

## **Stretched to the Limit: An Extensional Detachment Setting for the Gosowong Epithermal Goldfield, Halmahera, Indonesia**

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Quartz vein-hosted, low sulfidation, high-grade Au-Ag ores represent great prizes for miners, yet are notoriously difficult to explore for due to their narrow hydrothermal footprints and subtle petrophysical signatures. Development of predictive structural models via direct analysis of the vein arrays can also be hampered by non-Andersonian fracture mechanics in the near-surface environment and vein opening modes that do not produce the range of kinematic indicators classically used to decipher the structural history of mesothermal Au deposits. In this study of the world-class Pliocene Gosowong goldfield of Halmahera, we circumvent these limitations through the construction of a four-dimensional district-scale structural model, based on analysis of lithostratigraphic architecture. The method allows us to project controlling structures beyond the limits of the mineralized vein arrays, identify lithologic and hydrologic controls on vein propagation and alteration styles, and link the geometrically diverse ores that occur throughout the district.

Volcanogenic host strata record a progression from basaltic to dacitic magmatism and accumulation within an array of extensional and transtensional depocenters. Fundamental structures are anomalously shallowly N to NE dipping (15°–30°), akin to those formed in high-strain rate, high-magnitude displacement extensional settings. Tertiary detachment faults are well documented from neighboring North Sulawesi, where they have accommodated exhumation of metamorphic complexes, but at Gosowong they have been abandoned shortly after epithermal mineralization, accumulating 1 to 1.5 km throw on individual surfaces. The detachment faults are planar to corrugated and linked by laterally discontinuous NW- to NNE-striking transfer arrays. Evidence of growth exists in middle (andesitic) and upper (dacitic) levels of the volcanic pile. The latter, which record an abrupt upsection transition from lava-dominated to mixed pyroclastic, volcanosedimentary, and subordinate coherent facies, are affected by liquefaction/fluidization-related disaggregation, indicating high pore fluid contents during deformation phases. The fault array and rheological architecture of volcanic pile also controls the emplacement of dioritic to dacitic sills and lesser dikes, which are considered comagmatic with the upper stratigraphic levels, and include preepithermal-stage, subeconomic Cu-Au porphyries.

Detachment faults are inconsistently mineralized; high-grade Au ± Ag pods within relatively extensive quartz vein arrays occur in the immediate structural footwall and are localized about subtle perturbations in the shallowly dipping surfaces, the latter commonly linked to impinging sills. The hanging walls to high-grade pods are characterized by relatively high density subvertical fracturing and/or punctuations within otherwise mud-sealed detachment surfaces. These relationships indicate that both enhanced dilatancy and domainal cross-stratal permeability contribute to localization of Au.

Ore occurs within transfer zones, confined to moderately to steeply dipping (45°–90°), NW- to N-striking oblique-slip fault segments. NNE-striking transfer segments accommodate minor hanging-wall exhumation (i.e., transpression) and are typically poorly mineralized. Veins progressively shallow at depth and diminish in grade as the transfer segments sole into basal detachments. A similar relationship

occurs toward the top of ore-bearing veins in some deposits, whereas others are abruptly terminated below layer-parallel decoupling surfaces, imparting an extensional duplex morphology.

An additional lithologic control on the up-dip extent of vein arrays occurs in some deposits. Well-developed quartz vein arrays with associated near-neutral pH quartz-adularia-chlorite-illite gangue assemblages occur within favored basaltic and andesite host strata, and transition abruptly into upward-flaring domains of acidic vuggy quartz-dickite-pyrophyllite-APS-alunite assemblage within dacitic facies. Anomalous concentrations of Cu and Mo occur within the latter, and quartz vein formation is poor. The coincident lithologic, textural, and compositional boundary is interpreted to record late-stage input and enhanced reactivity of magmatic gases within a relatively unconsolidated, high-level aquifer. Rare vertical juxtaposition of classical low sulfidation Au-Ag and high sulfidation Au-Cu-Mo within the footwall and hanging wall of detachments, respectively, indicates that at least the latest epithermal stages occurred as extension waned.