# Compressional Tectonics of the Carlin Gold Trend

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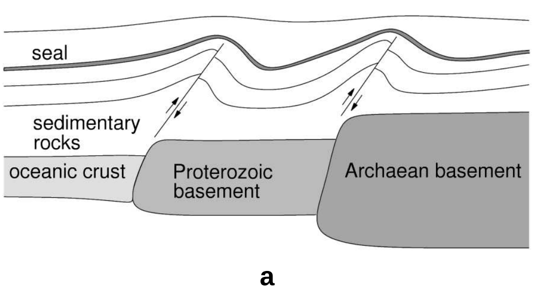
## Introduction

Pre-existing crustal structures are important in localising strain related to the large-scale evolution of an orogeny. Rheological contrasts between basement blocks will also influence the degree and location of faulting and relative uplift. In northern Nevada, U.S.A., basement architecture in the form of early rifted continental margins, formed during Proterozoic extension, may dictate the subsequent structural geometry of overlying sedimentary sequences during large-scale compression (Figure 1a). Within the region of the Carlin gold trend, specific anticlinal fold and thrust geometries in the sedimentary rocks, involved in various orogenies up until the Laramide, may focus fluid movement and provide effective traps to the system, resulting in the unique gold endowment of the area. Most mineralisation is situated less than 100 m below the Roberts Mountain thrust, which defines the lower boundary of the sequence of deep-water sedimentary rocks that has ridden over both the basement and younger sedimentary layers.

Muntean et al. (2003) argue that the Carlin and Battle Mountain–Eureka (BME) gold trends (Figure 1b) correspond to reactivated normal faults that likely had their origins in Proterozoic rifting. Numerical modelling offers a way to test the basic hypothesis by which "steps", relics of continental rifting, control the subsequent location of upper crustal faults and anticlinal structures during compression.



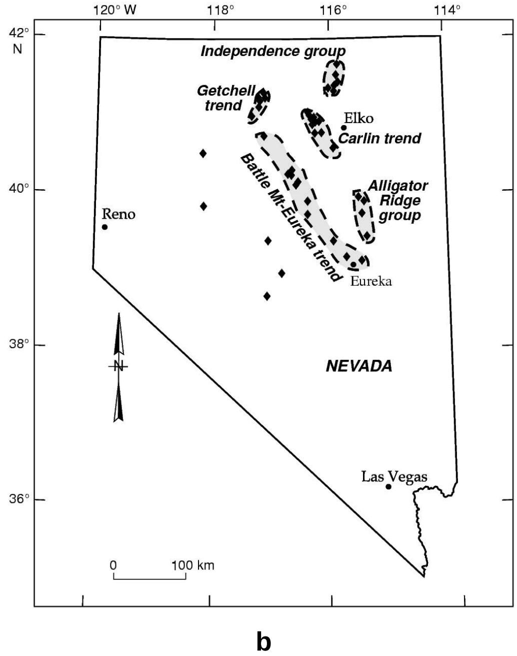
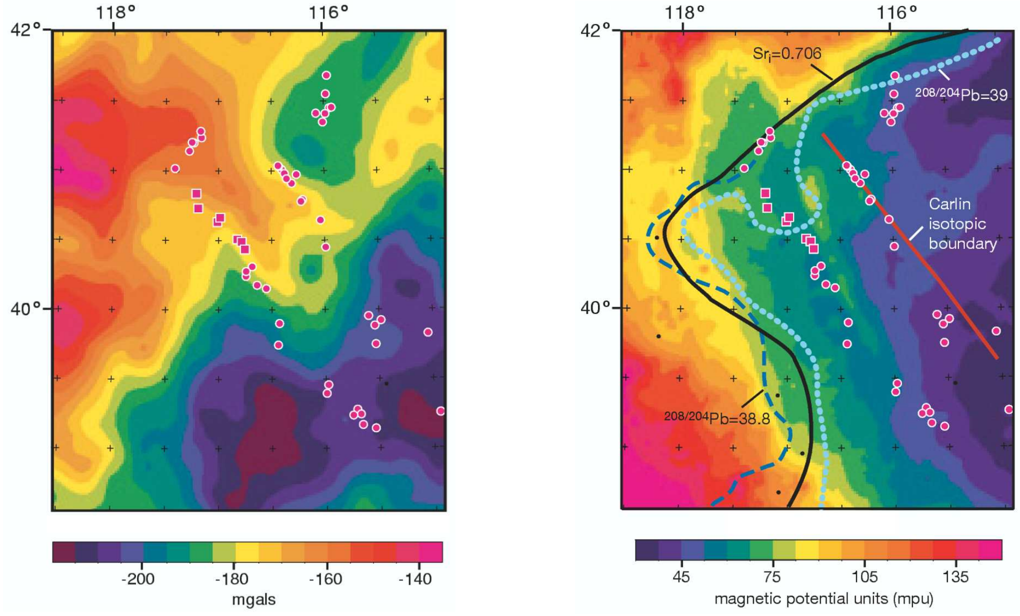


*Figure 1: (a) Schematic conceptual model for the structural setting of the Carlin trend above a basement normal fault that is reactivated during compression. Three crustal blocks represent the product of a rifted continental margin. (b) Gold deposit trends in northern Nevada, U.S.A. Image from Wooden et al. (1998).*



**a** **b**

*Figure 2: Gold deposits (circles and squares) on top of (a) 5 km upward continued Bouguer gravity anomaly with basin effects removed, and (b) magnetic potential with Pb and Sr isotope ratio boundaries. Images from Grauch et al. (2003).*

## Geological Setting

Following continental rifting in the Proterozoic through to Devonian, present-day northern Nevada has been subject to a number of compressional episodes of varying duration. These range from the Antler orogeny, approximately 340 Ma ago, through to the Laramide orogeny, which ended with the onset of Basin and Range extension about 50 Ma ago (Miller et al., 1992). The Roberts Mountain thrust, which defines a regional cap to the mineralisation, and probably acted as a permeability seal, occurred during the Antler orogeny. Subsequent events thrust more sedimentary sequences over the Roberts Mountain allochthon.

The linear arrangements of gold deposits along the BME and Carlin trends (Figure 1b) have prompted many researchers to look for evidence of large-scale structural controls, especially in geophysical data (e.g., Rodriguez, 1998; Grauch et al., 2003). The demarcation between ancient continental crust and younger oceanic crust is well established through Pb and Sr isotope ratios (Wooden et al., 1998; Grauch et al., 2003), but this boundary, although close, is not coincident with the major mineral trends. Processing of gravity and magnetic data by Grauch et al. (2003) has revealed features that align with mineral occurences; these are more persuasive for the BME than the Carlin trend (Figure 2). A 2D inversion of magnetotelluric data also shows narrow, vertically extensive, electrically conductive zones under the two trends, which Rodriguez (1998) interprets as crustal faults.

If the geophysical data are highlighting major crustal faults that control the locations of the mineral trends, these may be expressions of the reactivation of early normal rift faults at even deeper levels (Figure 1a). The relative offsets between reactivated normal faults and their propagated thrusts in overlying sedimentary rocks are likely to be complicated by multiple orogenies, gravitational slumping, and widespread extension in the Eocene and later.

## Numerical Modelling

The numerical approach has been developed explicitly to deal with unlimited strain, and can simulate the spontaneous localisation of shear structures (Moresi et al., 2001, 2002). The 2D section model follows an approximate ENE–WSW transect running from Archaean cratonic crust in present day Utah,

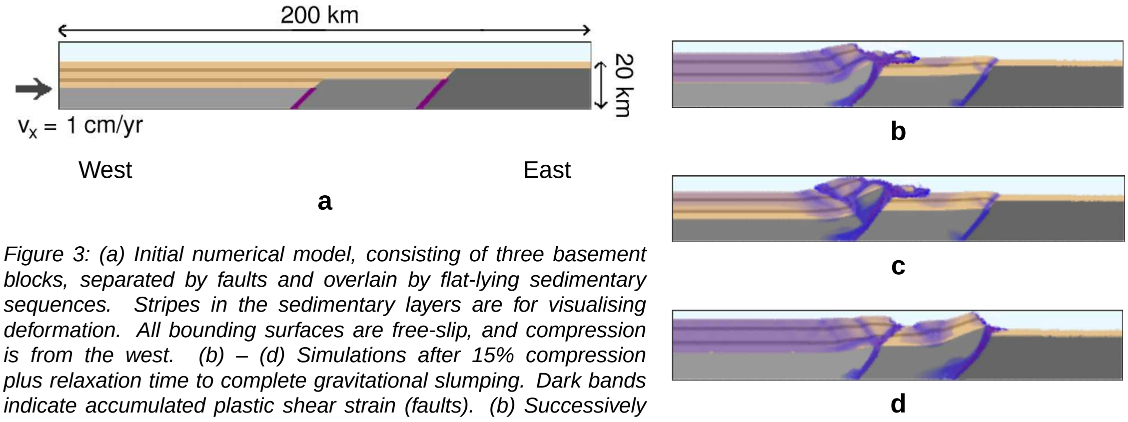


*Figure 3: (a) Initial numerical model, consisting of three basement blocks, separated by faults and overlain by flat-lying sedimentary sequences. Stripes in the sedimentary layers are for visualising deformation. All bounding surfaces are free-slip, and compression is from the west. (b) – (d) Simulations after 15% compression plus relaxation time to complete gravitational slumping. Dark bands indicate accumulated plastic shear strain (faults). (b) Successively less competent blocks from east to west, (c) equally competent oceanic and transitional blocks, and (d) stronger western fault.*

U.S.A, to the oceanic crust along the protomargin of western North America. The numerical model represents three basement crustal blocks – Archaean, transitional or Proterozoic, and oceanic – that are the product of continental rifting during the Proterozoic through Devonian (Figure 3a). These blocks are separated by normal faults that provide zones of weakness that will reactivate. The strengths of the different crustal blocks and the weakness of the faults vary, in order to determine the importance of fault reactivation versus rheological contrast in controlling the structural development in the overlying layers.

In the case of successively weaker basement blocks from east to west, and equally weak basement faults (Figure 3b), most slip occurs along the first fault, and the eastern fault is barely reactivated. The oceanic crust is thrust up against the transitional crust, providing the elevation for thrusting of western sedimentary rocks over eastern ones, mostly by gravitational slumping. Eastern sedimentary layers are isolated from deformation.

A lack of rheological contrast between oceanic and transitional basement (Figure 3c) does not affect the outcome in terms of strain partioning between basement faults. However, the more competent oceanic crust undergoes faulting rather than homogeneous thickening, which provides locally greater elevation for the sedimentary rocks in the vicinity of the basement thrust.

When the western fault is stronger, the eastern fault is not protected from reactivation (Figure 3d). Strain is equally partioned between both basement faults, with the result that neither area experiences the elevation of previous cases, and the sedimentary sequences are not thrust very far to the east.

## Discussion

The structural evolution of the sedimentary sequences that host Carlin-type deposits depends less on rheological differences between basement blocks (Archaean, transitional, oceanic) than the ability to reactivate deep faults, which then propagate into the overlying sedimentary rocks. The upper plate motion across the lower plate is largely a product of gravitational slumping rather than thrusting due to far-field stress, but this may be due in part to the steeper (45°) angle of thrusting that is an outcome of the constitutive model in the numerical code. Uplift is important for promoting slumping over great distances, and depends on basement rheology. Weaker blocks undergo greater thickening overall, but more competent blocks may experience localised uplift as a result of pop-up structures (Figure 3c).

Field evidence shows that anticlines are important for hosting Carlin-type gold deposits, and these would act as natural fluid ponding sites if seals are present. A ramp anticline often develops when there is compression across existing faults (e.g., Cooke and Pollard, 1997), or, as in the model, against a ramp between two basement blocks. The ramp is effective in localising an anticline in the sedimentary rocks above basement topography. The fluid ponding potential of such structures is enhanced if they remain unbroken by thrusting.

Another ubiquitous feature of the model is the nature of the first fault that forms in the sedimentary cover: a backthrust formed off the basement asperity (Figures 3b to d). The implication is that an early backthrust should exist in such a field situation, and it will reach the basement and thus be a candidate for tapping deep fluids. This feature of the model also explains anomalous west-vergent deformation associated with a geanticline that is locally, but not everywhere, subparallel to the Sr 0.706 line – the inferred edge of the continent (Madden-McGuire and Marsh, 1991; Saucier, 1997).

Elevated pore pressure is one of the most effective ways to change the stress regime and promote failure and fracturing where it would not otherwise occur. A low-permeability cap in the sedimentary layers, perhaps in the form of the Roberts Mountain thrust, would lead to elevated pore pressures in the rock column below as more material is thrust above (e.g., Hubbert and Rubey, 1959). This has the immediate effect of extending the depth of faulting towards the basement, possibly reaching more deeply sourced fluids and enhancing the control that basement features exert on fault locations. If a permeability seal can be kept contiguous, deeper faulting will be allied to an effective fluid trap until a significant change in the stress regime allows venting and mineral precipitation.

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