# THE SOURCE AND TIMING OF GOLD IN OROGENIC GOLD DEPOSITS - A CASE STUDY FROM THE GIANT BENDIGO DEPOSIT. IMPLICATION FOR EXPLORATION

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- **Despite differences of opinion regarding the formation of hydrothermal mineral deposits there is general consensus on the process of their formation. The mineral deposits are the result of combined processes: the mobilization of metals and their precipitation in local areas.**

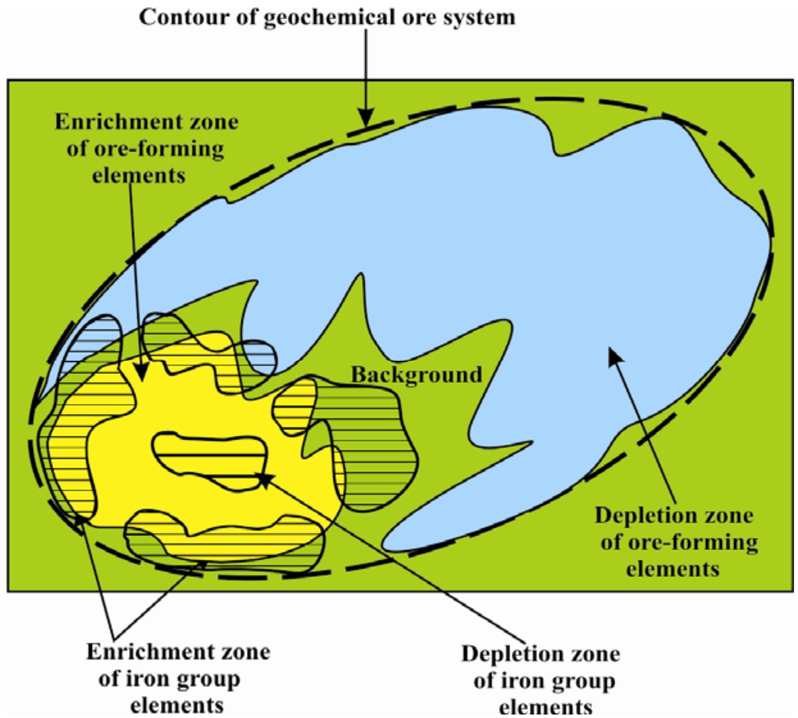
- **However, the location of mobilization regions as the metal sources is the most debated question. Two extreme points of view are discussed at length: whether the region of mobilization is located in proximity to the region of concentration or is it distant.**

- **The position of the region of mobilization near the mineral deposit can be established based on geochemical mapping. Such regions must be characterized by the lower concentrations of ore elements with respect to the background and it is mapped as depletion zones.  The pair of depletion and enrichment zones is combined with each other and can be represented as a single structure, which we have called: “Polar Geochemical Ore System”.**

# MODEL OF GEOCHEMICAL ORE SYSTEM

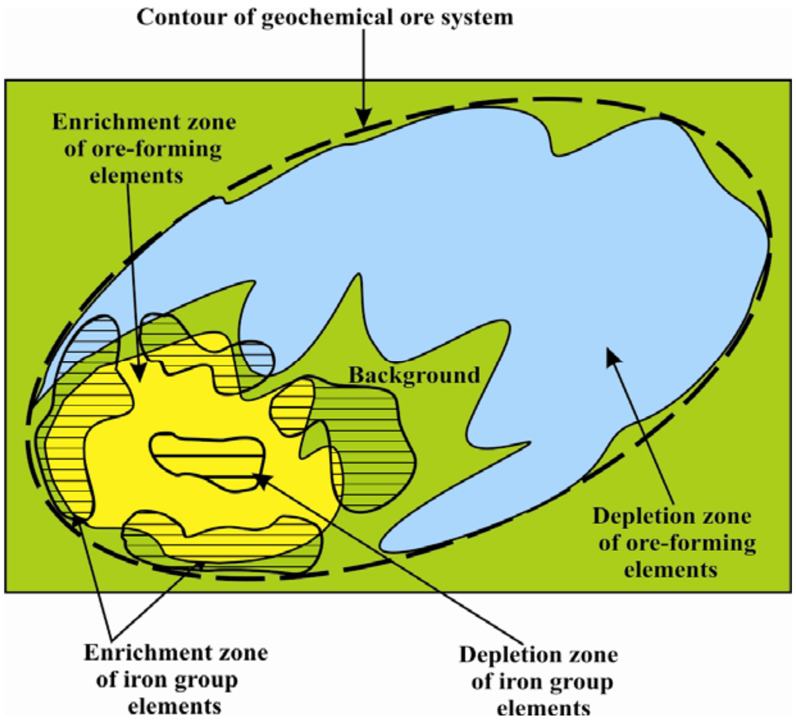
The 3 distinctive features of such systems are as follows:

1. The polar zoning of ore-forming elements is comprised of the enrichment zone and the outward depletion zone. The size of the geochemical ore deposit system can range between a few square km and few hundred square km. Geochemical systems of giant deposits can range from a few hundreds to several thousand square km.

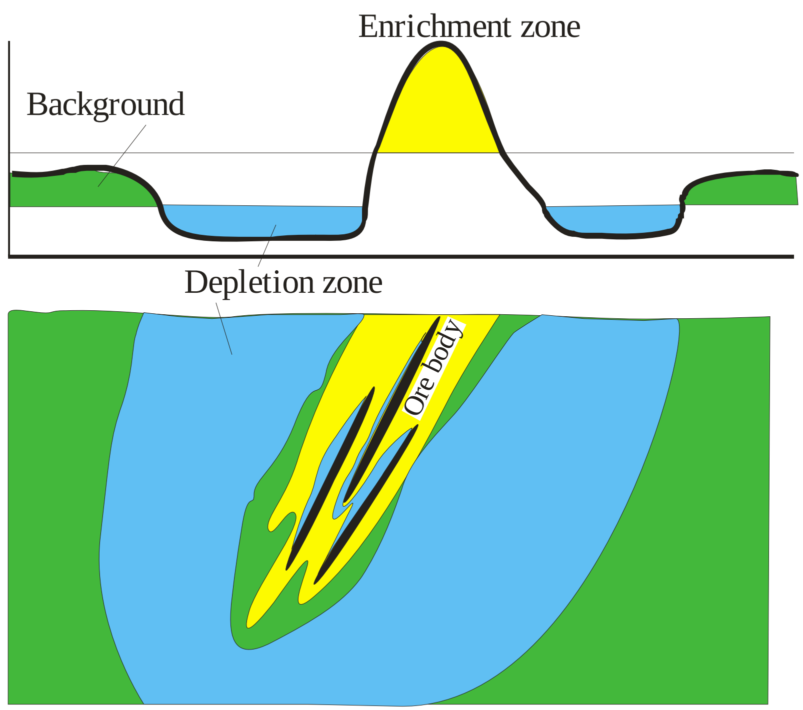


# MODEL OF GEOCHEMICAL ORE SYSTEM

**2. Polar zoning of ferrous group elements (i.e. Fe, Sc, Ti, Cr, sometimes Zn and/or Cu) - the external zone of the nucleus of the system is enriched with ferrous group elements and within the nucleus of the system the ferrous group is usually depleted.**



# MODEL OF GEOCHEMICAL ORE SYSTEM




**3. Geochemical systems are fractal and occur at all scales. This means, that they are characterized by continuous self-similarity. The geochemical system of the ore body are located in the nucleus of the geochemical system of the deposit.**

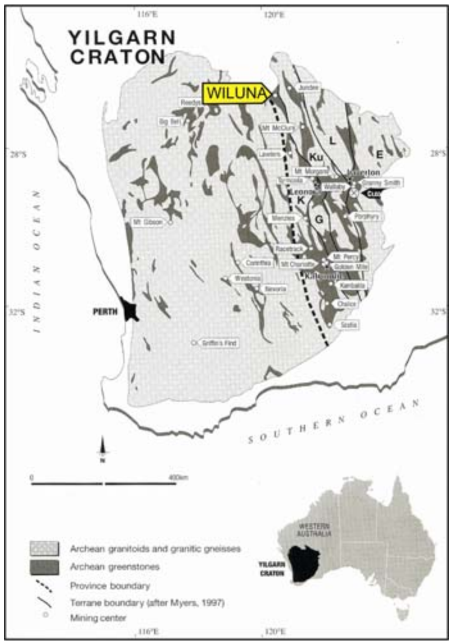
# MODEL OF GEOCHEMICAL ORE SYSTEM

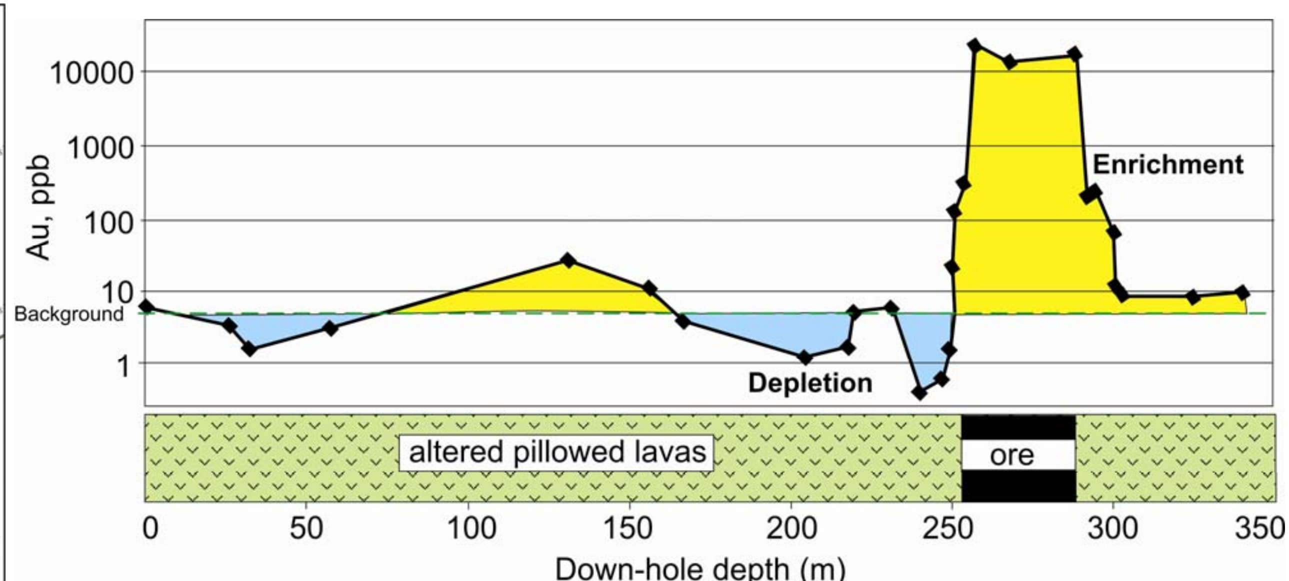
**Such geochemical systems are established for the mineral deposits of different compositions and structures.**

- **There is numerous evidence of the existence of depletion zones of ore-forming elements that include elements with low crustal abundances (gold and other).**
- **The degree of release of the ore-forming elements in the depletion zone is over 40-50%**

## Wiluna Archaean orogenic gold deposit.

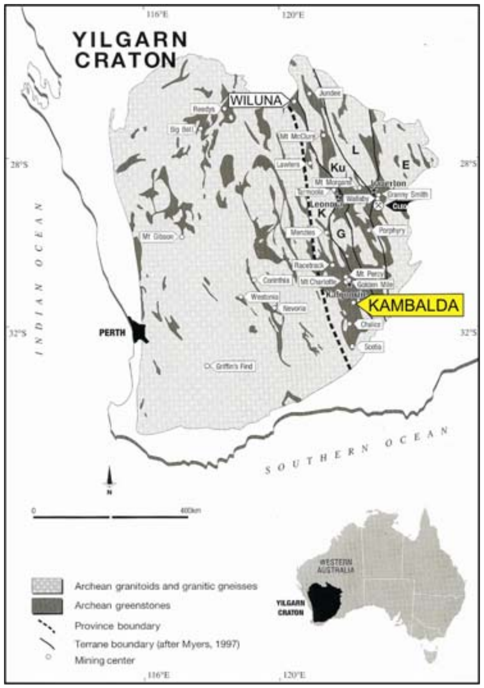
**Northernmost Norseman-Wiluna Belt in the Yilgarn Craton, Australia** (modified from P. Eilu & D. Groves, 2001)

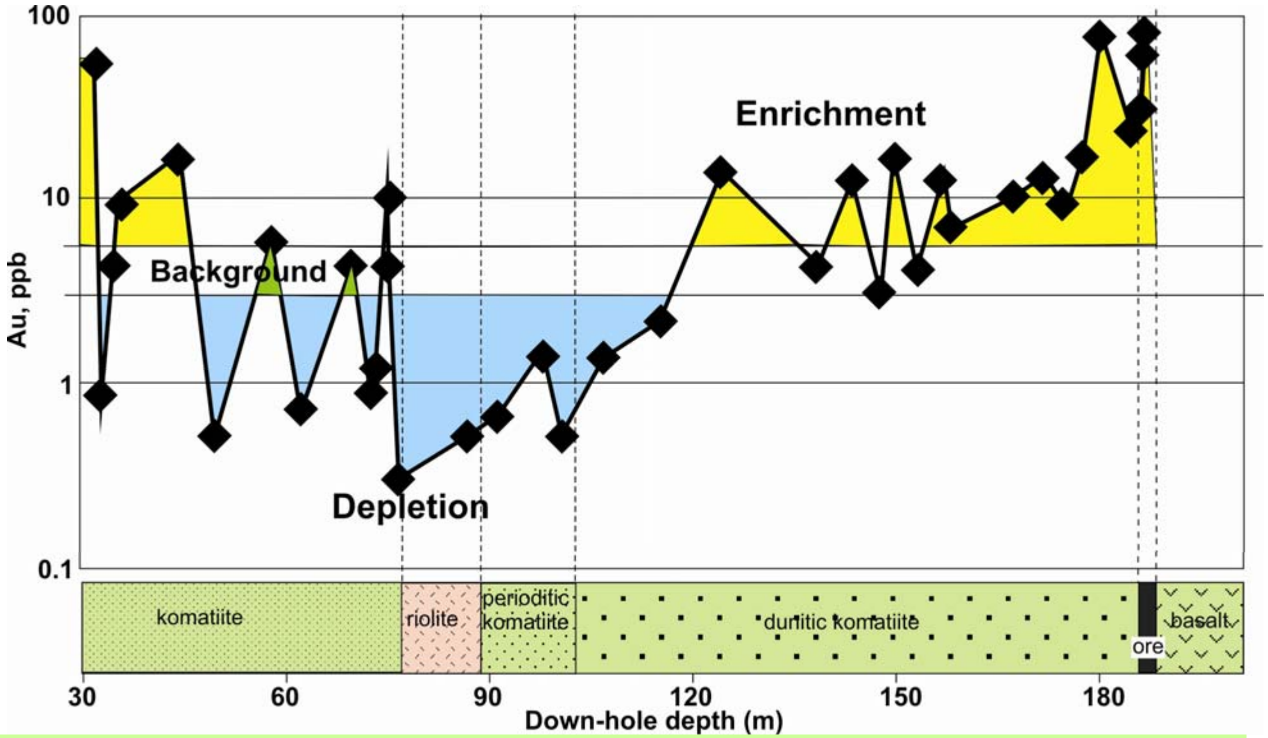



**The profile represents a section across the main ore zone. The gold deposit is hosted in basalt. *Background threshold value for Au estimated in 6 ppb*. The depletion zone is immediately adjacent to the ore body in the hanging wall. Gold content is 1.0 ppb and lower.**

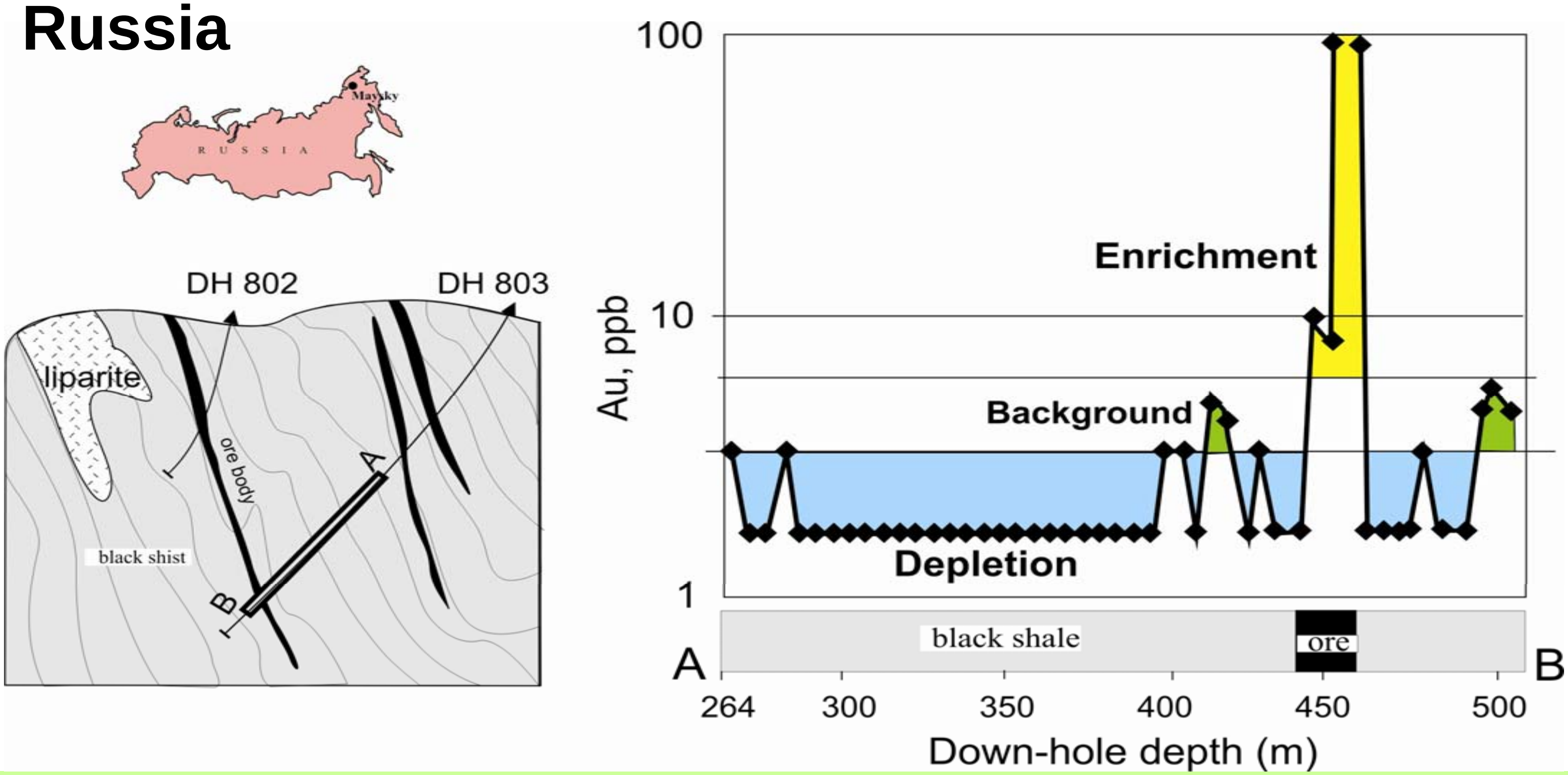
## Ni-Cu Kambalda deposit. Norseman-Wiluna Belt in the Yilgarn Craton, Australia (modified from Raid R. Keays, 1982)



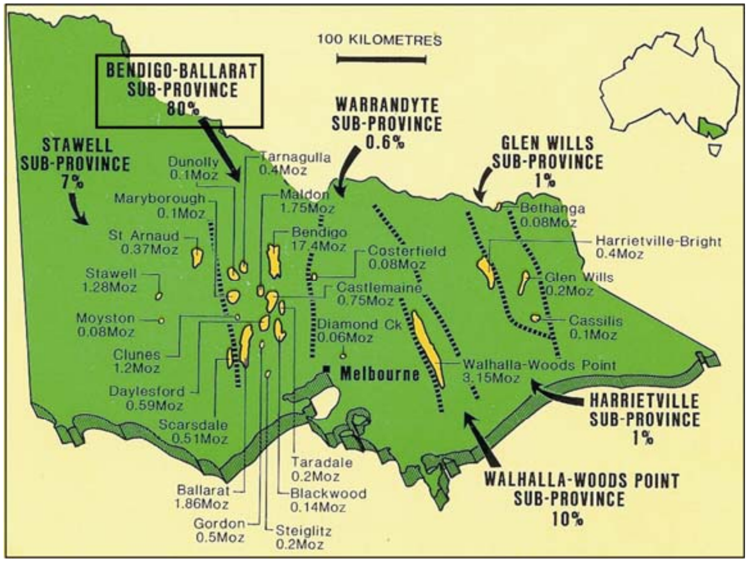

**The profile represents a section across the ore zone in the thick komatiite flows (drill hole KD 127). The Au value in the hanging wall tends to show extensive oscillation from 0.2 ppb up to more than 100 ppb. *Taking in account that the background levels are 5-6ppb,* then the width of the depletion is approximately 40m.**

# Maysky gold - arsenopyrite ore deposit. Chukotka. Russia

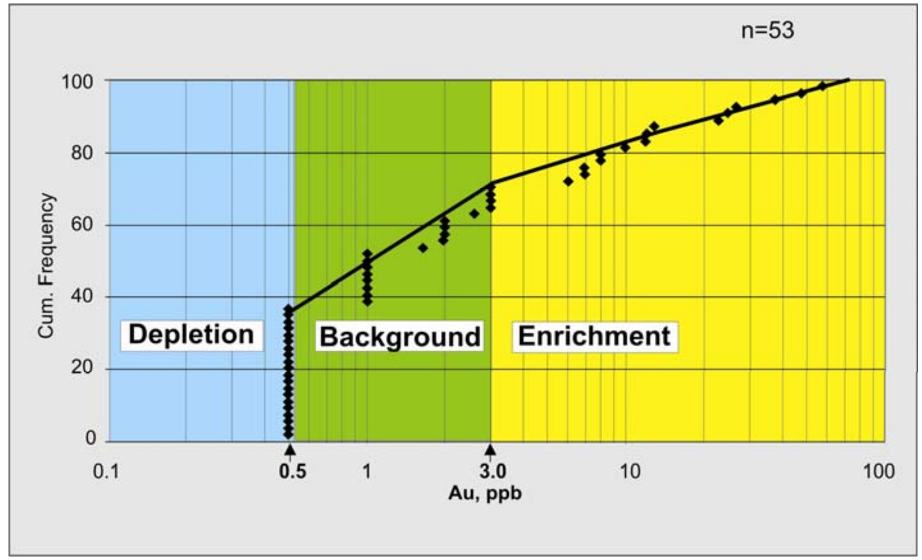



**The deposit (reserve 300t) occurs in a Triassic black shale flyschoid sequence. The ore zone on a whole is 800 m wide and more than 1 km deep. Gold mineralization forms wing-like veins. Gold, as discrete particles, is found within arsenopirite grains.** ***Background value for Au estimated from 3-7 ppb*****. Around the ore body there is a depletion zone in the hanging wall of more than 100 m with concentration less than 3 ppb.**

## Location of gold deposits



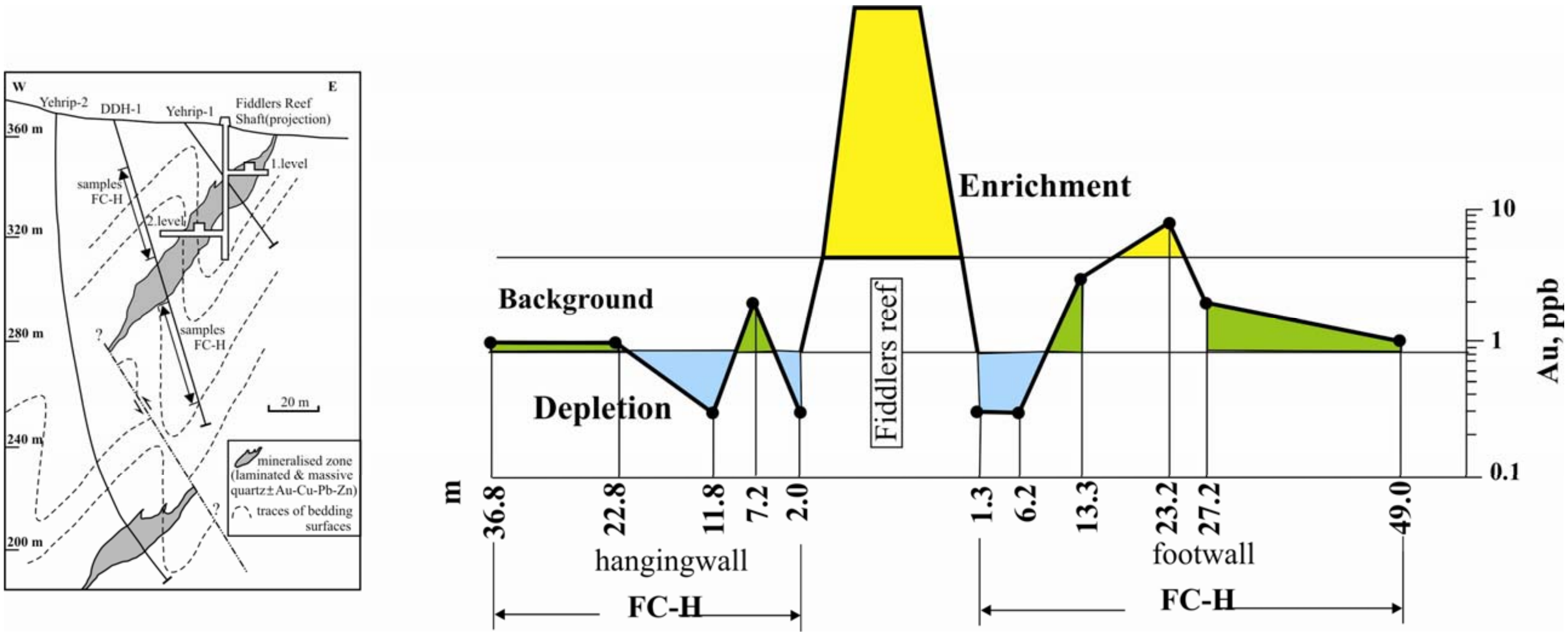

## Cumulative distribution plot of Au in host rock of Bendigo- Ballarat Sub- Province




**Frank Bierlein and his colleagues carried out a research of gold distribution at ore bodies in Fosterville, Fiddler's Reef, Maldon and Ballarat goldfields in Central Victoria, Australia. This graph shows the cumulative distribution plot of Au in mineralized zones and wall rock. Concentrations of <= 0.5 ppb are interpreted to represent gold depletion relative to background values from 0.5 ppb to 3 ppb. Values >= 3 ppb are interpreted to represent gold enrichment.**

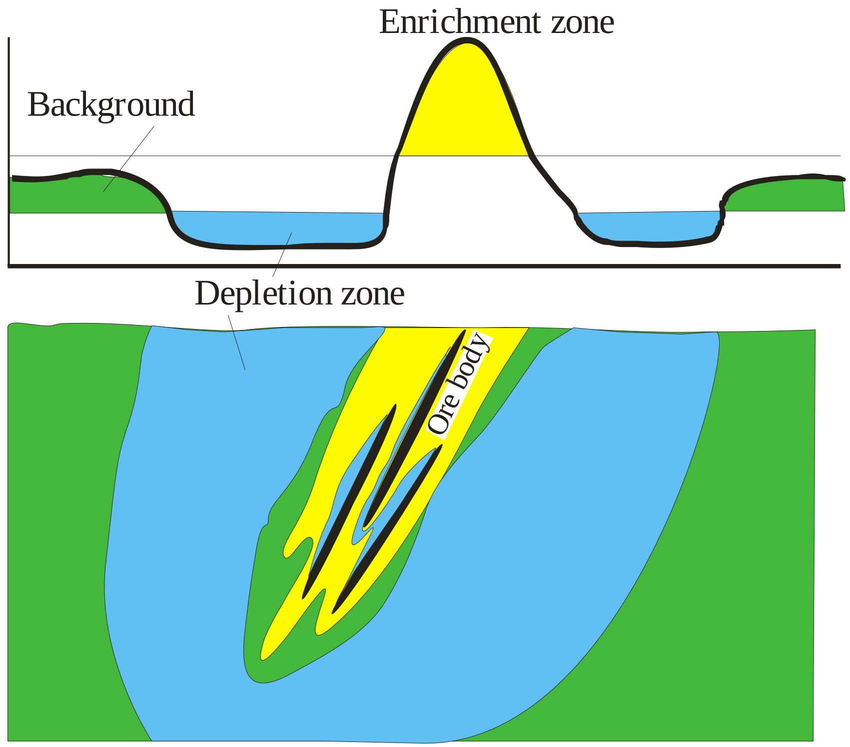
**Cross-Section through the Fiddlers Reef**

**Turbidity-hosted Fiddlers Reef gold deposit. Central Victoria, Australia**




**The profile represents a section across the main ore zone. The gold mineralization is hosted by turbidities. The depletion zones are immediately adjacent to the ore zone in both the hanging wall and the footwall. The width of the depletion zone in the hanging wall is up to 10 to 12 meters.**

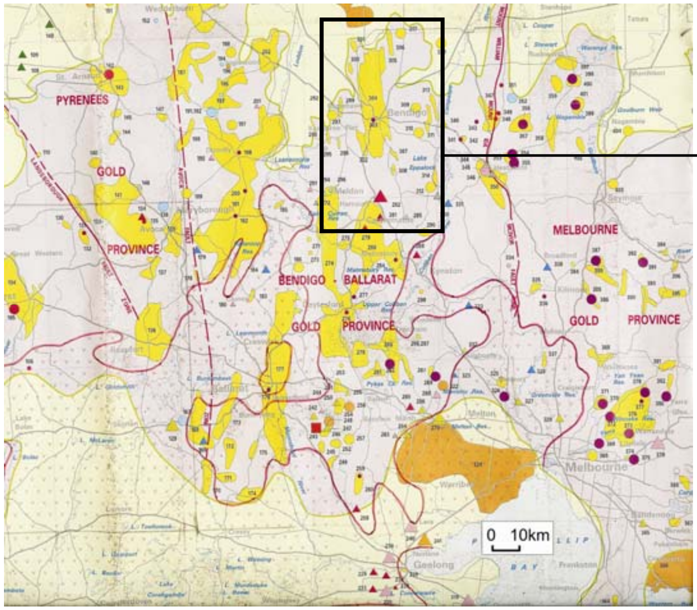
# POLAR ZONING OF GOLD DISTRIBUTION IN ORE DEPOSIT SCALE



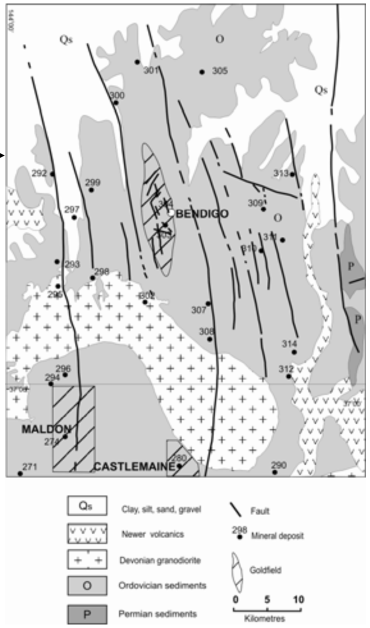

**In the deposit scale the ore mineralisation and dispersion halo is outlined as an enrichment zone. This zone is surrounded by a depletion zone of ore forming elements.**

In 2004 our company, IONEX Pty Ltd, completed a geochemical survey in the scale of 1:500,000 (to approximate a grid of 5 km x 5 km) covering 3750 km$^2$ in the Bendigo region, Central Victoria (Australia).

## Bendigo-Ballarat Gold Sub-Province

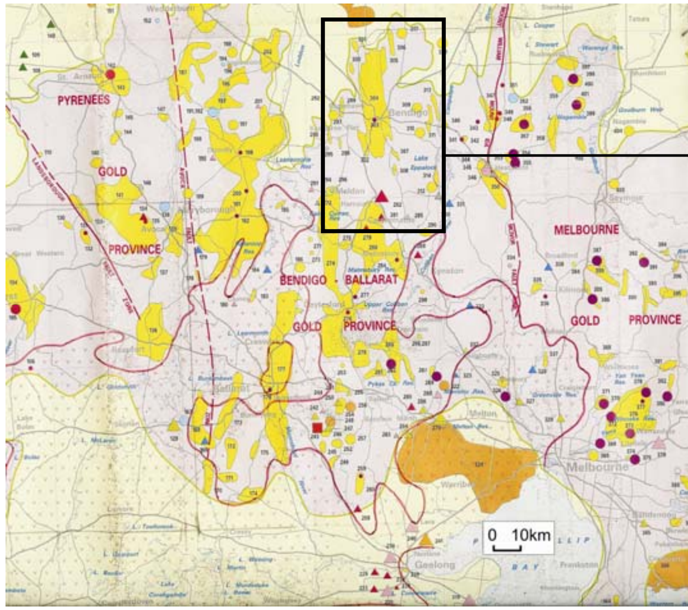



## Geological map of Bendigo region

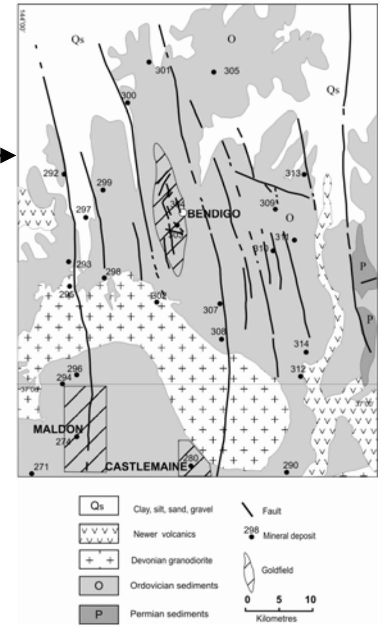



The Bendigo - Ballarat Gold Sub-Province (zone) in the western part of the Lachlan Fold Belt is one of the major gold districts in the world with total production of 2500t Au (i.e. 79M oz). The studied area includes the giant Bendigo goldfield, and the smaller goldfields of Maldon, Castlemaine and Fosterville.  A further 29 smaller goldfields and gold reefs are known to be located in the area

## Bendigo-Ballarat Gold Sub-Province



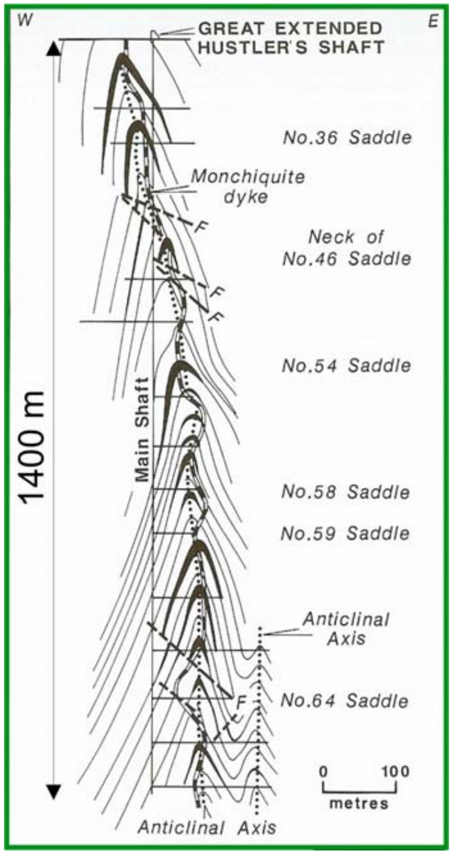

## Geological map of Bendigo region




**In 2004 our company, IONEX Pty Ltd, completed a geochemical survey in the scale of 1:500,000 (to approximate a grid of 5 km x 5 km) covering 3750 km$^2$ in the Bendigo region, central Victoria (Australia).**

**The rock is mostly flyschoid sedimentary facies, shales and muds of Cambro - Ordovican age. Regional metamorphic grade in sedimentary rocks appears to vary from prehnite-pumellyte to lower greenschist conditions. The sedimentary rock is folded, with a mostly submeridianal axis of folding. The sequence is intruded to post - orogenic granites generally of Early to Late Devonian age.**

**Shaft cross-section. Saddle type reefs** (from Herman, 1914)




**Saddle type quartz reef**

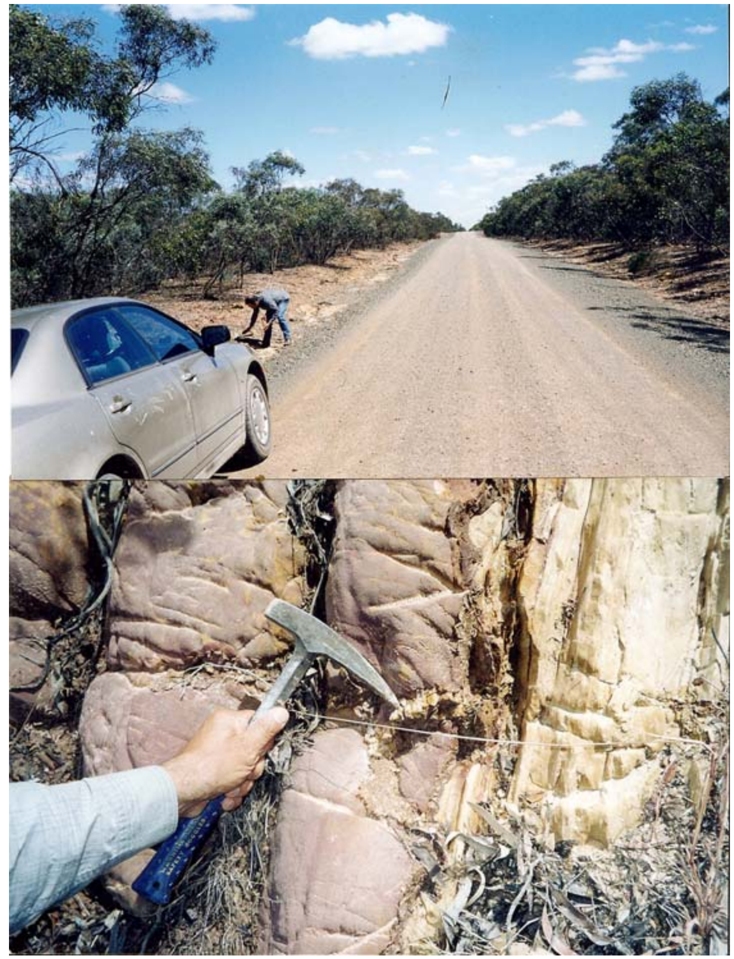
**Quartz-carbonate stockwork**

**This deposit is a classic example of a low-sulfide turbidity-hosted orogenic gold-quartz deposit (sulfide less than 2-5%) located in the folds of sandstone-shale rock as a saddle reef and as discordant veins and stockwork, predominantly in the anticlinal domes.**

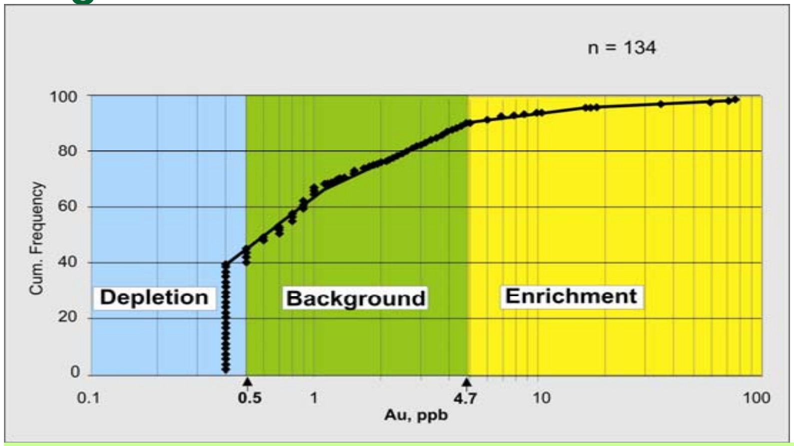
# Sampling and Analysis

- A total of 142 samples of both granitoids and sedimentary rocks were collected along roads and tracks. Samples were taken from outcrops at sites least affected by weathering; the weight of each sample was about 500 g.

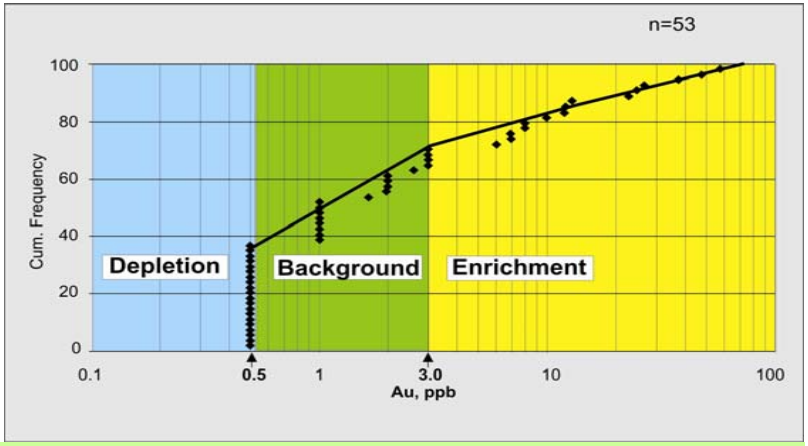
- The gold analysis was carried out at ALS Chemex in Brisbane by fire assay using a Pb bead and an ICP-MS finish (Hall and Pelchat, 1994).



**Cumulative distribution plot of Au in host rock of Bendigo region**




**Cumulative distribution plot of Au in wall rock of deposits of Bendigo - Ballarat Sub- Province**



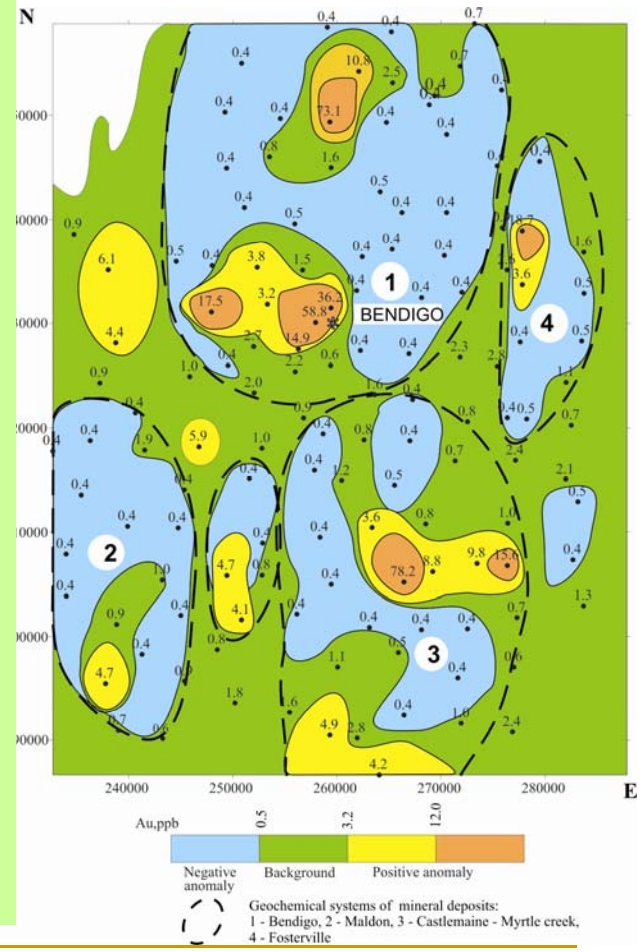

- **Cumulative distribution plot of gold according to surfical geochemical sampling of Au closely resembles the cumulative distribution plot of Au in the samples from the drill holes crossing wall rocks of gold deposits in the Bendigo Ballarat Gold Sub-Province. It can be an objective evidence proving that lower than background concentration of Au is not connected to surfical weathering, and indicates endogenetic phenomenon.**

- **Concentrations of <= 0.5 ppb are interpreted to represent gold depletion relative to background values of 0.5 to 4.7 ppb, close to an average crustal abundance for such rocks. Values >= 4.7 ppb are interpreted to represent gold enrichment.**

## Gold distribution in the Bendigo region

**Four polar geochemical systems are identified in the surveyed area. Smaller goldfields did not exhibit such a clear pattern, though it may be an expression of sampling density.**

**1. The Bendigo goldfield: The gold enrichment zone surrounding the Bendigo goldfield has an area of approximately 100 km$^2$. The highest concentration (59 ppb) coincides with the Deborah ore zone. To the north is an extensive gold depletion zone, which has not been completely outlined. The gold population of low concentration does not occur at random, but tends to cluster over relatively enriched areas. The depletion zone is 700 to 800 km$^2$ and characterized by rocks having uniformly low concentrations of gold of <0.5 ppb. Within the depletion zone there is a local gold enrichment zone that coincides with the Elysian Flat gold deposit. The combined zones occupy an area well in excess of 1,000 km$^2$.**

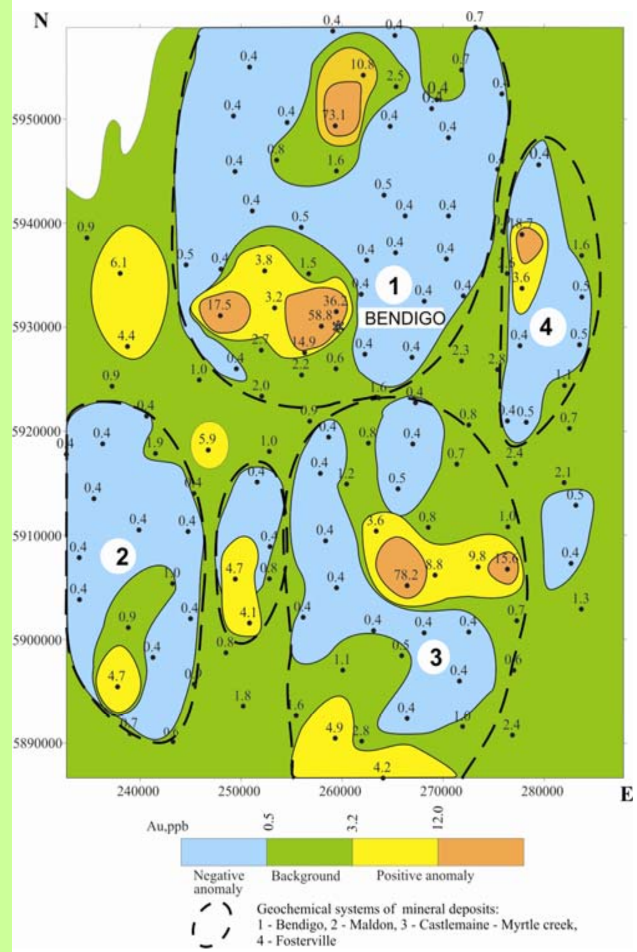


# BENDIGO REGION, CENTRAL VICTORIA.

***2.* The Maldon goldfield. The gold enriched zones have a combined area of about 300 km$^2$, coinciding with the location of the gold mineralization, but they have not been fully outlined to the south and west. A gold depletion zone of more then 200 km$^2$ surrounds (and continues to the north) of the enriched zones. The depletion zone has been observed both in sedimentary rock and Late Devonian granodiorite**

**3. The Castlemaine deposit. Two zones of gold enrichment are apparent; one in the south, which coincides directly with gold mineralization at Castlemaine , and one in the north which coincides with four smaller goldfields. Several zones of gold depletion that may be spatially associated with the gold enrichment zones have a combined area of about 300 km$^2$.**

**4. The Fosterville goldfield occurs within a zone of gold enrichment (40 km$^2$) that is surrounded by a zone of gold depletion (150 km$^2$).**



# The Source of Gold at Bendigo and other Turbidity-Hosted Gold Deposits in the Bendigo area

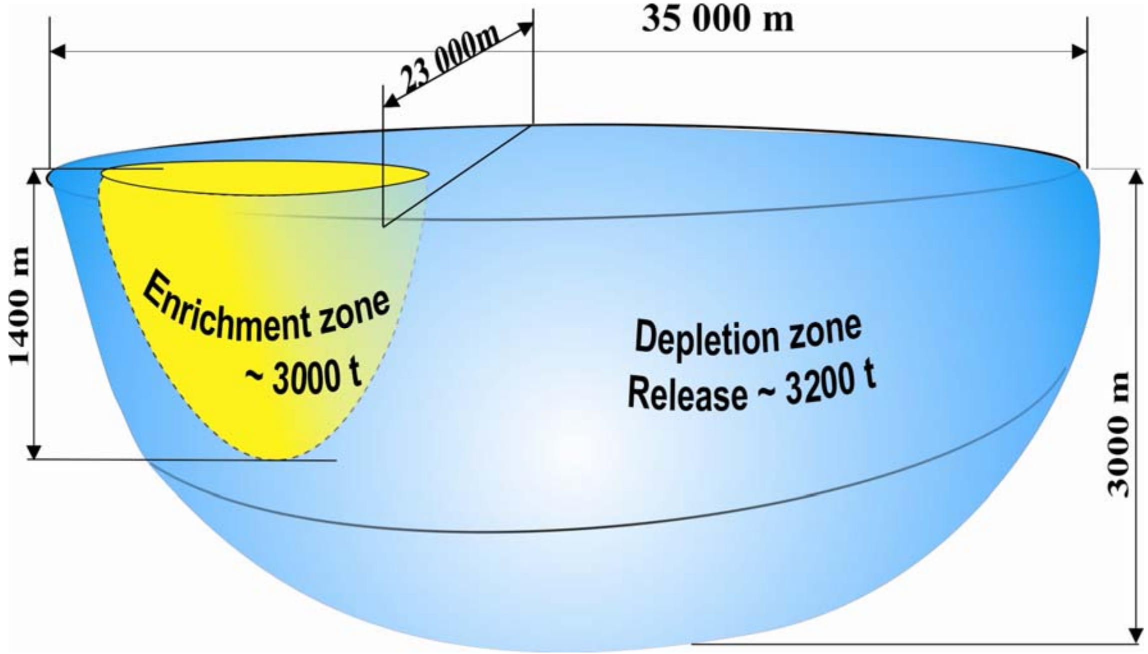
**The presence of intensive gold depletion zones suggests that these rocks could have been a source in these deposits. The table below support this concept.**

**Mass balance calculation**

| Zones | S, $km^2$ | $H_{depth}$, km | V, $km^3$ | $Au_{average}$, ppb | $Au_{enrich}$, ppb | $Au_{loss}$, ppb | R, t |
|---|---|---|---|---|---|---|---|
| **Enrichment zone** | **100** | **1.4** | **140** | **14** | **12.71** | | **~3000** |
| **Background** | | | | **1.29** | | | |
| **Depletion zone** | **800** | **3** | **2400** | **0.5** | | **0.79** | **~3200** |

**The calculation of Au mass in the enrichment zone, carried out for a depth of 1.5 km (taking in account that ore body reached a depth of 1.4 km) and area of 100 km². The calculation of Au released in the depletion zone carried out for depth of 3 km and area of 800 km². With the obvious approximation of this calculation, the order mass of Au enriched (3000 t) and depleted (3200 t) are matching. It means that 1.2 t of Au was released from 1 km³ of rock.**

## Model of the geochemical system of Bendigo gold deposit




- **The significant volume of the depletion zones in the Bendigo geochemical system, as well as in those of other deposits, suggests that turbidity-hosted rock is not only an active environment for gold precipitation, but can also be considered a significant source of the gold at Bendigo, and probably other gold deposits of the Victorian gold province.**

# Model of the geochemical system of Bendigo gold deposit

- The idea that gold concentrations are derived from host rock as the source of gold in deposits in Central Victoria, is not new. Australian geologist Daintree, studying the layers of gold, wrote into 1866: “I had long ago come to the conclusion, that most, if not all, the gold in the quartz reef was derived from the rocks in which these reefs occur”
- This quotation had been expressed by Robert W. Boyle in the section on secretion theories in his monograph “Gold: History and Genesis of Deposits” (1987).
- The collection  of new data makes it possible to revive the previously expressed idea about the significant role of the host rocks as the sources of metals.

# Timing of Mineralization

- In which period did the process of gold mobilization take place? Most authors relate the essential phase of deposit formation to the period of rock deformation. This ore type has been classified as "syndeformational turbidity-hosted gold deposit" (Solomon and Groves, 2000).

- Despite differences of opinion regarding the timing of gold mineralization in the province, there is general consensus that the process of ore formation predates the Late Devonian granitoids.

- Although the data from our geochemical rock survey does not date the commencement of the process, we believe the results show that ore formation continued after the intrusion of the Later Devonian granitoids. This conclusion can be made since the depletion zone of gold are noted also in the Later Devonian granitoids.

# Implication for exploration

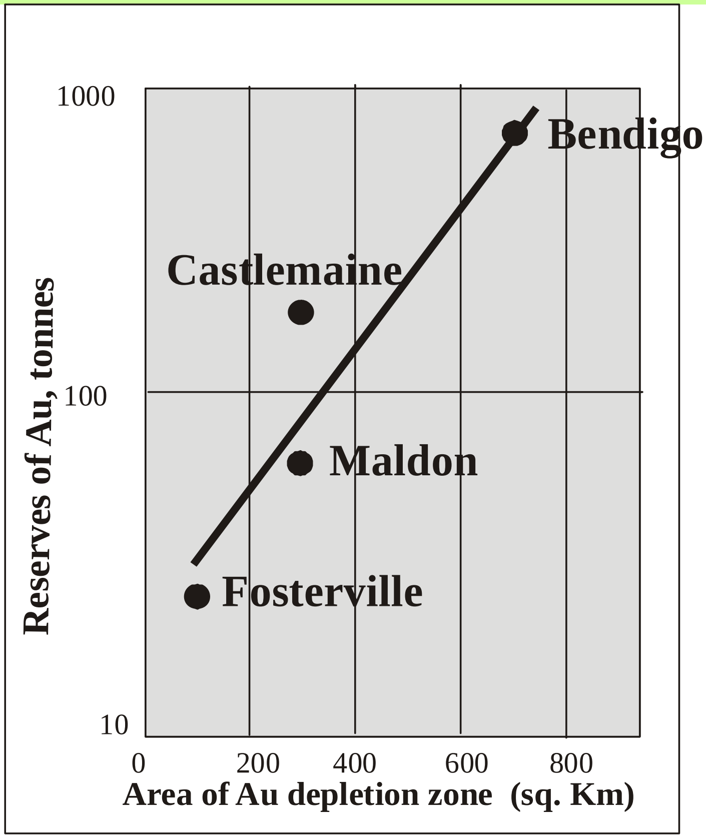
- **For appraising favorable areas the following main well known criteria are applied:**
  - **the magnitude of the positive anomaly;**
  - **the size and shape of anomaly areas;**
  - **the zonality of elements in anomalies;**
  - **geological setting;**
  - **the extend to which the local environment may have influenced the metal content and the anomaly pattern**

***Problems of appraising a favourable anomaly could be largely overcome by considering depletion zones which is currently almost ignored. A links with the enrichment zone suggests another criterion for appraising favorable areas:***

- **the link between the size of depletion zones and metal reserves in the ore deposits**

## THE CRITERIA APPRAISING FAVOURABLE AREAS

- **The link between the size of Au depletion zones and Au reserves in the gold deposits of the Bendigo region**



## PHILIP W. ANDERSON
## The 1977 Nobel Laureate in Physics

**"It proposes that nature is the way we would like it to be, rather than the way we see it to be , and it is improbable that nature thinks the same way we do"**