). In gold-bearing districts the gold content of spring, stream, river and lake waters is, likewise, low, generally in the range 0.001 to 1.0 ppb Au (*see* Table 21). It appears doubtful, therefore, if hydrogeochemical surveys using gold as indicator would be effective using any simple field method of estimation of the element in natural waters. More sophisticated analytical techniques utilizing coprecipitation, carrier, resin collection and solvent extraction methods followed by colorimetric, atomic absorption, spectrographic or neutron activation analysis are suitable for the determination of gold in natural waters, but they are slow and costly and require a well established laboratory. If such methods are employed, care must be taken to analyze the water samples as soon after collection as possible to avoid, among other problems, the extensive adsorption of the traces of gold on the containers. Analyses of evaporated residues of large amounts of water for gold, silver and other associated elements may be useful in certain districts to delimit the stream systems receiving soluble gold from deposits. In the writer's experience, however, the method is tedious and subject to numerous errors.

Numerous investigations have been published on the content of gold in natural waters as an indicator of its deposits. The results have been mixed, some investigators claiming success and others registering failure with the method. (*See also* the section on gold in natural waters in Chapter II).

Kropachev (1935) seems to have been the first to use gold as an indicator in water surveys. He concluded that most gold-bearing areas are marked by waters with gold contents greater than 0.06 ppb.

Konovalov (1941) found that the gold content of river and stream waters of the Sutar River basin was variable (0.000–0.10 ppb) on an areal basis as well as with respect to position in the water course and with time. He concluded that the general physicochemical factors of the migration of gold in natural waters are complex and largely unknown. The gold content of the waters cannot, therefore, be taken as a criterion of the gold content of the soils, rocks or deposits of a given drainage basin. On the other hand Albul and Miller (1959) considered that the gold content of natural groundwaters was effective in prospecting for gold-bearing deposits. In the groundwaters of a district in Transbaikal they recorded normal contents up to 0.05 ppb Au; in and near the gold deposits the groundwaters ranged from 0.2 to 80 ppb Au. Increased amounts of Ag (2.6), Sb (600), As (250) and U (7.8) were found to accompany the gold in the groundwaters in or near the gold deposits, all values being in parts per billion.

Razin and Rozhkov (1963, 1966) carried out an extensive investigation of the gold content of the various ground and surface waters associated with the Kuranakh-type gold deposits in the Aldan Shield, Yakutia region, U.S.S.R. (*see also* the section on placers in Chapter III.) The deposits are in the permafrost region in a mountain taiga terrain. The water types differentiated in the area include those in unconsolidated recent formations above the permafrost; those above and interpermafrost in the Lower Cambrian rocks; and those below the permafrost in the Lower Cambrian and Archean rocks. The authors noted that the content of gold in the various waters depended on the pH and in particular on the content of ferric ions in aqueous solution. The gold is said to occur in both a dissolved form and as a suspension, with the latter predominating. Mildly acid waters leaching the most productive parts of the karst deposits contained an average of 0.001 ppm dissolved gold and 0.009 ppm suspended gold. The authors considered that hydrogeochemical methods utilizing gold as an indicator were suitable for prospecting for the Kuranakh (karst) type of gold deposits in permafrost areas.

Sal'e (1965*b*) also dealt with hydrogeochemical methods of prospecting in the area of the Kuranakh deposits. He found that the subsurface and surface waters contained from traces to 1 ppb Au and were commonly enriched in Tl, As and Sb. The Tl and As were mainly restricted to dispersion halos in the waters near the gold-bearing deposits, whereas Sb had a much wider dispersion. Sal'e concluded that Tl, As and Sb were good indicators of the Kuranakh-type deposits in hydrogeochemical surveys utilizing water as the sampling medium.

Borovitskii *et al.* (1966) also noted increased amounts of As, Sb and Tl in the Kuranakh area waters. In the surface stream waters near the deposits they found less than 0.03 ppb Au, and in the groundwaters in the mines and near the deposits they recorded gold contents ranging from 0.03 to 10 ppb, maximum concentrations being present in those waters high in dissolved manganese and iron.

Vsevolozhskaya (1966) used semiquantitative spectral analyses of dried residues from the subsurface waters of the Aldan area in U.S.S.R. in hydrogeochemical surveys. She noted the presence of some 20 trace elements in the residues and found that Ag, Sb and As were particularly good indicators for metasomatic gold deposits. She noted some factors that decreased the efficiency of hydrogeochemical methods based on groundwater analyses in permafrost areas including: high organic content in the waters; dilution due to heavy precipitation of rain water; and dilution due to thawing of the permafrost.

Goleva (1968, 1970) found that the best indicators of gold deposits in the waters of the Balei district, eastern Transbaikal, U.S.S.R. are Au, Ag, As, Zn, Pb and Sb. Auxiliaries under certain conditions include Bi, Cu, and SO_4^{2-}. In the groundwaters in fractures and fissures the backgrounds were Au$<$0.07;

Zn<20; As<50; Bi<0.1; and Ag<5, all in ppb. Anomalous groundwaters near gold-bearing deposits contained the following amounts of the various elements; Au>0.15; Zn>30; As>60; Bi>1.5; and Ag>10, all in ppb. In alluvial and surface waters the backgrounds were Au<0.05; Zn<15; As<2; Bi<0.05; and Ag<3, all in ppb. Anomalous alluvial and surface waters contained the following amounts of the various elements: Au>0.1; Zn>20; As>5; Bi>1.0; and Ag>6, all in ppb. During detailed hydrogeochemical surveys Goleva recommended that Au be determined in addition to the other indicators because water anomalies with a similar association of elements may be created by sulphide and tourmaline veins that are barren of gold in the area.

Gosling *et al.* (1971), using neutron activation, investigated the gold content of natural waters draining gold-barren and gold-enriched rocks in the Colorado Front Range. They found a relatively small range in the total gold content of the waters, from nondetectable to 0.150 ppb. 'Solute' or dissolved gold concentrations (average 0.010 ppb) were generally higher than particulate gold concentrations (average about 0.003 ppb), and both were found to be unrelated to rock or water types. The authors concluded that hydrogeochemical prospecting using gold as an indicator in waters is unpromising.

Since gold is commonly only present in natural waters in the parts per billion range and is difficult to determine accurately, it is probably advisable to use other indicators of its deposits. These indicators depend on their concentration in the gold-bearing deposits and their mobility in the ground and surface waters. For any specific area the effective indicators may be quite different from those applicable in another area. It thus follows that a pilot survey should be run in an area before extensive surveys based on water analyses are undertaken. During the actual surface survey all springs and stream waters should be analyzed carefully and the results plotted. Analyses of groundwaters from drillholes, wells and other sources can be effectively applied to outline hydrogeochemical halos associated with gold deposits of practically all types. Some of the techniques useful in this type of work are outlined by Boyle *et al.* (1971).

In my experience and judging from investigations reported in the literature the most effective indicators in natural waters of most types of gold deposits are Zn, Ag, As, Sb and Cu. Ni and Co may be useful indicators where the gold deposits contain these elements; similarly with U and Hg.

Cavender (1963) found the arsenic content of springs in the area of the Getchell Gold Mine in northern Nevada effective in indicating areas of potential gold mineralization and corroborated similar findings from soil sampling. He also observed that the arsenic concentration in an individual sample was helpful in classifying the type or mineralization source of the other trace metals, found in the water sample.

Adilov *et al.* (1971) used antimony as an indicator in subsurface water surveys of a gold belt in the Kuraminsk Range, U.S.S.R. They noted that the Sb content is 10 times higher in waters of the nonoxidized zone than in waters of the oxidized zone that contained 0.8 to 6.0 ppb Sb. The investigators concluded that Sb can be used as an element-indicator in the search for deep-seated auriferous deposits. Makarov (1972) used Sb, As, Au and sulphate ion as the indicators in hydrogeochemical prospecting for gold-antimony mineralization in northeastern Yakutia, U.S.S.R., and Loginova (1972) noted that waters associated with gold deposits in Bashkiria contain more silver than those associated with copper deposits. Skryabin (1968) found Mo a useful indicator in waters, Sal'e (1965*a*) noted that Tl was enriched in waters near the Kuranakh-type deposits, and Goleva (1970) concluded that Bi could be used under certain conditions as an auxiliary indicator in the Balei gold district, eastern Transbaikal.

Waters leaching gold deposits enriched in Li, K, Rb and Cs may have high contents of these elements because of their marked solubilities as the sulphates and other salts. Se and Te may occur in increased amounts in natural waters leaching deposits containing enrichments of these elements. Finally, the SO_4^{2-} content of waters may be an indication of the presence of sulphides in which gold may occur. However, great care must be exercised in interpreting SO_4^{2-} results since the sulphate may derive from quite barren pyritic bodies, pyritic schists, gypsum bodies, etc.

In a recent study Kolotov *et al.* (1975*a*) have indicated that zones of potassic alteration (metasomatism) associated with auriferous deposits are reflected by higher contents of K in the hydrologic regime. Their section shows that most zones enriched in gold give coincident anomalies in the water that are high in potassium.

In the auriferous Lena region of U.S.S.R. Polikarpochkin *et al.* (1974) found that sulphate ion in surface waters could be used in prospecting for gold deposits. The anomalies have a fair contrast and the sulphate dispersion is extensive in this region; hence, sampling at widely spaced intervals (1–3 km) is effective. They also noted that the As and Mo contents of water were suitable indicators of auriferous mineralization under certain circumstances. In the waters Au, Zn and Cu were not particularly useful as indicators of the gold deposits.

Jonasson and Allan (1973) have proposed snow as a sampling media in hydrogeochemical prospecting in temperate and permafrost regions. They noted that such metals as Hg, Zn, Cu, Pb, Ni, Cd and Mn occur in snow samples overlying buried mineralization and that the dispersion aureoles are usually quite broad, especially near massive sulphide deposits. The dispersion pattern of Cu and Zn in snow samples showed anomalous trends in the vicinity of the Joe Lake Gold Mine in southeastern Ontario.

Stream sediment surveys have proven their usefulness in prospecting for base metal deposits of all types in most terrains. In recent years these types of surveys, including those based on lake sediments, have been applied in the search for precious metal deposits, particularly those bearing gold and silver. The literature is replete with examples of stream sediment surveys executed under practically all conditions, geological and climatic, but no effort will be made here to review any of the work in detail. Some of the stream sediment investigations carried out mainly in gold-bearing districts that have come to notice during compilation of this chapter include those by Safronov *et al.* (1960*a,b*), Petrov (1962), Osokin (1962), Fedorenko (1962), James (1965), Mazzucchelli (1965), Sal'e (1965*b*), Nichol *et al.* (1966), Gleeson *et al.* (1966–1968), Garrett and Nichol (1967), Jasper (1967), Smith (1968), Eakins (1968), Hale and Govett (1968), Nickerson (1972), Brosgé and Reiser (1972), Bell (1973), Plant and Coleman (1973) and Gundobin and Kolesnikov (1974). Some of these investigators used gold as a direct indicator of its deposits; others employed various other indicators particularly Cu, Ag, Zn, Tl, Pb, As, Sb, Bi, Ni, Co, Mo and W. My experience suggests that of the last group of indicators the most specific for gold-bearing deposits are As, Sb and Ag.

A number of other indicators may be useful in stream, river, pond and lake sediment surveys where the primary deposits contain them in enriched amounts. They include Ba, U, Ni, Co, Cd, Hg, B, rare-earths, Se, Te and F. Increased concentrations of boron in stream sediments reflect the presence of gold-quartz veins and Pb-Zn-Ag lodes in the Keno Hill–Galena Hill area Yukon (Gleeson *et al.*, 1968). Boron is in fact a most useful indicator of nearly all types of gold deposits since the element tends to be enriched either in the deposits or in the associated wall-rock alteration zones (Boyle, 1971). However, care should be taken in interpreting geochemical surveys based on boron as an indicator of gold deposits since the boron from country rocks containing tourmaline, dumortierite, etc., resulting mainly from metamorphism or igneous intrusion, may confuse or mask the dispersion patterns from the deposits. Manganese minerals are commonly abundant in epithermal (Tertiary) gold-silver deposits. Warren and Delavault (1959) suggest the use of manganese as a pathfinder for these deposits in stream sediments, soil and biogeochemical surveys.

While conducting surveys based on analyses of natural waters or stream, river, pond and lake sediments the geochemist should be constantly on the alert for precipitates of all kinds at the orifices of springs, on stream bottoms or on the stones and rocks in the streams. These precipitates should be carefully studied and samples taken for analysis. Limonite- or wad-cemented conglomerates, composed of stones, sand, rock chips and vegetable remains should receive detailed attention. Where found they should be carefully mapped and sampled and their location analyzed with respect to springs and the groundwater systems of the area. In many places these bodies occur near springs issuing from faults that either contain auriferous deposits or intersect such deposits along their course.

Limonite, wad and other precipitates are commonly enriched in gold near gold-bearing deposits (*see* Table 22). Similarly they may also be enriched in the elements that accompany gold in its deposits. Particularly indicative of gold deposits are enrichments of the following elements in manganese- and iron-rich precipitates: Li, Cu, Ag, Sr, Ba, Ra, rare-earths, Zn, Cd, Hg, B, Tl, U, Pb, As, Sb, Bi, Se, Te, Mo, W, F, Co and Ni. Of these the best indicators appear to be Ag, Zn, Hg, As and Sb. The other elements are generally only effective indicators if present in appreciable concentrations in the primary deposits. Factors such as the mobility of the particular elements under the prevailing conditions of Eh and pH, organic activity, etc. are also significant. Kanurkov and Stefanov (1968) found that gold in limonite was a reliable alternative indicator element to Se or Te in certain auriferous deposits in Bulgaria. Limonite derived from auriferous pyrite and chalcopyrite averaged 1.2 ppm Au whereas that arising from oxidation of iron carbonates averaged only 0.016 ppm. Siliceous precipitates (Table 22) are often enriched in gold and in many of the elements accompanying it in its primary deposits. Such precipitates are frequently associated with hot springs and are hence not necessarily related to primary gold deposits. However, gold-bearing siliceous precipitates should be looked upon favourably since the waters from which they derived may have deposited gold along the underground channels by which the water reached the surface. Carbonate, barite and other types of precipitates (Table 22) rarely contain above normal concentrations of gold, but some may coprecipitate many of the elements that accompany gold in its deposits. All should be tested.

Frequently hydrous manganese and iron oxides, particularly the former, coating stream, river, pond and lake sediments cause anomalies due to adsorption and/or coprecipitation of the metals from stream, river, pond and lake waters. In areas where some streams are manganiferous and others not, this may be a disadvantage since the manganiferous streams tend to concentrate the metals from a normal background, giving false anomalies. On the other hand in areas that are uniformly manganiferous the concentrating action may be advantageous, and one can make good use of manganiferous and ferriferous sediments. In this respect it is desirable, therefore, when carrying out stream sediment surveys to take note of the quantity of manganese and iron oxides present and devise a qualitative index for each stream or part of a stream surveyed. If spectrographic or atomic absorption analyses are to be carried out on the stream sediments, both iron and manganese should be determined and plotted. Comparison of heavy metal maps with those of manganese and iron will reveal the effects of these two elements in concentrating the metals.

In gold-bearing areas manganese oxides (wad) coating rocks, etc. tend to collect gold (and silver). Iron oxides may do likewise if there is some arsenic or antimony in the environment. Analyses of these oxide coatings may, therefore, indicate the presence of gold mineralization in an area. The same can be said for humic precipitates in some areas and for aluminous and siliceous precipitates in others.

Heavy mineral surveys of surface drainage systems are particularly effective in prospecting for gold. The methods are essentially the same as those discussed for soils. The sediments of gulches, creeks, streams, rivers, lakes, seas, oceans and beaches are panned, and the heavy concentrates are collected and analyzed mineralogically or chemically. The work should be made quantitative by taking either a standard weight of sediment (a full pan or two for example) from which all or an aliquot of the heavies are analyzed, or by taking a standard weight of heavy minerals for analysis and referring the result back to the amount of gravel or sand from which the sample was obtained. Care must be taken in panning to retain the fine (flour) gold, otherwise the values obtained on analysis will be low. (*See also* the discussion on panning in a subsequent section on analytical methods.) The age-old technique of counting colours is often satisfactory, if gold alone is used as the indicator. In practice the sample size for obtaining the optimum amount of heavy concentrates for mineralogical and chemical work has to be determined in the field since the content of heavy minerals varies widely in stream sediments, lake sediments, beach sands, etc.

It should be emphasized that if the stream sediment is sieved before panning for heavy minerals or gold the best sieve size to give the optimum contrasting anomalies for the heavy minerals employed must be ascertained. This can only be done by pilot surveys in an area. This feature is critical for gold particles since in any given area these tend to a relatively uniform size. If too small a sieve size is used, the majority of the gold particles may be screened out with the result that the analytical results will show spotty and often spurious anomalies that have no bearing on the actual occurrence of gold.

Where moss abounds along stream courses and spring flooding occurs, it is often advantageous to obtain samples of the moss at regular intervals since this plant tends to mechanically collect fine (skim) gold. In many cases the gold can be washed out of the moss when dry and the colours counted; alternatively the moss can be ashed and the gold determined chemically or by fire assay.

If mineralogical work is done on the heavy concentrates, several mineral indicators of gold deposits can be used in following the dispersion trains, particularly native gold, platinoids, arsenopyrite, stibnite, native bismuth, scheelite, barite, limonite, etc. Excess amounts of rutile in stream and lake sediments may be an indicator of certain types of auriferous porphyry copper deposits (*see also* the section on Pedogeochemical methods). The discussion on the mineral associates of gold in Chapter III will suggest others. A good textbook, such as that by Raeburn and Milner (1927), and the mineral atlas by Guigues and Devismes (1969), both describing alluvial minerals, are recommended, and where possible X-ray methods of identification should be used to confirm visual determinations whenever possible. The frequency of occurrence should be determined for each indicator mineral at each sample site. An increase in the frequency of occurrence of the indicator mineral or minerals generally signals an approach to the source.

When analyses of the heavy concentrates are employed several techniques can be used such as analysis of the whole heavy mineral suite, analysis of magnetic and/or nonmagnetic fractions, analysis of specific mineral fractions such as pyrite, magnetite or limonite or those that lie within certain specific gravity ranges and so on. Gold is generally the best indicator, but other elements such as Ag, As, Sb, Cu, Pb, Zn, Bi, Se, Te, etc. can often be successfully employed. A knowledge of the elemental and/or mineral associates of gold in the deposits of an area is desirable in ascertaining which indicators are the most likely to yield positive results.

The light mineral associates of gold in stream sediments, lake sediments, beach sands, etc. can also be used in tracing secondary dispersion trains in drainage systems. Vein quartz, chloritic pebbles, carbonates, limonite, wad and the other light associates can all be used. Before attempting work on light minerals, however, it is desirable to study the nature of the vein quartz, carbonates, oxidation products and so on in the known gold deposits of a district in order that proper comparisons can be made between the minerals in the primary deposits and those in the secondary dispersion trains.

Placers of all types, except those deeply buried and not being eroded, can generally be located by employing stream sediment and heavy concentrate surveys. The best indicator of these secondary deposits is of course gold, but some of the other more specific indicators that may give a clue to the presence of gold placers are platinoids, Ba (barite), Hg (cinnabar), As (arsenopyrite), Sb (stibnite, sulphosalts), Bi (bismuth, bismuthinite), Te (tellurides), W (wolframite, scheelite), Cr (chromite) and Ti (ilmenite). Some of these minerals (elements) are present in much greater abundance than gold, and hence their trains have a relatively high contrast with the background and are easier to follow.

With respect to prospecting for placers it should perhaps be mentioned in passing that not all areas containing gold lodes contain placers and *vice versa*. In many districts the placer production varies inversely to that from lodes; the causes are manifold; for example in some districts the placers that were formed have been destroyed by glaciation or other geological forces and in other districts the veins and lodes have not been eroded deeply enough to yield their gold. Some deposits, the great Witwatersrand bankets for instance, yield no placers for reasons that are obscure. Finally, telluride deposits yield few placers as they are eroded. In both these cases the liberated gold may be of such a fine-grained nature (flour gold) that it is swept away and dispersed through great volumes of sediment.

Two problems frequently arise in the interpretation of gold anomalies found in drainage sediments. One is the distance that the gold has travelled and the other is the source of the gold. The first has no certain answer since the distance travelled by native gold is highly variable and depends on many factors such as particle size, gradient of stream, frequency of flash flooding and a host of other parameters all of which are discussed in some detail in the section on placers.

Flour or flood gold, being very fine grained (1000 to 5000 colours worth 1 cent) may travel for hundreds of miles. It tends to collect in the upstream parts of river and stream bars particularly those on the inside of curves. There and elsewhere in drainage systems and in deltas where there is slack water, gold anomalies can often be expected in gold-bearing regions. In fact these 'skim bars', so called by the old prospectors because they are replenished practically each year and can be skimmed of their gold quite easily, led to many a disappointment in the early days before their nature was clearly understood. They are common along a 400 mi stretch of the Snake River in western Wyoming and southern Idaho (Hill, 1915; Hite, 1933*a*, *b*), all along the Fraser River in British Columbia and along a great stretch of the North Saskatchewan River in Alberta. Flour gold is a troublesome feature in interpreting geochemical prospecting surveys using drainage sediments. Its source can rarely be ascertained since its migration is so extensive. Furthermore, it may cause innumerable anomalies that are veritable pitfalls for the enthusiastic geochemist. One may think one has discovered Eldorado whereas what one really has found is an enrichment of gold particles that may have come from a source 100 mi or more away. It is difficult to obviate the problem of flour gold, but there are two techniques which may prove useful. One is that flour gold generally has a very high fineness (>950) an indication that it has travelled far from its source or that it is not derived from primary deposits such as veins and lodes (*see below*). Determination of the Au/Ag ratio of the fine-grained gold may, therefore, be of some assistance in the interpretation stage of stream sediment and heavy mineral surveys in ascertaining the nature and source of the gold. The other technique that can be used to sort out anomalies due to flour gold far from its source is to analyze the stream sediment and/or heavy concentrates for the common associated elements in gold deposits, particularly As, Sb, Te, Bi, Ag, B, etc. If these do not support the gold anomalies by being present in higher than normal amounts, the gold has probably travelled far from its source.

Coarse gold (>1 mm) on the other hand generally remains relatively close to its source in veins and lodes. Since the turn of the last century there have been many estimates of how far coarse gold migrates from its source. Most agree that 5000 to 20 000 ft is about the length of the highly anomalous paystreak from the primary source of the gold under normal conditions. In the Kolyma River basin where the natural rock riffles (fissility) are aligned perpendicular to the stream flow, Gorbunov (1959) estimates that the distance the maximum amounts of gold have travelled from their primary source average from 700 to 1500 m (2300–4920 ft). Tuck (1968) states that studies indicate that during some 5000 ft of erosion, coarse gold (>1 mg in weight) liberated at the beginning of the erosion cycle does not travel more than 10 000 to 15 000 ft horizontally. These distances agree reasonably well with my investigations in the Yukon and elsewhere, and I conclude that the downstream vector of the movement of coarse gold derived from primary vein and lode deposits is small in most places, measurable in miles rather than in tens of miles. The immobility of gold is emphasized in some places. There are many records of the gold in Tertiary placers being not far removed from its primary source, commonly only a few thousand feet. Later (Quaternary) streams that have downcut through the Tertiary placers almost at right angles are, likewise, enriched within a few thousand feet of the secondary (Tertiary) concentration of gold.

The problem of the precise source of gold in stream sediments and other drainage deposits does not enter into the geochemical considerations if only gold placers are sought. It is, however, of fundamental concern if gold is to be used as an indicator of its primary deposits. As discussed in the section on placers there are two sources from which the gold in stream sediments may come – one is primary veins and lodes; the other is widespread disseminations in quartz veinlets, blows and in pyrite and other minerals in large volumes of rocks. In the first case, use of gold as an indicator of its deposits is entirely valid; in the second, suites of rocks that are only slightly auriferous will be outlined.

There is probably no certain way to differentiate gold derived from the two sources mentioned above. Some clues may be obtained from the fineness of the gold. In general gold derived from veins and lodes decreases in fineness (the ratio Au/Ag of the native gold decreases) as the source is approached. This is generally not the case with fine-grained gold derived from weathered pyrite and from widely distributed small quartz stringers and blows in various rocks. This type of gold is commonly high in fineness throughout the sedimentary system eluvium-alluvium. Gold derived from the weathering of tellurides and aurostibite in veins and lodes and from massive sulphide bodies where the gold is held as microscopic or lattice constituents of the sulphides is, however, also commonly very high in fineness throughout the sedimentary system, a complicating feature that should be borne in mind by the geochemist. The physical nature of the gold may also give a clue to its origin. Gold derived from quartz veins and lodes containing the element mainly as native gold exhibits an increase in the porosity, roughness and hackly appearance as the source is approached. The size of the gold particles generally also shows an increase towards the source. Gold derived from pyrite in rocks or in disseminated small quartz stringers, blows, etc. is generally very fine grained with a smooth appearance, except where extensive accretion into large grains and nuggets has taken place. Gold derived from sulphide bodies where the element is held mainly as lattice constituents of sulphides and sulphosalts or as microscopic particles in these and other minerals may be very fine grained or may be accreted and be similar to that liberated from disseminations in large volumes of rock. These features complicate the picture, but they should be clearly recognized by the geochemist. Commonly accretion nuggets and grains derived from disseminations in rocks or from sulphide bodies are much smoother and more gnarled than the rough hackly nuggets or particles liberated mechanically from their source in gold-quartz veins and lodes in which the metal is present mainly in the native state. Further clues as to the source of the gold may be provided by visual and microscopic examination of the gold and its associated minerals. For example flakes and small nuggets of gold with attached vein quartz, carbonates or limonite-wad (gossan) generally indicate a nearby vein source. The type and nature of the heavy mineral associates of gold may indicate the type of source. Thus, the presence of abundant relatively angular particles or crystals of arsenopyrite, stibnite, sulphosalts, tellurides, bismuth, bismuthinite, scheelite, wolframite, tourmaline, limonite-wad (gossan), etc. commonly indicates a nearby lode source. On the other hand well rounded particles of these mineral associates indicate a lode source at some distance from the sample point. Similarly, microscopic inclusions of pyrite, quartz, arsenopyrite, tellurides, bismuthides, etc. in the placer gold generally indicate a lode source, although care must be taken to differentiate when possible minerals included during nugget accretion processes.

Probably the best way of differentiating the two types of gold that may produce anomalies in stream sediment and heavy mineral surveys is to analyze the stream sediment and/or heavy concentrates for the commonly associated elements in gold deposits, particularly As, Sb, Te, Bi, Ag, B, W, etc. If these do not support the gold anomalies by being present in higher than average amounts, the gold has either travelled far from its source (either primary lodes or disseminations in rocks) or the gold has been derived from a large volume of rock through which it is widely disseminated.

The trace and minor element content of native gold in stream sediments and placers may be a clue to the primary source of the gold. Warren and Thompson (1944) spectrographically analyzed a wide variety of native gold samples, mainly from British Columbia and Yukon, but also from other parts of Canada and other countries and found that the amounts of various elements such as Ag, Cu, Fe, Mn, V, Ti, Hg, Pb, Bi, Te, As, Sb, Zn, Cd, Sn, Pd and Pt varied widely. From this they concluded that the differences are more related to metallogenetic zones or provinces than to any difference in the type of deposit in which the gold is found. They thought that by detailed analytical work gold could be used as a pathfinder and that it should be possible to determine the metallogenetic province or zone, and in some cases even the deposit from which a particular sample of gold originates.

Fisher (1945, 1950) in two classic works on the fineness of gold states that the uses to which a knowledge of gold fineness can be put are manifold. Thus, the relative importance as sources of gold of the various areas drained by different streams can be assessed with some accuracy; similarly sudden changes in the fineness of gold along a stream may indicate the presence of important new sources of primary gold; and in areas where the fineness of gold associated with each type of intrusive has been well established, the fineness of the native gold not only gives one a definite lead towards its source, but may also indicate its probable geological associations and the type of deposit to be searched for.

Mustart (1965) carried out a study of trace and minor elements in the alluvial gold of the Dawson and Mayo (Dublin Gulch–Keno Hill–Highet Creek) areas, Yukon. The elements determined semiquantitatively by spectrographic methods in the placer gold included Ag, Cu, Fe, Sn, Hg, Pb, As, Sb, Bi, Zn and Mn. He found that certain assemblages of trace elements particularly Zn, Bi, As and Sb show a characteristic distribution and can often be correlated with the presence of known mineralization in the area. Thus, Zn, As and Sb were markedly concentrated in the Mayo samples indicating the characteristic Zn, As and Sb mineralization of this area. In the Dawson area these elements were present in only low amounts again indicating the general weak Zn, As, Sb mineralization of the Klondike.

Desborough (1970) and Desborough *et al.* (1970) examined placer gold grains from numerous localities in the western United States and Alaska for their silver and copper content and their mineral inclusions, mainly sulphides, by electron microprobe. Their work is detailed and merits close study. Briefly, they noted that the variation in the copper and silver content among grains from a particular locality is large, but that the mean silver content of the interior of the placer gold grains from each locality and (or) the variation in copper content may be of value in distinguishing lode sources and gold mining districts. Thus, microprobe analysis shows that the interior of gold grains is independent of chemical actions that affect the border of placer gold grains during their transport history, and it is evident that distinct compositional groups of different lode sources may be identified even in a single sample – information that may aid in recognizing the existence of concealed lodes that once contributed to a placer environment.

Antweiler and Campbell (1976) noted that the composition of native gold, i.e., its 'signature', may be a useful guide in mineral exploration since the mineral is associated with a great variety of ore deposits and has characteristic signatures for each of several types of deposits. These signatures comprise distinctive contents of Au, Ag and Cu, a unique suite of trace elements that includes Pb, Bi, Sb, As, Te, Zn, Sn, Cr and Ni, and characteristic Au/Ag and Au/Cu ratios. The authors list a number of ore deposits in the United States in which the gold has characteristic signatures, including porphyry copper, pyrometasomatic, contact metamorphic and hydrothermal vein deposits. They also noted that signatures of gold from the Central City district, Colorado correlate with zoning patterns. In this district the silver content of gold was found to increase from a low of 5 to 10 per cent in the central, productive high-temperature zone to a high of 35 per cent in the nonproductive low-temperature zone, whereas the copper content of the same gold samples decreases from a high of 500 to 1000 ppm to less than 100 ppm. From this the authors concluded that the silver and copper contents of gold may identify the zonal position of a vein and thereby help to predict its potential productivity. Finally, Antweiler and Campbell (1976) noted that another application of gold compositional data is in tracing placer gold to its bedrock source. As an example of this they mentioned the Tertiary quartz monzonite Montgomery Gulch stock in the Tarryall district in Colorado. There, the silver content of placer gold in the district differed from that of nearly all of the bedrock sources of gold found by early prospectors. However, one scarcely prospected area peripheral to the Montgomery Gulch stock was found to contain gold with a silver content similar to that of the placer gold. This area is thought by the authors to be the most likely source of gold in the productive placers and is a potential exploration target.

Comparisons of the internal structure of gold as observed microscopically following etching or other treatments may be a clue to the source of the stream or placer gold if sufficient control samples of both primary (lode) and secondary (placer) gold are available from a specific area. If control samples of the lode gold are not available comparisons cannot be made, and hence interpretation of the source may be difficult if not impossible since the internal structure of stream (placer) gold depends on many factors that are discussed in Chapters II and III. Those contemplating work on the internal structural characteristics of gold should consult the papers by Fisher (1935), Valpeter and Davidenko (1970) and Petrovskaya (1973).

The results of a number of heavy mineral surveys carried out in auriferous regions have been described in the literature. These are briefly summarized in the following:

Overstreet and Bell (1960) carried out a geochemical and heavy mineral reconnaissance of the Concord SE quadrangle, Cabarrus County, North Carolina. The sample points were widely spaced, generally one sample per stream tributary. Gold placers and vein deposits are known in and adjacent to the quadrangle. Gold and scheelite were used as indicators during the survey, gold being identified visually and scheelite by its fluorescence (ultraviolet radiation of 2500 Å wavelength). The authors concluded that the geochemical and heavy mineral reconnaissance provides a rapid and inexpensive method of locating high-background areas as a first step in the exploration for ore deposits.

Heavy minerals collected from the stream sediments in the Chinkuashih area of Taiwan by rocker were used by Li-Ping and Fang-Sung (1968) in prospecting for gold and copper deposits. The indicators chosen were native gold, barite and pyrite, which occur in the primary deposits. The distribution pattern of the native gold indicated an anomalous area of about 10 km², including all the known gold and copper deposits in the Chinkuashih area. No native gold was found in the heavy mineral samples outside the known or potential mineralized areas. The copper content of pyrite in the vicinity of copper deposits was found to be high (1100 to >1700 ppm), relatively low in and near gold deposits (40–480 ppm) and low in and near coal beds (100–120 ppm).

Analyses of nonmagnetic parts of concentrates panned from arroyo sediments near the Monticello Box, northern Sierra Cuchillo, Socorro County, New Mexico were used by Griffitts and Alminas (1968) to indicate possible concealed mineral deposits, mainly those of gold and silver in Tertiary volcanic rocks and in Paleozoic limestone. Concentrates southeast of Monticello Box were found to be anomalous, containing as much as 2 per cent Pb, at least 0.2 per cent each of Mo, Zn and Cu, and anomalous amounts of Ba and Ag. Te was found in the part of the original samples that passed through an 80-mesh sieve, but this material was found to be less useful than the concentrates in outlining the anomalies.

Fischer and Fisher (1968) experimented with panned concentrates from streams in the northwestern part of the San Juan Mountains, Colorado. The concentrates were analyzed for gold by the fire assay–atomic absorption method. Three types of areas where chosen for study (1) 'barren' areas, where gold mineralization might be geologically possible, but no deposits are known; (2) slightly mineralized areas that contain only a few known veins and prospects and small mines; and (3) well-mineralized areas that contain numerous veins and some very productive mines.

The results of the survey indicated that replicate analyses of large samples were consistent enough to permit placing considerable confidence in the results obtained for smaller samples on which only one analysis was made. For general field practice, it was necessary to pan enough sand and gravel to yield about 15 g of concentrate. The analytical results obtained were also quantitatively compatible with known geologic relations and indicated that a few samples from a stream are adequate to distinguish between 'barren' and mineralized areas and to determine the relative amount of gold in mineralized areas.

Guigues and Devismes (1969) carried out an extensive heavy mineral survey of the Precambrian Massif Armoricain in France, one of the indicator minerals being gold. They display a map showing marked concentrations of alluvial gold in Brittany in the Fosse Centrale Amoricaine and in Normandy, the native metal being localized both at the border and some distance from granitic bodies. The Paleozoic Châteaulin Basin is also shown as having concentrations of alluvial gold. This report is a fine example of how to carry out heavy mineral surveys, and in addition contains an excellent alluvial (heavy) mineral atlas.

Panned concentrates have been used extensively for many years in U.S.S.R. apparently with considerable success (Sigov, 1939). Two recent investigations of interest based on gold and associated heavy minerals include those by Gurev (1970) and Zavorotnykh (1971, 1972). Komov (1966) mentions that panning and heavy mineral studies have been used effectively together with other geochemical and geophysical methods in prospecting for primary gold deposits and placers in the Yenisei Range, U.S.S.R.

The gold content of the heavy mineral concentrates of stream sediments in the Keno Hill area, Yukon was investigated by Boyle and Gleeson (1972). The concentrates were analyzed for gold by the fire assay–atomic absorption method. The results of the survey showed that the gold contents in the heavy mineral concentrates reflect the presence of four northeast-trending vein systems, two being known and two being suspected from the data obtained. These comprise an early gold-bearing pyrite-arsenopyrite assemblage and late pyrite-galena-sphalerite-freibergite lodes. In some systems the former predominate; in others the latter are well developed. All of the known gold placers of the area were indicated by high gold contents in the sediments, and some streams, not known to contain placers, were found to have relatively high gold values.

A heavy mineral survey was carried out by Good *et al.* (1973) in two areas (one mineralized and the other barren) in the northeast striking gold–base metal belt in Goochland, Fluvanna and Louisa counties of the Central Piedmont of Virginia, United States. The heavy mineral fraction obtained by sieving and panning 20 lb samples of stream sands was analyzed for gold by atomic absorption. Samples of concentrate from the mineralized auriferous region yielded values greater than 100 ppm Au in the immediate vicinity of the Shannon Hill–Caledonia cluster of mines and 10 to 100 ppm Au up to 1 mi downstream. Farther downstream the values were less than 1 ppm Au in the concentrate. In the barren area only 10 samples out of 128 reported gold contents greater than 1 ppm, the highest being 7 ppm. The heavy mineral survey proved more effective for delineating gold mineralization than reconnaissance surveys of soils, mull (humus), leaf ash or ordinary sieved stream sands. Further details of this survey are given in a later paper by Good *et al.* (1977).

Ocean sediments were tested for gold along the southeast coast of Nova Scotia in 1968 (Libby, 1969). Samples were obtained by a unique drilling method employing a high pressure water jet stream pipe and an air lift pipe for vacuuming the hole cuttings and conveying them to the ship through hoses. On shipboard the samples were passed over riffles in a sluice box, and the gold and heavy minerals were collected for study and evaluation. The survey outlined three significant marine placers off the Ovens Peninusla with a combined total volume of 42 million yd^3 of auriferous material. Other investigations concerned with recent marine placers are outlined in the section on placers in Chapter III.

Gold placers and stream sediments enriched in gold may indicate the presence of various types of metalliferous deposits, particularly massive sulphide bodies, polymetallic lodes and porphyry copper deposits. There are numerous instances of these circumstances in the Canadian Cordillera, one striking example being the Casino porphyry copper deposit in Yukon (Archer and Main, 1971). In the western United States and Mexico several of the great porphyry copper desposits had associated gold placers, a good example in Utah being the placers in Bingham Canyon and tributary drainages, which were derived mostly from oxidized copper and lead-zinc-silver ores (Johnson, 1973*b*). Learned and Boissen (1973) have pointed out that gold is a useful pathfinder element in the search for porphyry copper deposits in Puerto Rico. One could go on at great length relating the presence of gold placers as indicators of metalliferous deposits but this seems unnecessary. Figure 67 shows clearly that the distribution of gold placers marks metallogenic zones throughout the world where glaciation has not been severe. Even in glaciated areas the gold content of till, stream sediments, etc. often indicates the presence of metalliferous deposits.

Biogeochemical methods

The biogeochemistry of gold is discussed in some detail in Chapter II where it is stated that the gold content of most plants, animals and their fossil residues is low. For plants the normal range is 0.005 to 0.10 ppm in the ash; for animals <0.0001 to 0.02 ppm in the dry matter; and for coal, petroleum and other fossil organic materials <0.05 ppm in the ash. In general it can be said that the gold contents of flora and fauna tend to exceed the norm by a factor of 2 or more in the vicinity of gold deposits.

Prior to 1950 the analytical determination of gold in organic materials was plagued by many difficulties, and the results are semiquantitative at best. In recent years the determination of gold in organic materials by neutron activation and fire assay–atomic adsorption methods is more reliable but still beset with a number of problems. Because of sampling problems and analytical difficulties biogeochemical methods have not been widely used in prospecting for gold deposits.

The techniques employed in biogeochemical surveys are varied. One technique employs the indicator qualities of certain plants and animals; another utilizes analyses of plants and animals for gold or its indicator elements in the search for deposits; and still others employ analyses of fossil residues of plants and animals, canine sniffing and so on. The methods and procedures employed in biogeochemical prospecting are discussed at length by Brundin (1939), Thyssen-Bornemisza (1942), Viktorov (1955), Cannon (1960), Malyuga (1964), Nesvetaylova (1970) and Brooks (1972).

There are probably no indicator plants that are specific for gold (or silver), although some plants may be specific indicators of soils or waters rich in As, Sb, S, Se, Te, Cu, Mn and other elements that commonly accompany gold in its deposits. A discussion of these indicator plants, however, lies outside the scope of the present treatise. The interested reader should consult the works of Sykora (1959), Chikishev (1965), Nesvetaylova (1970) and Brooks (1972).

Lidgey (1897) and Dorn (1937) mention a number of plants that are reputed to be indicators of gold and silver-rich areas. In Brazil *Crecropia laetivirens* Hub.; *C. palmate* Willd; *C. lyratiloba*; *Alpina speciosa* Schum.; *Typha latifolia* L. (cattail) and *T. dominguensis* Kunth, all containing gold in their ashes, are reported to be gold indicators, and it is said that *Eriogonum ovalifolium* (buckwheat family) is a silver indicator, which led to the discovery of several silver deposits in Montana. Sykora (1959) made brief reference to a number of plant indicators for gold and silver, and Carlisle and Cleveland (1958) gave a list of sampler plants for silver and other elements. There are also some very interesting references to indicator plants for silver and gold in old Chinese writings (Needham, 1954, 1959). For instance, it is stated that the *tshung* plant (the ciboule onion, *Allium fistulosum*) is an indicator for silver, and the *hsiai* plant (*Allium bakeri*) indicates gold. Sykora (1959) quoting others says that certain psammophytic (silica-loving) plants may be indirect indicators of gold deposits. He further remarks that the early prospectors in California were guided in their search for placer fields by certain psammophytic shrubs, which in spring are especially visible from great distances on account of their white flowers. He does not name the shrubs.

There are no references in the literature to chlorotic or other effects, if any, induced in plants by soils enriched in gold (or silver).

Since 1950 a number of investigations using analyses of plants in the search for gold-bearing deposits have been described in the literature. Some have employed gold directly as the indicator element; others have used arsenic and other elements that commonly accompany gold in its deposits.

Warren and Delavault (1950) examined the gold and silver content of some trees and horsetails in British Columbia; a gold-bearing area (north fork of Watson Creek) and a number of areas barren of gold were chosen for the study. In the former, the ash of horsetails, Douglas fir, aspen, willow and dwarf juniper contained from 0.17 to 1.02 ppm Au; in the latter the recorded gold values did not exceed 0.03 ppm. The corresponding silver values were: positive area, nil to 0.39 ppm; negative areas, 0.10 to 1.40 ppm. Some of the negative areas (i.e., barren of gold) contain silver-rich deposits, e.g., Sullivan Mine. More recent work by Warren and Hajek (1973) in an auriferous zone in the Stirrup Creek area (a northern tributary of Watson Bar Creek) has shown that stems of white pine and Douglas fir contain from 0.50 to 0.60 ppm Au in the ash. In addition Mountain Phacelia (*Phacelia sericea*) contains from <0.01 to 1.20 ppm Au in oven-dried material. This plant also reports tellurium in amounts ranging from <0.05 to 3.5 ppm in oven-dried material.

Razin and Rozhkov (1963) investigated the gold content in the ash of a number of whole plants and roots over the Kuranakh ore deposits, Yakutia (*see* the section on placers in Chapter III for a description of these deposits). The plants chosen for study were varied and included larch, pine, birch, alder, poplar, rosemary, blueberry, horsetails, mosses, etc. Outside the mineralized zones gold was not generally detected in the ash of these plants. Within the confines of the ore zones the average gold content of the plant ash was about 0.45 ppm. Details should be sought in the original publication. The authors concluded that analyses of plants for Au (and Cu and Zn) are effective for outlining zones in the rocks enriched in gold. (*See also* the section on pedogeochemical and hydrogeochemical methods where the results of these surveys in the district of the Kuranakh deposits are described.)

Warren *et al.* (1964) used arsenic in the ash of Douglas fir (*Pseudotsuga menziesii*) as an indicator of Au, Sb, Pb and Zn mineralization in British Columbia. They noted that in unmineralized areas the ash of Douglas fir seldom carried more than 2 ppm As; in the vicinity of mineralization arsenic contents in the ash ranged from 7 to 10 000 ppm, the values being higher in the present year twigs. In addition, most of the biogeochemical anomalies were more marked than the pedogeochemical. In a later paper, on the same subject Warren *et al.* (1968) found that Douglas fir commonly contained 10 to 100 times more As in its ash than any of the trees and lesser plants normally associated with it. An analysis of all of their data indicated that in areas where there is no known arsenical mineralization, the ash of first year Douglas fir twigs will generally contain less than 100 ppm As. In the vicinity of mineralization the ash contains from 100 to >1000 ppm As. First year needles and all older growth generally carry much smaller amounts of arsenic than first year twigs.

In India, Dekate (1971) has carried out a number of investigations of gold in soil and plants in areas of gold mineralization. He found gold enrichments in humus-rich soils developed on zones of gold mineralization and noted that plants producing hydrocyanic acid such as *Sorghum saccharatum Pers* are capable of preferentially absorbing gold from the soil, at times, to the extent of depleting the gold in the soil in the proximity of plant roots (*see also* the section on biogeochemistry in Chapter II). Dekate (1971) concluded that cyanogenic plants could be used advantageously in biogeochemical surveys mounted to prospect for gold in areas of gold mineralization.

A number of surveys utilizing analysis of plant ashes for gold and its indicator elements have been carried out in the arid desert areas (Tamdytau, Kyzylkum, etc.) of Uzbekistan, U.S.S.R. in the search for gold deposits (Khamrabaev *et al.*, 1965; Aripova and Talipov, 1966; Talipov, 1968; Talipov *et al.*, 1968; Talipov *et al.*, 1969; Talipov *et al.*, 1971; Glushchenko *et al.*, 1973; Talipov and Khotamov, 1973, 1974). The region is one where the gold deposits contain abundant arsenic and where the surface is covered with from 3 to 5 m of residual materials and loose rock. The vegetation includes many desert varieties principally wormwood (*Artemisia*) perennial grasses, saltwort (*Salsola*), *Lagochilus intermedius* and giant fennel (*Ferula*). The ashes of *Artemisia* proved to be the best sampling medium, but other plants were useful in certain areas. Over buried gold deposits up to 85 ppm Au was found in the ash of *Artemisia,* and this herb was also commonly enriched in As and Sb. In general the ashes of the desert plants were manyfold higher in gold in gold-bearing areas than the corresponding plants in background areas, most plant ashes contained from 40 to 150 times the amount of gold in the surface soils and residuum. Elevated contents of Sb, Ag, Pb, Cu, Zn, Cr, Ni, Sn and Mo were detected in a variety of plant ashes in a number of areas containing gold mineralization, and As was found to be much higher in content in the plants in gold-bearing areas compared with its normal abundance in plants. In a number of places a direct correlation between the As and Au and Sb and Au contents of the ash of plants was noted with the presence of gold-bearing deposits. Most authors concluded that the biogeochemical method is superior to the lithogeochemical methods of prospecting in the deserts of Uzbekistan and Kazakhstan. The best time for sampling was found to be in April and May while the plants were blooming. Later in the summer, and in September and October, the conditions were unfavourable for sampling and biogeochemical surveys in general. Other details should be sought in the original papers.

A number of investigations involving the determination of gold in plants by neutron activation have been carried out in Austria, Hungary and Czechoslovakia by Schiller *et al.* (1971*a*) and Kaspar *et al.* (1972). At Bockhard, Austria, *Aconitum napellus* growing near a tunnel in an old gold mine contained 60 ppb Au (in the dry plant), whereas samples taken from an area about 2 km distant had only 15 ppb Au. *Allium victoralis* (garlic) collected in the same localities contained 20 and 6.5 ppb Au respectively. In the Jilové area, some 20 km from Prague, gold occurs in gold-quartz veins and silicified zones in mica schists near a granodiorite pluton of Paleozoic age. Profiles of plant samples across the veins showed that the plants contained 8 ppb Au (in the dry plant) over the vein zone and from 1 to 3 ppb Au at distances ranging from 1 to 4 km from the zone. Shallow rooted plants and shrubs proved to be the best sampling media; deep rooted trees were unsuitable. In a later communication Schiller *et al.* (1973) reported that studies on maize and grass plants showed that the highest gold collecting efficiency was in the spring, probably caused by factors such as intensive uptake of elements by plants during this season, a higher rainfall and a more intensive movement of subsurface waters. Finally, these investigators stress the importance of further research in order to place biogeochemical surveys for gold on a quantitative basis since it is still uncertain how and under what conditions gold is taken up by plants.

In the Donets Basin of U.S.S.R., Dvornikov *et al.* (1973) examined the biogeochemical dispersion halos of a number of chalcophile elements (Pb, As, Ga, Ge and Tl) in 10 species of plants growing on auriferous deposits. The concentrations in fescue (*Festuca sulcata* Hack), *Euphorbia esula* and *Artemisia campestris* L. were higher than in any of the other seven species examined. The authors recommended that *F. sulcata* and *A. campestris* could be utilized as indicator plants in prospecting for auriferous deposits.

In the permafrost regions of U.S.S.R., Pitul'ko (1973) states that the analyses of tree leaves or aqueous extracts from these leaves can be used in prospecting for tin and gold placers. The best indicators proved to be Mo, B, Ag and Ti.

Quin *et al.* (1973) investigated the efficacy of plant and soil indicators of quartz reefs, some auriferous and argentiferous, in the Maratoto Valley, New Zealand, the species analyzed being *Berilschmiedia tawa, Brachyglottis repanda* and *Dysoxylum spectabile*. They established that the best indicators of the reefs were elevated silver concentrations in the A horizon soils; a 'negative mercury anomaly' of less than 0.23 ppm in the B horizon; low values of chromium and magnesium in C horizon soils; and elevated copper concentrations in all three species studied. The high copper levels they thought, were associated with the presence of this element in silver ores in the area and the negative mercury anomaly may be due to loss of this element at the temperature of formation of the reef. The low values of chromium and magnesium probably reflect the lower concentrations of these elements in the lodes than in the andesitic country rocks.

The recent paper by Talipov *et al.* (1975) on the use of gold in plants as a prospecting aid in the Chatkalo-Kuraminsk region, Uzbek S.S.R. contains much of interest. They noted that the accumulation of gold (and a number of other elements) in plants depends to a large degree on the concentration of the element(s) in the groundwaters. They also observed that some elements have an antagonistic effect on the uptake of certain elements in plants; thus high calcium contents in groundwaters decreased the migration of gold and hence its accumulation in plants.

In a further paper on the gold and antimony distribution in plants in the auriferous Chatkal-Kuraminsk region Talipov *et al.* (1976) observed a direct proportionality between the gold and antimony contents, a relation that they concluded could be used in surveying the potential of gold deposits in the eastern Almalyk area. Certain plants such as *Spiraea* and honeysuckle were found to accumulate large amounts of gold when growing in the vicinity of the auriferous deposits. Also in the Almalyk area (Talipov *et al.* 1974) a linear correlation was observed between the chemical composition of plants, soil and water and the content of Au, Ag, Cu, Zn and Pb. Soil, water and plant ashes from the auriferous deposits had 2 to 10 times the Au content of the auriferous zones of the Cu-Mo and complex ore deposits. The highest Cu, Ag and Pb concentrations were observed in southern Almalyk plants. The authors concluded that the good correlation between plant composition and metal distribution indicates that a biogeochemical method can be used in prospecting for Au and Cu-Mo ore deposits on the northern slope of the Karamin Range.

At the Ogofau Gold Mines, Dyfed Wales the gold orebodies are quartz veins containing auriferous pyrite and arsenopyrite in Silurian and Upper Ordovician shales and siltstones. The veins also contain abundant hydromuscovite, minor galena and sphalerite and rare cookeite (Li silicate). Six species of vegetation (birch, oak, hazel, ash, hawthorn and gorse) from the Ogofau area were sampled by Steed *et al.* (1976) and analyzed for Pb, Zn, Rb, Mn, Cu, Ni and Fe during a pilot survey. The results showed a marked dependence on the species and to a lesser extent on the type of plant material (twigs, leaves, bark), aspect and seasonal effects. Two year old twigs were the most satisfactory sampling materials. Birch trees gave the greatest anomaly contrast and magnitude, and these were used in the main survey, being supplemented by oak trees to cover areas where birch trees were absent. Rubidium reflected the pattern in the soil and proved to be the most useful pathfinder for the auriferous mineralization. Further details should be sought in the original paper.

The gold content of plant juice is recommended as an efficient method of prospecting for auriferous deposits by Kyuregyan and Burnutyan (1972). In the Zodsk gold belt, Armenian S.S.R., they found that the gold content of the juice from several plants was significantly higher than that in aqueous extracts of the plants or soil. The technique for obtaining and analyzing the plant juice is given in the original paper.

Krendelev and Pogrevniak (1977) have suggested another novel way of prospecting for gold deposits utilizing the analyses of birch tree sap. One of the advantages of the method over conventional biogeochemical methods cited by the authors is that the results of the sampling require no corrections for the time of sampling since the flow of the sap in the spring begins and terminates at the same times over large regions. Another advantage cited is the widespread occurrence of birch forests in U.S.S.R., a feature that should also apply to other countries in the northern latitudes such as Canada, Finland, Sweden and Norway. Further advantages are the simplicity of obtaining and processing samples and the fact that the sap is a ready-made natural metal-bearing solution that can be subjected to activation analysis and atomic absorption analysis without any preliminary preparation. Samples of sap obtained by tapping the birch *Betula platyphylla* were taken during the spring sap run along profiles across a pyritic gold deposit in western Transbaikal. The gold content of the sap varied from 1.5 to 133.0×10^{-9} g/l, the higher values clearly coinciding with anomalous gold contents present in the secondary lithochemical (soil) halos over the deposit.

The utilization of sap as a sampling medium should be applicable to regions that have a widespread distribution of certain species of tree. The maple and various conifers come to mind in Canada, and these and other species should be considered as sampling media elsewhere.

Organic deposits such as bogs, muskegs and marshes are commonly enriched near gold-bearing deposits in many of the elements associated with the gold, particularly Cu, Ag, Ba, Zn, Hg, Pb, As, Sb, U, Se, Te, Mo, W, Co and Ni. Gold may show slight enrichments in these organic deposits, but so far as my experience goes they are not marked. Where bogs are found enriched in metals and other elements commonly found in gold deposits, the source of the metals should be sought by tracing their dispersion in the surface or underground water courses that debouch into the organic deposits. The bogs may overlie the auriferous deposits or their distribution pattern may take the form of halos or partial halos about mineralized zones.

In rocks containing coal fragments, carbonized plants or thin coal seams the general presence of auriferous mineralization may be indicated by higher than normal amounts of gold in the coaly materials, but more generally by the indicator elements found in auriferous deposits. During surveys using these carbonaceous materials samples of the coaly fragments, beds, etc. should be collected whenever found in outcrop or drill core, ashed and analyzed for gold, silver and their indicator elements. The results should then be plotted on plans and sections of the geology of the area in which the work is being carried out. Such representation may reveal general zones of mineralization or stratigraphic members that enclose auriferous deposits. It should be cautioned in passing that coaly materials tend to concentrate numerous chalcopile elements and other indicators of gold from groundwaters traversing relatively barren rocks. In general, coaly fragments in barren areas are not as highly enriched in the various indicator elements as those in mineralized areas. By using pilot surveys and one's experience it is usually possible by judicious screening to eliminate those samples that indicate mineralization from those that are ordinary natural collectors of stray amounts of As, Sb, Te and other indicator elements from circulating stratal waters.

Bitumen and various solid hydrocarbons particularly anthraxolite and thucholite can be used as sampling media in the manner just described above for coaly fragments. It should not be forgotten that the great bulk of the gold of the enormous Witwatersrand deposits is either in or closely associated with thucholite.

Two novel ways of utilizing biological agents in prospecting for gold have recently been advocated. One involves the use of termite mounds in Rhodesia and the other is concerned with 'man's best friend' the dog.

'Termite prospecting' has received considerable attention in Rhodesia, particularly in areas covered by Kalahari sand (Chamber of Mines Journal, Rhodesia, 1968, 1969*a,b*). The termites are thought by some to bring particles of mineralization up from depth and deposit them in their mounds. Analyses of the mounds for gold and its indicator elements may, therefore, reveal anomalies that are related to auriferous deposits. It appears, however, from the work by Watson (1970) that termites do not bring up mineralized material rich in zinc from depth, but rather that this element, as well as copper and lead, move upward in the soil solutions in Kalahari sand. Watson concluded from this that it is possible to prospect for hidden deposits by standard geochemical techniques, and that no advantage is gained by sampling termite mounds. In a more recent article concerned with gold in the Rhodesian termite mounds Watson (1972) concluded that: "The passage of termites through a gold-bearing fissure in the Basement Complex at 23 m depth and the presence of anomalous concentrations of gold in the 3 m thick overburden of Kalahari sand suggest that termites may have carried material containing gold from gold-bearing fissures in the Basement Complex to their mounds at the surface whilst excavating galleries to the water table at about 27 m depth. Subsequent erosion of mounds would have dispersed the gold in the surrounding soil. However, the difference between the mean concentrations of gold in termite mounds and soils is small and not statistically significant. It is, therefore, probable that the gold in existing termite mounds was derived mainly from soil carried by termites from less than 3 m depth in the course of constructing their mounds."

A further contribution to geochemical prospecting using the metal content of termite mounds is provided by d'Orey (1975). In central Mozambique he found that the copper and nickel contents in termite mounds of the *Macrotermitidea* family were enriched above a group of known copper deposits that are hidden by deep transported soil and were not revealed by geophysical and normal soil sampling surveys. d'Orey noted that sampling of termite mounds is also excellent for discriminating between different types of geological formations and, in the area investigated, for distinguishing between extrusive and intrusive serpentinites. He concluded that the sampling of termite mounds is a valuable supplement to established geological methods of prospecting, and recommended further investigation of the technique in places where there are deep-penetrating termites.

Dogs have long been known to have an acute sense of smell and were used to sniff out such objects as mines and other explosives during World War II. It is only natural that the scenting ability possessed by man's best friend should be turned to more peaceful pursuits, but it is not clear who first suggested the use of dogs to sniff out float boulders of oxidizing sulphides. Apparently the idea developed in Russia and Finland about the same time, probably in the early 60's. In Finland Dr. Aarno Kahma of the Geological Survey of Finland conceived the idea in 1962 that dogs should be able to scent ore boulders and thereby aid in outlining ore boulder trains and fans. Subsequently, dogs were trained in Finland, Sweden and Canada for this purpose. The method of training and the problems involved in using 'prospecting dogs' are outlined in some detail by Orlov *et al.* (1969), Brock (1972) and Nilsson (1973). It would appear that the use of dogs in prospecting for auriferous deposits is most effective where the deposits contain abundant sulphides.

Finally, Pagliuchi (1925) records an interesting case of the biogeochemical association of a bird, a particular tree and the occurrence of gold in southeastern Venezuela. He called it a "Feather guide to gold" and says:

> While engaged in the examination of the above-described mines and prospects, I constantly heard the sharp cry of a bird which is seldom seen, as its habitat is in the dense foliage of tall trees. The bird is gray in colour and about the size of a robin. It is called "El Minero" (the Miner). The natives informed me that this bird is always found in the vicinity of gold mines or whenever quartz is abundant. Thereafter, as I rode through the country, whenever I heard the cry of El Minero either I saw a quartz ledge extending across the trail or was able to find one by looking about a little. Apparently the natives were correct. Why the affinity which seemed to exist between bird and quartz ledges? My investigations and attempts to solve the mystery left me still puzzled. Finally a miner told me that if I wanted gold I must always look for the Mora tree. He pointed out to me some trees which grew next to the quartz ledge that I was examining at that moment. Then the solution of the puzzle dawned on me. The Mora tree grows and thrives only in siliceous-ground, and El Minero feeds on the berries of this tree; hence whenever his cry is heard, one is assured of finding a quartz vein in the vicinity. Of course the quartz may or may not be auriferous, but when prospecting in a country known to be auriferous, it must be admitted that the bird is a helpful guide to the prospector.

Atmogeochemical methods

The ascent of warm exhalations from fissures in the earth, often containing mineral deposits, has been observed for centuries. Agricola writing in his classic, *De re metallica* says: "Further, we search for the veins by observing the hoar-frosts, which whiten all herbage except that growing over the veins, because the veins emit a warm and dry exhalation which hinders the freezing of the moisture, for which reason such plants appear rather wet than whitened by the frost."[34]

Gases associated with mineral deposits form both mobile and static gaseous aureoles. Four principal origins for the gases can be recognized:

1. Those that form mobile gaseous aureoles due to radioactivity, oxidation of mineral constituents or in certain places to present day metamorphism of mineral constituents. The gases produced are He, Rn and Ar in the case of deposits containing the radio-elements Th, U and K, and SO_2, H_2S, other thiocompounds, CO_2 and various volatile metallic organic and inorganic compounds in the case of oxidation and metamorphism.

2. Those migrating along faults and other structures some of which contain mineral deposits. The source of these gases generally lies in the rocks at depth, and their origin is commonly unknown. The gases most often encountered are H_2S, CO_2, N_2, CH_4 and the inert gases.

3. Those that form mobile gaseous aureoles and are related to present day mineralizing processes as in hot springs and fumaroles. The gases involved are generally H_2S, CO_2, H_2 and various volatile B, As, Sb, F and Cl compounds.

4. Those that form static gaseous aureoles and are related to past mineralizing, diagenetic and metamorphic processes in the rocks. These gases are trapped in inclusions in the lode and wall-rock minerals, along grain boundaries, and in small faults, fractures and other discontinuities in the lodes and country rocks. The gases and volatile compounds encountered are many and varied including H_2S, CO_2, N_2, CH_4, H_2, inert gases and so on (*see also* the discussion on liquid inclusions in the next section of this chapter).

Sampling materials utilized in atmogeochemical surveys

[34]H.C. Hoover and L.H. Hoover; Translation of Georgius Agricola, *De re metallica*, 1912, p. 37.

may include rocks and lode materials, soils and glacial materials, surface and underground waters and the air (atmosphere). Specialized techniques are required to extract and analyze the gases in all of these materials. Discussion of these lies outside the scope of this monograph; those wishing to pursue the subject further should consult the reference listing.

Gold forms no common inorganic volatile compounds that occur in nature in concentrations that are readily measurable. The element does, however, form a number of organic compounds, including alkyls (methylated compounds), organic arsenic compounds and chelates, some of which have a high volatility. None of these, so far as is now known, have been recorded in nature. One would expect such compounds to be present in highly organic environments where bacteria are particularly active. Some of the common elements associated with gold yield volatile compounds or gases by various processes. Here, we may mention particularly Hg, As and Sb, which form a number of volatile methylated compounds; in addition mercury as the metal has a relatively high volatility, and arsenic and antimony form volatile hydrides (arsine and stibine). Sulphur is perhaps the most common associate of gold that forms abundant gaseous compounds, often in some concentration as a result of oxidation processes, bacterial activity, metamorphism, etc. (e.g., SO_2, H_2S, various inorganic thiospecies and a host of organic sulphur compounds such as the mercaptans). Other volatile compounds of interest among the Group VIA elements include H_2Se, SeO_2 and various other inorganic and organic seleniferous species where high selenium contents are present in auriferous ores; also perhaps organic tellurium compounds in telluriferous ores. Where uranium and thorium are associated with gold, helium and radon gases are evolved. Zinc-rich ores containing gold may give rise to volatile methylated zinc compounds where bacteria are especially active. Fluorine and chlorine occur in some abundance in certain auriferous deposits, and these elements or their gaseous compounds may be of interest as atmophile indicators.

From the literature there appears to have been only a few atmogeochemical surveys carried out particularly to locate gold deposits. Frederickson *et al.* (1971) describe an airborne and truck-borne mass spectrometer–computer technique for regional exploration utilizing the F, Cl, Br, H_2S, SO_2, AsH_3 and Hg content of near surface air as a sampling medium. Only the briefest details are given, but when the system was tried in the auriferous Cripple Creek area of Colorado the results were successful. A total of 31 stations were occupied by the truck-mounted unit in 1 day. In addition eight stations were occupied up to five times each to demonstrate the repeatability of results. Because of the fairly extensive road network in this area, good areal coverage was obtained. Anomalies three or more times greater than background were obtained for fluorine, chlorine, hydrogen sulphide and (questionably) mercury. Comparison of the results with the more extensive ground geochemical survey by Gott *et al.* (1969) showed good correlation of anomalies. Furthermore, comparison of the fluoride results with unpublished fluorine data in the area also showed good correlation.

Other investigations include one by Eremeev *et al.* (1973) that outlines one profile of a high contrast helium anomaly over a gold deposit in northern Kazakhstan. The writer has noted low concentrations of CH_4, CO_2 and H_2S rising along various structures that contain auriferous bodies in the Canadian Shield; one of these is well documented (Boyle, 1961*a*). The source of these gases is unknown. One can only say in summary that it seems probable that atmogeochemical surveys utilizing rocks, soils, waters and the air will prove useful in the future for locating structures in which auriferous deposits may be found. In some cases perhaps atmogeochemical surveys using the volatile compounds of gold and its associated elements may actually prove useful in locating auriferous deposits directly. Those seeking further information on atmogeochemical surveys should consult the recent papers by Dyck (1969), Bristow and Jonasson (1972), McCarthy (1972), Ovchinnikov *et al.* (1973), Eremeev *et al.* (1973) and Meyer and Peters (1973).

Other methods

A number of other methods may be useful in locating gold deposits. These include plotting the distribution of various mineral indicators, panning of gossans, radioactive surveys, isotope variations and certain other geochemical-geophysical methods.

Quartz, one of the most resistant of minerals to chemical and mechanical agencies, is a universal associate of gold in nearly all types of auriferous deposits. These facts have been appreciated by prospectors for thousands of years, and it is no exaggeration to say that most of the great gold mines of the world have been found by tracing quartz float to its source in gold-quartz veins or other types of auriferous siliceous deposits. All types of quartz may be auriferous with perhaps the exception of rose quartz, which seems to occur only in quartz pegmatites. However, certain varieties of quartz are more indicative of gold mineralization than others. Prospectors tracing quartz float in Precambrian terranes should pay particular attention to black, grey and mottled quartz and to crushed and recrystallized white quartz since these are the most common auriferous varieties. In Paleozoic and Mesozoic terranes milky and grey varieties predominate in gold-quartz veins. Amethystine, crustified and chalcedonic varieties of quartz are particularly indicative of Tertiary gold deposits. All quartz floats exhibiting limonitic (iron oxide) staining or containing sulphides should be considered as a favourable indication of aurificity and should be assayed. In fact where quartz occurs relatively abundantly in any terrane a number of floats should be assayed on a routine basis.

More details on the varieties of auriferous quartz are given in the section on associated minerals in Chapter III, and the more sophisticated uses of quartz as a mineral indicator are mentioned in other contexts below.

Gold is associated in many deposits with galena, which oxidizes slowly to anglesite and cerussite. Often these two secondary minerals form only crusts on the galena preventing further oxidation. These partly oxidized nodules of galena collect in the soil, eluvium and in places in the stream beds. The panning of such stream beds, eluvium or soil may indicate the presence of gold (and silver) deposits, which can be traced by following the small particles of galena to their source. In some areas the oxidized galena may occur in relatively large masses, enabling one readily to follow the train of float in the soil, rock talus, etc. In other areas the galena may be finely comminuted, requiring microscopic and spectrographic or other chemical examination of the pannings. Often a simple map indicating the location of each piece of float, the grain count of comminuted galena, or the chemical analysis of the soil pannings for lead, gold and silver will reveal the float train and help in locating the source. By the same token a stream map of the area with similar data plotted on it may indicate the locale from whence the galena, gold and silver came. Numerous other heavy resistant minerals can be employed in a similar manner. Some of these include auriferous pyrite and arsenopyrite, oxidized stibnite particles, various sulphosalts, cinnabar, barite, scheelite, wolframite and chlorargyrite, the last being common in the oxidized zones of some gold-silver veins in arid environments (*see also* the sections on pedogeochemical and hydrogeochemical methods in this chapter).

The panning of gossans during prospecting for auriferous deposits is an ancient technique mentioned by Pliny (*Historia naturalis,* Book XXXIII). He describes how the Romans used the method in Spain; by panning *segullum,* a red earthy (limonitic) residuum in the oxidized parts of gold veins they were able to estimate the approximate worth of the (oxidized) veins. It is interesting to note that *segulla* is still the term used by Castillian prospectors for oxidized residuum on auriferous deposits.

Gossans of all types should be panned carefully for gold. Particular care should be paid to the oxidation products of indigenous gossans, and a search should be made for the oxidation products of minerals that accompany gold in its deposits such as anglesite, cerussite, jarosites, bindheimite, scorodite, antimony ochers, silver halides (chlorargyrite) and malachite (*see also* Chapter IV). Assays and spectrographic analyses are useful in determining the presence of gold and silver and should be done on a routine basis on all gossans. Gold and silver and other metals may be nearly completely removed from some indigenous gossans leaving them barren except for traces of gold, silver and other metals. In such cases deep trenching or diamond drilling may reveal the presence of economic concentrations of gold and silver at depth. Gossans resulting from the transportation of iron, manganese and other elements should be analyzed by spectrograph or other geochemical methods for silver, zinc, copper, lead and other metals. Often such transported (or pseudo) gossans result from the oxidation of pyrite in slates, iron-bearing carbonates in sediments, etc. and are not related to metallic deposits. In other cases they show a direct relationship to metallic deposits, yet they may not be significantly enriched in the metals present in the primary ores. The reason for this behaviour is not clear, but it seems to be related to the colloidal behaviour of hydrous iron and manganese oxides and the recrystallization processes that go on to make limonite and geothite. During such processes any adsorbed metals seem to have been leached out in a number of transported gossans the writer has investigated. It is, therefore, not possible with our present knowledge to tell which transported gossans are related to metallic deposits and which are not. Until further research elucidates this problem the cardinal rule with respect to gossans of all types is that they should not be left until all geological and chemical possibilities concerning their origin and possible relationship to metallic deposits have been exhausted.

Certain gold-bearing deposits and their alteration halos contain uranium (and thorium). Many of these deposits occur in Tertiary rocks (e.g., Central City district, Colorado), but others are known in rocks of all ages including Precambrian (e.g., Witwatersrand, South Africa; Box Mine, Lake Athabasca district, Saskatchewan; Richardson Mine, Ontario; Tennant Creek, Northern Territory, Australia). Such deposits can often be detected by geiger, scintillometer or X-ray spectrometer surveys or by using uranium (and thorium) as an indicator element in rock, soil, stream sediment or water surveys. At Tennant Creek for instance, Large (1975) observed an umbrella-shaped halo of uranium values that capped one of the auriferous magnetite-chlorite orebodies. Contents greater than 80 ppm U coincided with the outer edge of the auriferous zone.

Many types of gold deposits, particularly those in basic and intermediate volcanic and intrusive rocks, are characterized by enrichments of potassium in their wall-rock alteration zones (*see* the section on wall-rock alteration in Chapter III). Since the potassium isotopic species contains a radioactive member, ^{40}K, it should be possible using suitable detection apparatus to outline positive anomalous potash-rich zones which may be related to gold mineralization. Alternatively, potash metasomatism and other types of pervasive alteration may have removed elements such as U, Th and Ra from the rocks leaving negative or subnormal gamma-emitting aureoles. There appear to have been few surveys carried out in North America, Europe or Africa with the aim of discovering gold deposits using highly sensitive gamma-ray spectrometers either on the ground or airborne, although such methods have been used extensively to locate other types of deposits (Darnley and Grasty, 1971; Bennett 1971; Cook *et al.,* 1971; Johnson, C.H., 1971). Eight references to these types of surveys were noticed in the literature on gold deposits in U.S.S.R. Ostrovskiy *et al.* (1970) studied the possibility of using an aerial survey of radioactivity along the 3500 km long Okhotsk-Chukotka Mesozoic-Cenozoic volcanic belt where there are a number of gold-silver occurrences. In this belt the gold-silver mineralization occurs mainly in volcanics and associated sediments and is associated with adularization resulting from potassium metasomatism, which is accompanied by a decrease in radioactivity due to loss of Th, U and Ra. On the other hand, the radioactivity is higher outside the adularized rocks. The profiles and plans presented are most interesting; over the adularized zones 'highs' are recorded for potassium, and these are matched by corresponding lows for thorium and radium (Fig. 99). Details should be sought in the original paper. Gamma-ray spectrometric surveys carried out by Blyumentsev *et al.* (1974) at the surface and in diamond-drill holes near gold deposits in a similar geological environment exhibited patterns almost identical to those reported by Ostrovskiy *et al.* (1970). Both groups of investigators concluded that surveys employing gamma-ray spectrometry are useful in outlining areas of adularization associated with gold deposits. In the Darasun Goldfield Zashchinskii *et al.* (1970) used a potassium radiometric survey to outline tectonic fracture systems to which the auriferous deposits are related, and Portnov *et al.* (1971) used aerial γ-ray spectrometric and hydrogeochemical methods to define zones of adularization that mark Au-Ag mineralization at the Karamkensk deposit, localized in paleovolcanic caldera structures. In the alteration zone of a near-surface gold deposit in the U.S.S.R. Grebenchikov *et al.* (1974) noted that uranium and thorium formed a negative halo whereas potassium was found to increase towards the ore; sodium was leached. Somewhat similar results were noted by Zhokhov *et al.* (1975) in the auriferous Kokpatas field. There, in comparison with the volcanic-sedimentary host rocks, they found that the hydrothermally altered rocks differed sharply in their potassium content but did not differ noticeably in their uranium and thorium content. In the near-surface zone of hydrothermally altered rocks, however, an increase in uranium was observed, being caused by the sorption of uranium by iron hydroxides and other oxidation products. The authors concluded that the gamma-ray spectrometric method was useful in mapping the zones of hydrothermally altered rocks in which gold-sulphide mineralization was localized. Fel'dman *et al.* (1975) also found gamma-ray spectrometry of use in localizing auriferous deposits. Using the (U+Th)/K ratio they noted that the auriferous lodes were marked by minima; on the graph for the K content the positions of the gold lodes are marked by increased values. Krendelev *et al.* (1976) used gamma-ray spectrometric methods for contouring auriferous ore zones in the Transbaikal region, U.S.S.R. The method was capable of locating and rapidly outlining ore zones that formed with the redistribution of the natural radioactive elements in the host rocks. Zones of high gold content (quartz-pyrite-disseminated gold) were distinguished by a minimum K content and high U content. High U and occasional Th and K contents were commonly noted in rocks close to ore zones in tectonic structures (faults, shear zones).

Gross (1952), noting that some auriferous deposits are located in and around the boundaries of igneous intrusives such as small stocks and batholiths, examined the radioactivity (alpha activity) of nine intrusives including the Athona stock, Goldfields, Saskatchewan; the Falcon Lake stock, Manitoba; the Rice Lake intrusive, Manitoba; the McKenzie stock, Red Lake, Ontario; the Dome stock, Red Lake, Ontario; the Eagle Lake intrusive, Ontario; the Turnbull Township intrusive, Ontario; the Pearl Lake porphyry, Timmins, Ontario; and the Larder Lake intrusive, Ontario. The results of these surveys showed that stocks and batholiths of igneous or sedimentary (granitization) origin have a zone of higher-than-normal radioactivity in the vicinity of ore structures. Intrusives with no important structures close at hand have no such concentration. The determination of the distribution of the radioactive elements, can therefore, be used as a general guide to ore structures. Furthermore, the distribution of zirconium, silica and the heavy metals can be used in much the same way as radioactivity. Zirconium, however, appears to be less reliable as a structural indicator in granitized sediments, whereas in more basic rocks, silica is more critical than radioactivity. (*See also* the review of another paper on this subject by Gross in the section on lithogeochemistry.) Gross (1952) considered the radioactive technique to be of practical value as it enables the prospector to restrict his detailed work to relatively small areas around an intrusive body. Furthermore, if no major concentrations of radioactivity, zirconium, etc. are found, the intrusive may well be eliminated from detailed prospecting.

Gold has only one isotope, and as noted in a previous publication on silver (Boyle, 1968*b*), there are no variations of any consequence in the isotopic abundance of this most common associate of gold. There does not seem, therefore, to be any way of using either silver or gold isotopes in prospecting at the present time. Two common elemental associates of gold are lead and sulphur, both of which exhibit differences in their isotopic ratios depending on the mode of formation of their minerals and other factors. These two elements and a few others offer some possibilities in prospecting for gold-bearing deposits.

Neglecting details, metallic deposits, containing lead minerals tend to have a distinctive lead isotopic composition for all of the epigenetic lead minerals. For instance, lead minerals in uranium deposits tend to have a high proportion of uranium-lead, that is they are enriched in ^{206}Pb and ^{207}Pb the derivatives of ^{238}U and ^{235}U; in thorium-rich deposits a high enrichment of thorium-lead, ^{208}Pb can be expected in the

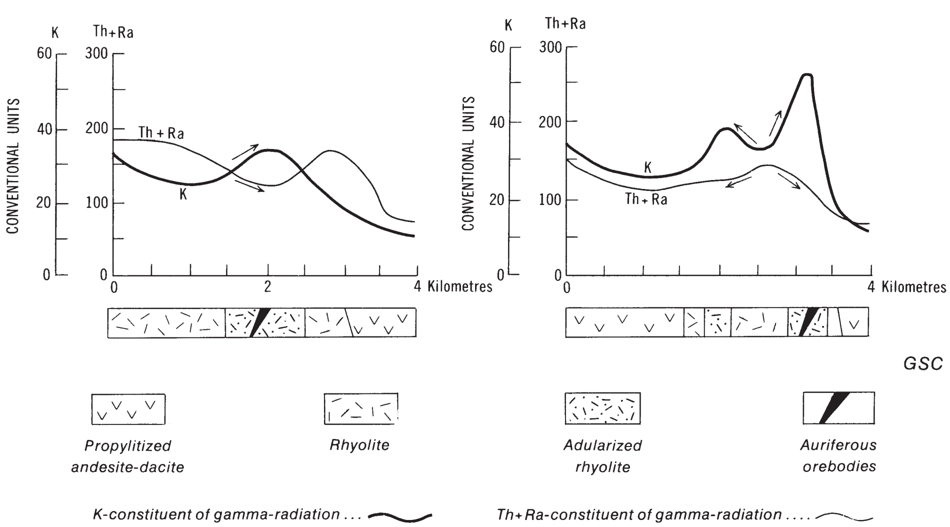

Figure 99. Typical radiation aeroprofiles over auriferous adularized zones in unaltered Tertiary volcanics, Okhotsk-Chukotka Belt, U.S.S.R. (after Ostrovskiy *et al.*, 1970).

lead minerals. In ordinary lead-bearing deposits the lead minerals have a component of original (primal) lead isotopes (^{204}Pb, ^{206}Pb, ^{207}Pb, ^{208}Pb), plus varying amounts of radiogenic lead (^{206}Pb, ^{207}Pb, ^{208}Pb) depending among other factors on the age of the deposit. And finally there are deposits in which the lead minerals have isotopic ratios that are unusual or anomalous (the J-lead of the Mississippi Valley deposits, but also of such deposits as Keno Hill, Yukon and elsewhere). The reasons for the variable isotopic composition of lead in deposits is extremely complex and certainly not yet understood. We need to understand the processes involved in the migration and concentration of lead isotopes before our theories can be placed on a firm basis (Boyle, 1959). These problems notwithstanding, it is possible to 'fingerprint' lead deposits and minerals derived from lead-bearing deposits by means of their isotopic ratios. This particular feature can be used in prospecting for gold- and silver-bearing deposits containing lead as Boyle (1968*b*), Angino *et al.* (1971), Cannon *et al.* (1971) and Antweiler *et al.* (1972) have suggested. The last two papers are particularly instructive in this matter. Cannon *et al.* (1971) observed evidence for a lead isotope gradient in the Leadville district, Colorado that appeared to point toward the focus of mineralization and also found favourable prospecting indications in the Mississippi Valley district, which do not concern us here. They concluded from their work that nearly all of the lead isotopic analyses presented in their paper represented galenas collected from mines or prospects in bedrock, and that the field is wide open for the use of isotopic analyses to evaluate geochemical lead anomalies in soils and waters.

In the Hayns Peak area of Colorado Antweiler *et al.* (1972) examined the lead isotope composition of galena in deposits, feldspar in rocks and placer gold in an effort to determine the origin of the placer gold, whose source has been variously attributed to rocks or disseminated mineralization of Precambrian, Mesozoic and Cenozoic (Tertiary) age. Briefly, the geology of the area involves a setting of Precambrian basement rocks overlain by late Paleozoic, Mesozoic and Tertiary sediments, all of which are intruded by a Tertiary (Pliocene) rhyolite porphyry stock and sills. The known bedrock mineralization includes Pb-Zn-Cu-Ag deposits and small widely distributed gold-quartz veins in a variety of rocks. The data from the lead isotope study are complex, but briefly the trace amounts of lead extracted from the placer gold is very close in isotopic composition to that in the galena associated with the Tertiary intrusions, and it lies on a compositional line joining the galena-leads with the feldspar-lead in the Tertiary porphyry. Furthermore, the isotopic composition of the lead in the placer gold has nothing in common with ore leads from the Precambrian sulphide deposits. The investigators concluded that this evidence implies that most of the placer gold was derived from the epigenetic Tertiary mineralization.

These examples suggest that lead isotopic ratios in placer gold, as well as in various minerals associated with gold such as pyrite, galena and lead sulphosalts, in soils, eluvium and stream sediments may be used to 'fingerprint' the source of the lead and may be an ancillary aid in various types of geochemical surveys carried out to locate gold deposits.

A number of detailed sulphur isotopic studies of wall rocks and ores in gold and polymetallic sulphide deposits have been done in recent years mainly to elucidate the nature of the ore-forming processes. Some of the results suggest that sulphur isotopes may be useful in detailed prospecting for gold-bearing deposits. Wanless *et al.* (1960) observed in a series of profiles across country rock, alteration zones and gold-quartz lenses at Yellowknife, Northwest Territories that as the ores are approached there is a progressive increase in ^{34}S content of sulphides (mainly pyrite and arsenopyrite) with a maximum enrichment in the gold-quartz lenses. Similar enrichments in the ^{34}S content of sulphides with approach to ore were noted by Shima and Thode (1971) in polymetallic deposits in Japan and Canada. Such phenomena are, however, not invariable as Boyle *et al.* (1970) found in the Keno Hill–Galena Hill area, Yukon. There, the sulphides in the gold-quartz and Pb-Zn-Ag-Cd lodes were lower in ^{34}S content compared with the host sedimentary rocks. From this it follows that before isotopic ratios can be used in estimating approach to mineralization the nature of the sulphur isotopic dispersion profiles about the deposits must be known. When this is clear, sulphur isotopic ratios in sulphides from drill cores may be a useful ancillary procedure in conjunction with lithogeochemical ratios for estimating nearness to ore (*see also* the section on lithogeochemical methods).

In a more general way sulphur isotopic ratios may be an aid in prospecting for gold-bearing deposits. Jensen (1971) reviewed the state of sulphur isotopic work in prospecting and concluded that:

> Measurements with high-precision, dual-collector mass spectrometers of the stable sulphur isotope ratio $^{34}S/^{32}S$ have enabled the economic geologist to determine if sulphide minerals have formed at low temperatures (bacteriogenically – generally syngenically) or at high temperatures (epigenetically). Primary sulphates can readily be distinguished from secondary sulphides and from primary sulphides in hydrothermal deposits by the differences in $^{34}S/^{32}S$ ratios of their respective sulphur. In some deposits, primary sulphates are associated with primary metal values and secondary sulphates are not. In addition the distinctions between a magmatic hydrothermal and a sedimentary origin of sulphide deposits can generally be resolved by sulphur isotopic measurements.

The differentiation between primary and secondary (supergene) sulphates by sulphur isotopic analyses has been clearly shown by Field (1966) for a number of deposits in the western United States and by Jensen *et al.* (1971) at Goldfield, Nevada. In all of these deposits there is a measurably distinct isotopic dissimilarity between the primary sulphates, which commonly are greatly enriched in ^{34}S with respect to associated sulphides, and supergene sulphates, which usually have ratios similar to the primary sulphides from which they were derived. With respect to alunite related to gold mineralization it is advantageous to be able to distinguish the primary alunite (which is associated with primary gold mineralization) from secondary alunite that may not bear any particular relationship to the period of gold deposition. At Keno Hill (Boyle *et al.,* 1970) the sulphur isotope ratio of supergene sulphates in the oxidized zones of the deposits reflects the ratio in the hypogene sulphides and is quite different (enriched in ^{32}S) from that in hypogene barite. Similarly, the ratio in the sulphate of the meteoric waters leaching mineralized zones reflects the ratio in the ores, a fact that can be used in hydrogeochemical surveys to 'fingerprint' sulphur derived from ores from that originating from the country rocks.

The isotopic ratios of various elements may also be of value in prospecting for gold-bearing deposits. Of interest may be the ratios of various elements so commonly associated with gold, particularly Cu (2 natural isotopes), Sb (2 natural isotopes), Te (8 natural isotopes), Cd (8 natural isotopes), Tl (2 natural isotopes), B (2 natural isotopes), Zn (5 natural isotopes), Hg (7 natural isotopes) and so on. There are no data on the distribution of the isotopes of these various elements in gold deposits. Jensen (1971) remarks that $\delta^{18}O$ surveys of rock and mineral samples may be of use in prospecting, permitting the plotting of isopleths, i.e., lines of equal $\delta^{18}O$ values, indicating increasing temperatures that existed as the source of the mineralizing solution is approached. Figure 100 illustrates this approach in an idealized manner.

Akopyan *et al.* (1976) studied the oxygen isotope constitution of quartz in ores, wall-rock alteration zones and host intrusive rocks of the Megradzorsk gold deposit, Armenia, U.S.S.R. They observed that the $\delta^{18}O$ values of the intrusives relative to SMOW (Standard mean ocean water) increase from early to late differentiates (6.25 to 10.60 °/oo). $\delta^{18}O$ values within the narrow range from 11.95 to 12.25 °/oo characterize the quartz of the hydrothermal stage with which increased contents of gold are associated. Furthermore, the quartz of the productive veins and their associated wall-rock alteration zones have the same or similar $\delta^{18}O$ values, a feature that led the authors to conclude that this fact is useful in detecting productive parts of the deposit enriched by circulating hydrothermal solutions.

Menke (1951) describes an isotopic method of geochemical prospecting based on the identification of ^{198}Hg. This isotope results from fast neutron bombardment of gold such as might occur where the precious metal occurs in association with uranium and thorium minerals. The mercury so formed may be rendered mobile and may hence be used as a travelling indicator of gold deposits. In using the method it is necessary that the small amounts of mercury not be masked by very much larger amounts of ordinary mercury (which contains some 10% of ^{198}Hg).

Reference has been made in previous sections to the use of gold fineness in surveys based on soils, eluvium and stream sediments. The fineness of gold may also be used in a practical way in developing deposits already discovered. Thus, a detailed study of the fineness of gold at various levels of a mine may furnish useful data with regard to the amount of leaching and secondary enrichment that has taken place (Fisher, 1945,1950). Similarly, according to the same author, the fineness may be of value in determining the possible extension in depth of an orebody. For further details the interested readers should consult the section on Au/Ag ratios in Chapter III.

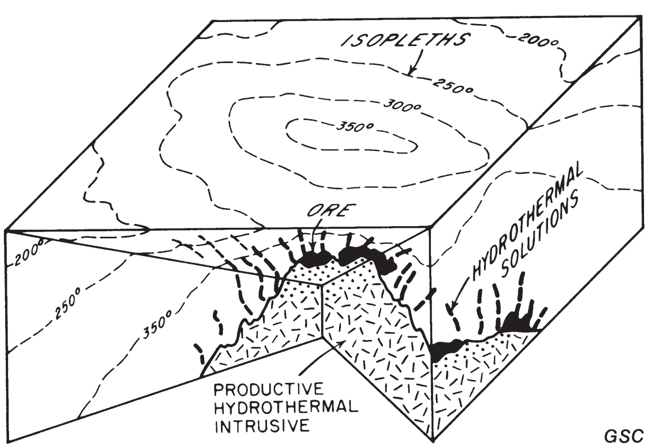

Figure 100. Idealized potential application of $\delta^{18}O$ studies to hydrothermally altered contact zones near a mineralizing fluid source (after Jensen, 1971).

Numerous studies of the quartz of gold-bearing deposits have been carried out with a view to using the data in prospecting. Microscopically and macroscopically the quartz of gold deposits is extremely varied. There are, however, numerous features that distinguish gold-bearing vein quartz from other types of quartz, and these can be used in detailed lithogeochemical, pedogeochemical and stream sediment surveys if samples of the quartz can be obtained. *A priori* knowledge of the types and the features of vein quartz in an area are advisable before attempting to use the mineral as an indicator. Some of the specific characteristics of auriferous quartz are outlined in Chapter III.

Vertushkov *et al.* (1970) discuss various ways of distinguishing orebearing from barren quartz in gold districts in the Urals and elsewhere. Their method is based on statistical evaluation of such features as texture of the quartz aggregates, translucency, losses in heating and composition of gas-liquid inclusions. The last expressed as a 'water index' (V_{H_2O}/V_{CO_2}) is said to vary according to the content of gold in the quartz. For instance the following results were obtained from the Byn'gi deposit

'Water index'	Au content (ppm)
8.7	0.6 (barren quartz)
6.0	3.5
2.5	9.2 (ore quartz)

Maps are made of the quartz occurrences and indices for the various features are plotted. It is said that these maps aid in prospecting for gold deposits by differentiating areas of gold-bearing quartz from those that are barren. Details of the methods of computation of the indices should be sought in the original paper.

Pyrite and arsenopyrite are almost universal minerals in auriferous deposits, and both are excellent indicators of gold. Many studies of these two sulphides in auriferous deposits have been done (*see* the section on associated minerals in Chapter III). Certain crystallographic, X-ray, trace element and electrical properties sometimes characterize and 'fingerprint' the pyrite and arsenopyrite from specific auriferous deposits or belts. Pyrite or arsenopyrite with this 'fingerprinting' found in alteration zones, eluvium, soils and stream sediments can often give a clue to the presence of unsuspected deposits in unprospected or heavily overburdened parts of specific auriferous belts.

Studies based on liquid inclusions in minerals, especially quartz and the decrepitation characteristics of minerals in gold deposits may be of interest in prospecting for deposits or extending knowledge of those already known. The techniques of studying liquid inclusions in minerals and decrepitation methods are described at length by Scott, H.C., (1948), Smith and Peach (1949*a*, *b*) and Peach (1949). There is an extensive review and bibliography on both subjects by Smith (1953), and numerous investigations of gold-bearing quartz in a variety of deposits are described in Smith *et al.* (1949–1951). More recent work on liquid inclusions and decrepitation can be found in the works by Kashiwagi *et al.* (1955), Takenouchi (1962), Yermakov *et al.* (1965), and in the Proceedings of COFFI (Roedder, 1968–1974).

A general outline of the basis of liquid inclusion and decrepitation methods has been given in Chapter III. Here, we shall deal briefly with a few of the investigations extant in the literature that bear on prospecting for epigenetic gold deposits.

Since pressure and temperature largely control the deposition of gold in vein systems, and since these parameters can be estimated by liquid inclusion and decrepitation measurements in conjunction with other physico-chemical methods and calculations, it has been considered possible, in ideal situations, to predict the direction of flow of mineralizing solutions, the location of ore shoots and other features of gold mineralization. It is on this basis that a number of investigations of gold deposits have been carried out using decrepitation and other methods.

An early investigation of the ore deposition temperature and pressure by decrepitation of quartz and use of the pyrite geothermometer at the McIntyre Mine, Timmins, Ontario by Smith (1948) indicated two separate stages of mineralization in the gold-quartz bodies in greenstones and quartz porphyry, the first extending over the range of 630 to 400°C at a depth of 10 km and the second at 150°C but at a much shallower depth. Variations of temperature of deposition of pyrite were found to be unrelated to depth in the mine and to individual veins but were found to be related to the distance from the contact of the porphyry and the wall rock. A gradient of the mean temperature of deposition was found to be 14°C per 100 ft, from 500 ft within the porphyry to 500 ft outside the porphyry intrusive.

In a later paper Smith (1951) used the combined decrepitation and pyrite geothermometer methods to predict the maximum depth of the gold deposition in the Archean Ontario-Quebec gold belt comprising the McIntyre Mine at Schumacher (Porcupine Belt), the Kerr Addison Mine east of Kirkland Lake and the Malartic Gold Fields Mine in western Quebec. It was calculated that the vertical extent of the epithermal (late stage low temperature) mineralization was at least 9000 ft below the base of the Proterozoic Cobalt sediments (the datum level).

Blais (1954) investigated the auriferous quartz veins at the O'Brien Mine, northwestern Quebec by decrepitation methods. There, the ore shoots have a long vertical extension and are localized in or near vein rolls, vein intersections, vein deflections and graphitic shears where concentrated fracturing and shattering of the vein quartz afforded minute openings for the migration of auriferous solutions and deposition of late gold. The observed relationships indicated a connection between late gold and secondary liquid inclusions. Auriferous quartz was found to decrepitate in the temperature range 75 to 120°C, whereas barren quartz decrepitation began above 130°C. Many trend lines of low decrepitation temperature were found to correspond to ore shoots.

Boyle (1954) examined the quartz of two gold-bearing shear zone systems (Campbell and Negus Rycon) by decrepitation methods at Yellowknife, Northwest Territories over a vertical extent of some 1400 ft. There, the ore shoots occur in quartz veins and lenses some of which have been intensely crushed and recrystallized. Much of the free gold occurs in late fractures and recrystallized parts of the quartz veins, and some gold is intimately associated in a submicroscopic form with arsenopyrite and sulphosalts that are respectively early and late in the mineralization sequence. Curves of decrepitation temperature (135–250°C) and intensity (1–5) where drawn on the ore shoots and examined for existing patterns. The details are complex, but the following generalities are evident:

1. The quartz of the ore shoots is not characterized by consistently higher or lower decrepitation temperatures than that outside the ore shoots, although there is a tendency for higher decrepitation temperatures to occur in the ore shoots.

2. The gold in the orebodies is markedly concentrated in the crushed and recrystallized quartz, and in this respect the zones of higher decrepitation temperatures and lower decrepitation intensities mark the ore shoots.

3. In the Campbell System there is a decrease in decrepitation temperature in both early and late quartz with depth; however, this relationship is not pronounced in the Negus-Rycon System.

4. The decrepitation temperature and intensity apparently are controlled to a large extent by the proportion of microcrystalline quartz to medium-grained quartz in the sample; thus the greater the proportion of microcrystalline quartz the higher the decrepitation temperature and the lower the decrepitation intensity. Detailed petrographic study indicates that the microcrystalline quartz is probably developed by crushing and recrystallization of medium-grained quartz. It seems logical that during the crushing and brecciation large numbers of liquid inclusions would be destroyed; at the same time it is possible that the tensile strength of the quartz would be increased in a similar manner to that of a metal that has been work-hardened. The reduction in the number of liquid inclusions accounts for the decrease in decrepitation intensity and the probable increase in the tensile strength may produce the higher decrepitation temperatures. Thus, the variation of decrepitation temperatures and intensities is related to some extent to the amount of crushing and recrystallization that the quartz has undergone. The instrumental effect must be considered, however, when there are only a few liquid inclusions in the sample. In this case the slope of the decrepitation curve may be so low, that the point of break is difficult to determine, in which case there is a tendency to select a decrepitation temperature higher than the true value.

5. The significant decrease of the decrepitation temperature with depth of the early and late quartz in the Campbell System may be caused by decreasing crushing and recrystallization of the quartz at depth; that is, the control may be structural. On the other hand, the decrease in decrepitation temperature with depth may be explained by the temperature and pressure gradient existing at the time of formation of the secondary liquid inclusions. Petrographic and structural studies tend to substantiate the first of these conclusions.

It was concluded that there are certain poorly developed patterns in the decrepitation results that may be significant in the analysis of the ore-forming process, but none appeared to be clear-cut enough to determine the direction of flow of mineralizing solutions or predict the possible location of ore shoots. The reason for the poorly developed patterns is the complexity introduced by extreme crushing and recrystallization of the quartz. In this respect the quartz in the Yellowknife orebodies is not suitable for decrepitation studies.

At the Lamaque Mine, Bourlamaque Quebec, Smith (1954) examined the quartz of the No. 6 vein with a view to determining the direction of flow of late solutions that probably deposited much of the gold. Briefly, the vein is composed of a coarse, glassy to white quartz with some ankerite, tourmaline, pyrite and native gold. The vein cuts across a zoned granodiorite-diorite plug and greenstone. When heated the quartz decrepitates between the range 80 to 124°C. High grade ore specimens have a relatively rapid rate of decrepitation; low grade specimens have a relatively slow rate. The measured decrepitation temperatures when plotted in the plane of the vein, and contoured, show that the lower values are near the central part of the vein, where it crosses the principal granodiorite-greenstone contact, and the higher values are around the outer limits of ore in the vein. Smith (1954) concluded that if the assumptions are made that the measured decrepitation is due to filling of secondary liquid inclusions trapped during the stage of gold deposition, and that the measured variation of decrepitation is due to variation of pressure during that stage, the contoured data can be taken to mean that the later gold-bearing solutions entered the quartz vein at the principal wall-rock contact and moved up and down the dip, depositing gold during and possibly due to, the drop in pressure.

In recent years an enormous amount of work has been done on liquid inclusions by all methods of study. Most of this work has involved geothermal projects and elucidation of the nature of the ore-bearing solutions. Only scattered references deal with prospecting for gold deposits. Abstracts and summaries of the various investigations can be consulted in the proceedings of COFFI (Roedder, 1968–1974).

It is difficult at present to evaluate the effectiveness of methods based on liquid inclusions in prospecting for gold deposits. It would seem that up to now the methods have been of limited practical value in detailed prospecting but have given considerable information on the temperature, pressure and nature of solutions from which gold has been deposited. Perhaps we cannot expect more at this stage of the research.

One approach to using inclusions and decrepitation in prospecting for gold may lie in 'fingerprinting' quartz and other minerals. Thus, the auriferous quartz of a mineralized belt is usually marked by specific liquid inclusion and decrepitation characteristics. If such quartz is found in soils, stream sediments, etc., it signals the fact that auriferous quartz veins lie uphill or within some local drainage basin.

The thermoelectric properties of pyrite have been investigated as a means of detailed prospecting for deposits containing the sulphide and gold. The pyrite geothermometer developed by Smith (1947) is based on the assumption that crystals of pyrite (an electronically conducting mineral) deposited at a high temperature have a more positive thermoelectric potential than crystals deposited at a low temperature, and that the thermoelectric potential varies continuously between any given limits of the temperatures of deposition.

In the McIntyre Mine, Schumacher Ontario, Mutch (1952) found that there were distinct differences in readings obtained by pyrite geothermometer in the ore-bearing parts of the No. 25 vein as compared with those obtained outside the vein. In the ore-bearing parts positive readings were obtained whereas outside only negative readings were found. He reasoned that since the area of the vein containing the pyrite giving negative readings is in excess of the ore section, determination of thermoelectric potential of pyrite may have an application in locating and outlining gold orebodies. Rozova and Gavrilov (1970) also noted a zoning of thermo-e.m.f. changes in pyrite in the Kokpatas gold deposit, central Kyzul-kum U.S.S.R. There, the pyrite occurs in a disseminated gold-sulphide deposit in metamorphosed carbonaceous sediments and volcanic rocks. Mineral zoning consists of an intensely sulphidized zone in the centre (mainly arsenopyrite) surrounded by zones with increasing amounts of pyrite. The thermo-e.m.f. changes in the pyrite outlined five separate zones with the thermo-e.m.f. increasing toward the periphery of the deposit. Corresponding changes in the specific electrical resistivity of pyrite were also found. A relationship between the thermo-e.m.f. of pyrite and the arsenic content of the mineral was noted.

Thermoluminescence of minerals has been proposed as a detailed prospecting tool, and some work has been done on auriferous quartz and in alteration halos around various types of mineral deposits. Thermoluminescence (thermostimulated phosphorescence) is the property of a mineral or rock to emit light (photons) when heated below red heat (below about 400°C). The phenomenon is due to unstable electronic conditions (trapped electrons) within the crystal lattice. These conditions can be induced by radioactive bombardment, stress, heat absorption and a variety of other causes not yet well understood. Details should be sought in the book edited by McDougall (1968).

MacDiarmid (1963) observed a general erratic distribution of thermoluminescence in the vicinity of hydrothermal deposits. On the other hand, McDougall (1964,1966) considers that his investigations indicate that thermoluminescence should have at least limited application as an exploratory tool. He observed a number of patterns adjacent to orebodies, some carrying gold, as follows (1) no thermoluminescence is observed; (2) thermoluminescence is present, but no distinctive change is observed as the zone is approached; (3) thermoluminescence is low or nil immediately adjacent to the ore zone and rises to a higher background level at some distance away; (4) thermoluminescence is low or nil immediately adjacent to the ore zone, rises to a higher value at some distance away, and then drops to a more or less uniform background (or to nil values) at a still greater distance; and (5) thermoluminescence is high immediately adjacent to the ore zone and decreases away from it to a more or less uniform background (or to nil values). The profiles figured by McDougall are remarkedly similar to those obtained for trace elements, including gold, in the primary halos in rocks surrounding orebodies.

Grishin *et al.* (1971) examined the thermoluminescence of quartz from a number of primary gold deposits of northern

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Kazhakhstan, U.S.S.R. They found that quartz with visible gold and quartz devoid of gold showed no difference in their thermoluminescence. There was also no particular relationship with any specific trace element in the quartz. They did, however, note significant differences in the glow curves of the quartz with different typomorphic characteristics (e.g., cryptocrystalline, fine grained, coarse grained, columnar, sugary, etc.) that they related to the conditions of formation of the quartz. In this respect the authors thought that thermoluminescence of quartz could be useful in ascertaining the conditions of formation of the auriferous quartz and thereby gain some knowledge on the possible distribution of orebodies within a district.

The possibility of applying neutron activation analyses of rock, soil, sediments, etc. in situ for locating gold deposits has been considered by a number of investigators. Senftle *et al.* (1969) have suggested the use of ^{252}Cf as the source of neutrons and a Fe(Li) crystal as the gamma-ray detector. This technique was used to obtain spectra of marine manganese nodules and gold ore (0.3 oz/ton) in a simulated marine environment. Siegel (1971) details the techniques and problems of prospecting by in situ neutron activation apparatus in the marine environment.

Fire is the test of gold
–Seneca

Analytical methods for estimating gold

Gold can be determined in geological materials by a variety of methods, including fire assay, colorimetric analyses using mainly organic reagents, inorganic analytical methods, spectrography, combined assay and spectrography, atomic absorption spectrography, spot tests, neutron activation and panning. Only the last can be employed as a field test as will be discussed subsequently.

The analytical method employed to determine gold depends essentially on the type of geological material to be analyzed and the level of the gold content. It should be borne in mind that the gold contents of normal rocks, soils, glacial materials, stream sediments and spring precipitates usually lie within the range 0.0005–0.01 ppm. In normal natural waters the average is 0.00003 ppm (0.03 ppb) and in normal biological materials (dry weight) the gold content only rarely exceeds 0.01 ppm. Ores range widely in their gold contents but generally between 5 and 35 ppm. Placers, likewise, range widely in their gold contents; most carry less than 1 ppm Au. *See also* the extensive data given in Chapter II.

There are a number of treatises, textbooks and papers dealing with practically all aspects of the sampling procedures for analysis, analytical chemistry and fire assaying of gold, including those by Fulton and Sharwood (1929), Dillon (1955), Sandell (1959), Furman (1962), Stanton and McDonald (1964), Wise (1964), Herz (1966), Chow (1966), Beamish (1966), Huffman *et al.* (1967), Thompson *et al.* (1968), Van Sickle and Lakin (1968), Popova (1971), Green *et al.* (1971), Hildon and Sully (1971), Beamish and Van Loon (1972), West (1973), Purushottam *et al.* (1973), Brown and Hilchey (1975), Rajan and Raju (1975), Sighinolfi and Santos (1976*b*), Beamish and Van Loon (1977) and Haffty *et al.* (1977). Numerous mineralogical texts and treatises outline the mineralogical and chemical methods for the determination of native gold and its minerals. The reader is referred particularly to those by Short (1940), Palache *et al.* (1944,1951), Ford (1958), Ramdohr (1960), Hey (1962,1963), Chukhrov (1960–1965), Berry and Thompson (1962), Uytenbogaardt and Burke (1971) and Galopin and Henry (1972).

Fire assay methods using lead, tin or other collectors are best adapted to ores or rocks enriched in gold. With proper attention being paid to fluxes and procedures fire assay methods for gold are accurate and highly reproducible. Fire assay methods can also be combined with a number of other methods for the estimation of gold. One method involves the optical spectrographic determination of the gold in the assay beads; others involve solution of the gold-silver beads by aqua regia or cyanide followed by determination of the gold by colorimetric and other wet chemical methods such as atomic absorption spectroscopy or neutron activation. The combination methods are adaptable to practically all geological materials except water.

Colorimetric and other types of wet chemical methods are not generally satisfactory for the direct determination of gold in geological materials because of the relatively low amounts of the metal present. If combined with enrichment or preconcentration (collector) techniques such as fire assay, solvent extraction, ion exchange or addition of tellurium or mercury compounds as collectors the wet chemical methods are satisfactory but tedious and are not suitable for rapid determination of gold in large numbers of samples.

The limit of detection of gold in the DC arc is about 10 ppm, and hence direct optical spectrographic methods are generally not suitable for the determination of the metal in most types of geological materials. Even for ores the spectrographic method is unreliable because of the erratic and often particulate nature of gold. X-ray spectrographic methods are, likewise, unsuitable for the determination of gold in most geological materials because of the low detection limit of the methods (~10 ppm). The detection limits for trace analysis of gold by spark-source mass spectroscopy are, likewise, high being 0.01 to 0.1 ppm (Beske, 1974). Suitable enrichment or collector techniques such as fire assay, ion exchange, solvent extraction, etc. followed by spectrographic determination of the gold in the beads, (ashed) resins, (ashed) solvent extracts, etc. have been employed with success, but the methods are tedious and the reproducibility is commonly low.

Atomic absorption spectroscopy for the determination of gold following collection of the metal by suitable means including fire assay, solvent extraction, ion exchange, tellurium and mercury compounds, etc. have found wide usage in geochemistry (Angino and Billings, 1972). A thorough review of the methods applicable for determination of gold in rocks, soils, waters and biological materials with a bibliography up to August 1972 is given by Sen Gupta (1973).

Spot tests are not generally suitable for the qualitative determination of gold in most geological materials because of poor sensitivity. They can be employed, however, for the qualitative determination of gold in minerals such as the tellurides, sulphosalts, etc. Feigl (1958) lists a number of specific tests for gold in solutions.

Neutron activation methods are extremely sensitive and particularly adaptable for the determination of gold in most geological materials. The methods are costly and tedious, but in recent years they have been successfully adapted to geochemical prospecting surveys where large numbers of samples are involved. They are also especially useful in fundamental geochemical studies on the distribution of gold in geological and biological materials. Most of the methods involve a preconcentration step, especially when dealing with water. Details are discussed in the books and papers by Lobanov *et al.* (1966,1967*a,b*), Barnett *et al.* (1968), Rowe and Simon (1968), Simon and Millard (1968), Fritze and Robertson (1969), Nikanorov *et al.* (1971), Schiller *et al.* (1971*b*), Santos and Walters (1971), Leushkina *et al.* (1971), Stoyanka and Dancheva (1972), Rehman (1972), Plant and Coleman (1973) and Nadkarni and Morrison (1974).

Various collectors and carriers of gold are employed in analytical methods including among others activated charcoal, metal sulphides, mercury and tellurium compounds in conjunction with various reductants and various resins. Among the last is an ion exchange resin with high selectivity for gold (Koster and Schmuckler, 1967) as well as other noble metals. This resin, a styrene-divinyl-benzene copolymer with a resonating amino group was found by Green and Law (1970) and Green *et al.* (1971) to quantitatively collect gold from acid solutions over a wide range of acid concentrations. The common metals were not collected by the resin nor did they seriously interfere with the collection of gold. They proposed X-ray spectrographic and neutron activation analytical methods for gold based on the use of paper disks containing this resin.

Native gold is readily recognized by its golden colour, its hardness (2.5), its high specific gravity (19), its marked malleability and its resistance to attack by all common acids. It is, however, readily soluble in aqua regia and in alkali cyanide solutions. It is rarely misidentified, although pyrite and chalcopyrite may sometimes be mistaken for gold. The brittleness of these two sulphides and their solution in nitric acid distinguish them readily from gold.

The gold tellurides, aurostibite and fischesserite are not easily identified by eye. Most gold tellurides have a brilliant metallic lustre and are steel grey to silver white in colour. Some incline to a slight yellowish tinge. When treated with nitric acid they are decomposed with the formation of a residue of rusty coloured gold. Aurostibite is metallic grey in colour with a bright to dull lustre. Treatment with nitric acid yields a residue of rusty coloured gold which may be obscured by white and yellow ochers of antimony oxide. Fischesserite resembles the tellurides, especially petzite. In polished sections it is isotropic under crossed nicols and has a pink colour in reflected light. If tellurides, aurostibite or fischesserite are suspected in ores, the minerals should be X-rayed to establish their positive identification.

The presence of gold in sand, gravel, soil and in ores of various types can be readily ascertained by the age old method of panning. The method can be used directly where the materials are unconsolidated. For ores a given weight of the material should be crushed, ground to a fine powder and roasted in a tin can or some other convenient receptacle in the camp fire overnight. The oxidized material is then carefully panned. By counting colours one can estimate fairly accurately the value of placer sands or various types of gold-bearing ores.

Numerous types of gold pans are in use throughout the world, including the gourd, the common gold pan, the batea and others. The operation of panning for gold cannot be adequately described; it must be seen and practised but can be easily learned by anyone. One can wet-pan if water is available, or dry-pan where there is no water by simply allowing the material to fall a variable distance onto a ground sheet the dross being removed by a suitable wind. Those wishing more details about panning should consult the three excellent papers on the subject by Mertie (1954), Theobald (1957), and Wells (1973). The techniques described in these works are also particularly applicable to geochemical methods using heavy minerals as indicators or as a sampling medium. When employing panning it should be emphasized that if the soils, glacial materials or sediments are sieved one must ascertain the best sieve size to give the optimum contrasting anomalies for the heavy minerals employed. This feature is critical for gold particles, since in any given area these tend to a relatively uniform size. If too small a sieve size is used the majority of the gold particles may be screened out with the result that significant anomalies for gold may be missed.

In addition to the pan a number of primitive apparatus can be employed in the field to separate gold from the dross. Here we need only mention the rocker, the sluice and the dry washer. The latter is often used in the desert and other arid regions. A description of this machine is given by West (1971).

When small samples are to be tested for gold a miner's spoon or oxhorn spoon should be used to separate the precious metal from the dross.

The touchstone, a piece of grey or black chert, has long been used to test gold. Agricola used it and touch-needles (a series of strips of gold alloys of graded composition) for examining bullion, coins and jewelery. The golden streak left on the touchstone is unaffected by nitric or hydrochloric acid but is removed by aqua regia.

> All is not golde that hath a glistering hiew,
> But what the touchstone tries and findeth true.
> –Times Whistle