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LETTER/DISCUSSION

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Mineralization and deformation of the Malanjkhand terrane (2,490–2,440 Ma) along the southern margin of the Central Indian Tectonic Zone

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Abstract The Malanjkhand Cu–Mo–Au deposit, located near the northwest margin of the Malanjkhand batholith (terrane), is a strategic and significant porphyry-style deposit that experienced a protracted 50 m.y. deformational history shortly after its formation at 2,490 ± 8 Ma (Stein et al. 2004). In a recent study, Panigrahi et al. (2004) averaged U–Pb SHRIMP zircon data from a pooled set of samples from the Malanjkhand batholith to advocate a meaningless intermediate age of ~2,476 Ma for the Malanjkhand granitoid and its Cu–Mo–Au deposit. In the northwest part of the Malanjkhand batholith, Re–Os dating of occurrence-specific molybdenite captures not only the age of porphyry-style mineralization and associated magmatism, but also elucidates a complex deformational history that extends to ~2,450 Ma. In the central part of the Malanjkhand batholith, Re–Os dating of delicate spindles of accessory molybdenite occurring with pristine muscovite in miarolitic cavities within the undeformed microgranitoid at the Devgaon Mo prospect unequivocally shows that deformation ceased at this location no later than 2,470–2,465 Ma. The deformational history recorded at the Malanjkhand deposit in the northwest most likely reflects prolonged transpressive convergence and docking of the Malanjkhand terrane with units in the poorly understood (proto) Central Indian Tectonic Zone (CITZ) along its southern margin, the Central Indian shear zone. The timing for this convergence is Late Archean–Early Paleoproterozoic.

Keywords Malanjkhand · Devgaon · Re–Os dating · Molybdenite · Deformation · Central Indian Tectonic Zone

Introduction

A recent article by Panigrahi et al. (2004) reports ion microprobe (SHRIMP RG) U–Pb ages for pink and grey granitoid from the Malanjkhand Cu–Mo deposit in Central India. These data are most welcome, as they are a great improvement over previously reported Rb–Sr ages with very large uncertainties. Panigrahi et al. (2004) use their U–Pb results together with Re–Os data from Zimmerman et al. (2002) to argue for a link between granitoid and Cu–Mo mineralization, a conclusion with which we agree (Stein et al. 2004).

There are several points, however, that merit discussion regarding both the citation of our Re–Os data and the interpretation of their published U–Pb data. We submit this combined letter–discussion to Mineralium Deposita in a constructive spirit to clarify geochronological results for readers less versed in the details of the subject. Malanjkhand is a significant Cu–Mo–Au deposit in a region of India with little hard geochronology, and it is important that the age relationships are interpreted realistically and accurately. Also, Malanjkhand holds a record number of discussion-reply articles, as its origin has been intensely debated.

This communication consists of (1) a discussion of a recent U–Pb data set reported by Panigrahi et al. (2004), as we feel the interpretation of this data is in error, and (2) the introduction of recently acquired Re–Os data to further clarify the magmatic–hydrothermal and ensuing deformational history in the Malanjkhand terrane. We also include the first pictorial documentation of the Malanjkhand pit and some of the granitoid textures observed within the deposit (Fig. 1). The new Re–Os

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Comment on “Age of granitic activity associated with copper–molybdenum mineralization at Malanjkhand, Central India” by Panigrahi MK et al. (Mineralium Deposita 39:670–677)

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data (Table 1) are from samples collected during a visit to the Malanjkhand area in January 2005. These data reveal the post-magmatic evolution of this highly deformed Archean–Palaeproterozic Cu–Mo–Au deposit, and the temporal and geologic history of the hosting Malanjkhand batholith (Fig. 2). Further analytical work is planned at AIRIE.

Previous Re–Os and U–Pb Geochronology

As is commonly the case for data reported in abstracts, numbers are subject to slight refinement on final journal publication. Neither the U–Pb nor the Re–Os data differ significantly from abstract to article. Panigrahi et al. (2002) reported 2,478 ± 9 and 2,476 ± 10 Ma for grey and pink granitoids at Malanjkhand, respectively. Panigrahi et al. (2004) report like ages of 2,476 ± 7 (concordia age) and 2,476 ± 7 (^{207}Pb/^{206}Pb age) for grey, and 2,477 ± 8 (concordia age) and 2,477 ± 7 (^{206}Pb/^{207}Pb age) for pink granitoid. They opted to reject 4 out of 14 and 2 out of 10 analyses for grey and pink granitoids, respectively. This rejection was based on paired ^{206}Pb/^{238}U and ^{207}Pb/^{206}Pb ages (corrected for common Pb) that differed by more than 5%, "in order to increase the likelihood that the pooled ages represent reliable magmatic ages." The pooled U–Pb results, obtained from one-sigma spot ages, many with large analytical uncertainties, are collectively used to provide a seemingly accurate age result at high precision that Panigrahi et al. (2004) attribute to (1) the crystallization age for both grey and pink granitoid varieties and, (2) the age of Cu–Mo mineralization.

Re–Os data for Malanjkhand molybdenite were first presented in abstracts by Zimmerman et al. (2002), Hannah et al. (2002), and Stein et al. (2003). For comparison with their U–Pb ages, Panigrahi et al. (2004) utilized the Re–Os data from Zimmerman et al. (2002) interpreted as recording 40 m.y. of protracted deformation with continuous (or episodic?) deposition of new molybdenite. The Re–Os ages were slightly modified in a final paper by Stein et al. (2004), but are not significantly different from the Re–Os data published in the abstracts. These final data include a 2,489.5 ± 1.4 Ma isochron for which the statistical error on the regression (i.e. goodness of fit of the line) exceeded the ± 8 m.y. error implicit in the uncertainty of the ^{187}Re decay constant. Therefore, 2490 ± 8 Ma is the Re–Os age for comparison with other isotopic systems. This Re–Os isochron was built from four different samples at Malanjkhand—two from molybdenite disseminated in the granitoid, one from the quartz reef, and one from a late quartz vein that cuts pink granitoid. These four sample occurrences span a large part of the magmatic–hydrothermal process associated with porphyry-style deposits. Thus, our diversity of samples with the same age is pivotal to the interpretation that Malanjkhand is a porphyry-style Cu–Mo–Au deposit (Stein et al. 2004). That is, the age of at least part of the quartz reef, disseminated, and vein Cu–Mo–Au mineralization are essentially identical at 2,490 Ma.

Targeted drilling of molybdenite from two additional samples of the quartz reef provided two different and younger ages (~2,475 and ~2,450 Ma) attributed to local molybdenite deposition associated with regional metamorphism and deformation of the Malanjkhand deposit (Stein et al. 2004). These two younger ages were replicated with a second mineral separate from that specific occurrence, to test and assure geologic accuracy. If the original isotope systematics yielding a 2,490 Ma isochron age were merely disturbed by a later event, it is highly unlikely that discrete mineral separates targeting a specific molybdenite occurrence would show exactly the same level of disturbance. We reiterate here that careful targeted drilling at the hand specimen scale to extract multiple mineral separates is a test for geologic accuracy whereas simply reanalyzing the same vial of mineral separate tests only analytical reproducibility. Re–Os dating of occurrence-specific molybdenite, using the model age approach is essential in the metamorphic environment (Stein 2005).

Discussion points: U–Pb dating and interpretation

In this section, we discuss seven points addressing the zircon U–Pb data set and interpretation published by Panigrahi et al. (2004). Their U–Pb data (^{207}Pb/^{206}Pb ages) are presented in Fig. 3, together with a Re–Os data set for molybdenites from Stein et al. (2004). Four points with high common Pb (> 1%, Panigrahi et al. 2004, Table 1) and unrealistically younger ages (2,422–1,822 Ma) are excluded from our plot.

1. We doubt that the 2,477–2,476 Ma U–Pb age presented by Panigrahi et al. (2004) defines the magmatic-intrusive age. Rather, this age is defined by the molybdenite isochron as 2,490 Ma.

It is clear that the grey and pink granitoids form a continuum of apparent ages with large one-sigma analytical uncertainties that span the interval from 2,493 to 2,451 Ma. Furthermore, the analyzed spots shown in Panigrahi et al. (2004, their Fig. 2) show complex zircon structure with pits clearly transgressing multiple zones and at least one fracture. Panigrahi et al. (2004) attribute structure and zonation in Malanjkhand zircons to magmatic growth. Panigrahi et al. (2002, pers comm, cited in Stein et al. 2004) report that rims gave about the same ages as cores. By combining age information spanning core to rim analyses, we suggest that Panigrahi et al. (2004) have lost precious information on the temporal history at Malanjkhand.

Stein et al. (2004) suggest that Malanjkhand represents a calc-alkaline intrusion with porphyry-style Cu–Mo–Au mineralization that formed at 2,490 ± 8 Ma. This deposit was subsequently deformed along the margin of a (proto) Central Indian Tectonic Zone

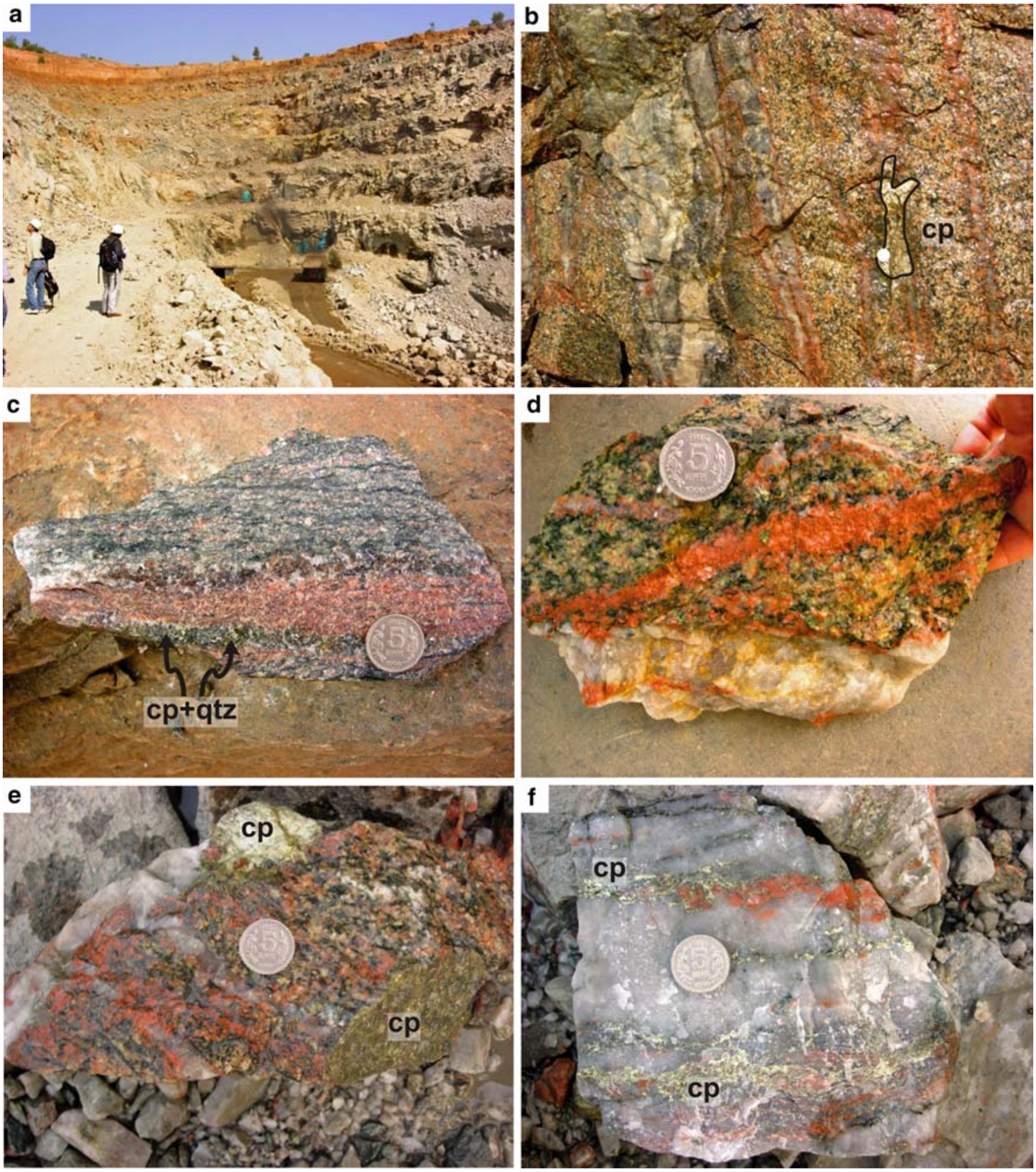

Fig. 1 The Malanjkhand Cu–Mo–Au open pit and textures, veining, alteration, and mineralization in the Malanjkhand granitoid. **a** An overview of the north end of the Malanjkhand open pit. Supergene mineralization characterizes the upper levels whereas the lower levels are marked by unweathered potassically-altered granitoid and sulfide. Spectacular waterfalls of chalcanthite, forming present day, are seen in the background. The deepest level of the pit exploits the quartz reef, where mineralization is open at depth. **b** Outcrop in the Malanjkhand open pit (N end, 484 level). Coarse-grained Malanjkhand granitoid, locally porphyritic, is highly deformed with pegmatitic quartz + K-feldspar ± chalcopyrite ± minor molybdenite veining displaying well-developed primary potassic halos. Veins have been transposed into the vertical plane of deformation, although at other nearby locations some variable vein orientation (interpreted as ghost stockwork) is observed. A 2-cm diameter five rupee coin marks the lower left margin of a massive 16-cm patch of vein-hosted chalcopyrite (outlined in *black*). **c** Mylonitic texture in Malanjkhand granitoid from within the quartz reef (N end, 536 level). Asymmetrical K-feldspar vein contains chalcopyrite + quartz along its lower margin. Coin in photos c to f is 2 cm in diameter. **d** Bright orange (*natural colour*) K-feldspar + quartz mega-stockwork veins in altered Malanjkhand granitoid from within the quartz reef (central block, 448 level). Disseminated cp + py are observed both in veins and in the granitoid. **e** Freshly blasted chalcopyrite-rich ore hosted in Malanjkhand granitoid with intense bright orange potassic alteration. Smaller quartz veins, interpreted as vestiges of variably oriented stockwork, are highly deformed. **f** Freshly blasted ore from the central part of the Malanjkhand pit (central block, 448 level). Deformed and laminated quartz-reef rock hosts high-grade chalcopyrite-rich ± molybdenite ore. Primary bornite is also locally abundant in the deep central area (Sindhupe, personal communication 2005), evidence for a hypogene core characterizing porphyry-style Cu–Mo–Au mineralization

Table 1 Re–Os data for molybdenites from the Devgaon Mo prospect and Malanjkhand Cu–Mo–Au deposit, Central India

AIRIE run #	Locality, sample number and occurrence	Re (ppm)	^{187}Os (ppb)	Age (Ma)
Devgaon Mo prospect				
433	IN05-DV1 weathered mm grains (Re loss)	50.54 (3)	1,953 (2)	3,581 ± 12
434	IN05-DV1(a) weathered mm grains (Re loss)	35.40 (2)	1,479 (1)	3,864 ± 13
436	IN05-DV1(b) weathered mm grains (Re loss)	40.38 (2)	2,050 (2)	4,662 ± 15
437	IN05-DV2 fresh molybdenite + muscovite spindles	107.87 (5)	2,846 (2)	2,468 ± 8
438	IN05-DV2(a) fresh molybdenite + muscovite spindles	68.43 (6)	1,804 (1)	2,466 ± 8
Malanjkhand mine (DDH 28003, 343.7–344.1 m)				
449	IN05-MK16 deformed platelets	314.9 (3)	8,265 (6)	2,455 ± 8
461	IN05-MK16(a) deformed platelets	138.96 (8)	3,645 (3)	2,454 ± 8
Malanjkand mine, central block, 448 level				
462	IN05-MK20(a) undeformed individual rosette	196.6 (1)	5,122 (4)	2,438 ± 8
481	IN05-MK20(b) undeformed individual rosette	346.8 (2)	9,041 (7)	2,439 ± 8

Assumed initial ^{187}Os/^{188}Os for age calculation = 0.2 ± 0.1

Absolute uncertainties shown, all at 2-sigma level, for last digit indicated

Decay constant used for ^{187}Re is 1.666×10^{-11} yr^{-1} (Smoliar et al. 1996)

Carius tube dissolution with double Os spike method (Markey et al. 2003)

Age corrected for Re blank = 4.77 ± 0.04 pg, total Os = 4.09 ± 0.02 pg, ^{187}Os/^{188}Os = 0.229 ± 0.002

Ages calculated using $^{187}\mathrm{Os} = {}^{187}\mathrm{Re}\,(e^{\lambda t} - 1)$ include all analytical and ^{187}Re decay constant uncertainties

Each entry represents an individual molybdenite separate from a specified occurrence with sample weights from 3 to 40 mg

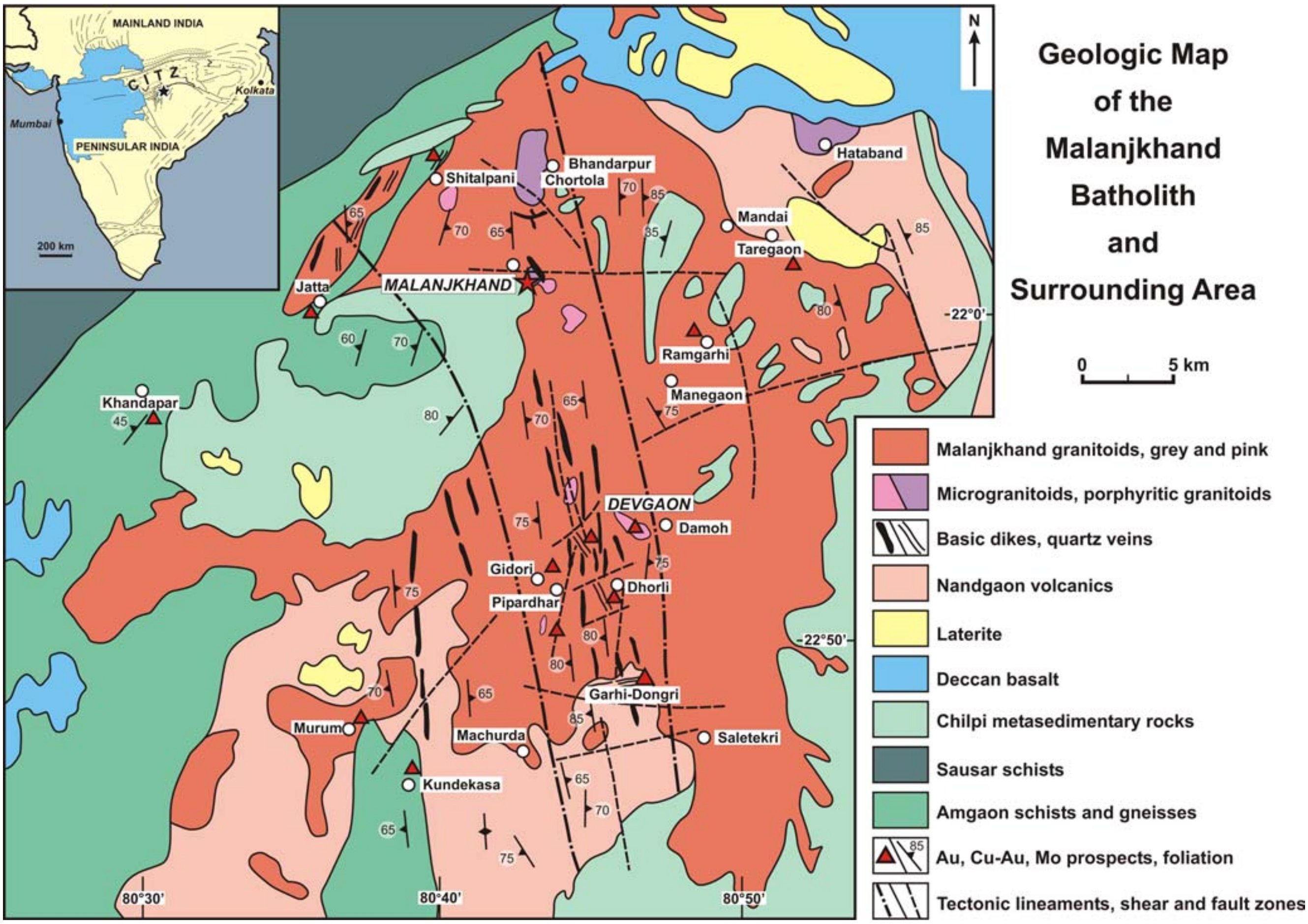

Fig. 2 Geologic map of the Malanjkhand batholith with location of the Malanjkhand Cu–Mo–Au mine and other Au, Cu–Au, and Mo prospects (modified from Bhargava and Pal 2000; Kumar et al. 2004). Additional Re–Os data reported in this communication are from the Devgaon Mo prospect hosted in microgranitoid. Inset shows location of the Central Indian Tectonic Zone (CITZ) and the black star depicts the location of the Malanjkhand Cu–Mo–Au mine along its southern margin, known as the Central Indian shear zone

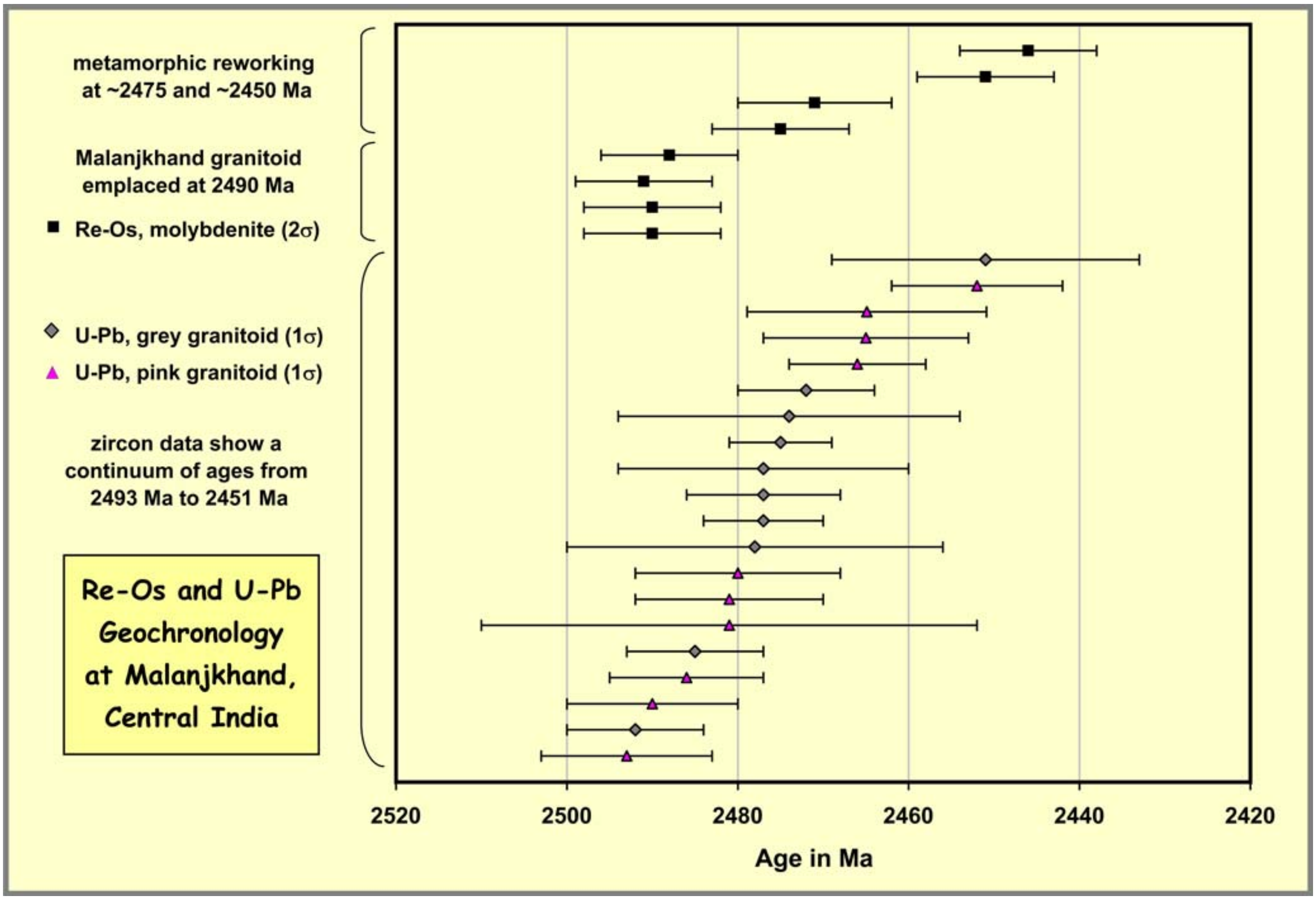

Fig. 3 Comparison of Re–Os ages for molybdenite with ion microprobe (SHRIMP RG) U–Pb ages for composite samples of pink and of grey coloured granitoid rocks from the Malanjkhand batholith and Cu–Mo–Au deposit in central India. Two-sigma Re–Os ages are from Stein et al. (2004) and one-sigma U–Pb ages are from Panigrahi et al. (2004). The U–Pb data form a continuum of ages with large uncertainties that do not correlate with pink versus grey samples. The Re–Os data document the formation of a Cu–Mo–Au porphyry-style deposit at ~2,490 Ma, and record the subsequent metamorphic reworking of this deposit (Stein et al. 2004)

(CITZ) with prominent episodes of deformation potentially occurring at 2,475 and 2,450 Ma. Nearly continuous metamorphism is recorded in zircon and additional dating of molybdenite may also produce a continuum of ages. Stein et al. (2004) propose that deformation configured the quartz reef, formerly the high-silica and high-grade ore cap of a porphyry-style deposit. Some redistribution and addition of silica and metals during this process is almost certain. The unusual elongate quartz reef with a strike length approaching 3 km, mylonitic deformation, and widespread destruction of classical stockwork veining (Stein et al. 2004) has led many previous workers to invoke peculiar models for ore deposition, for example, "emplacement of the quartz reef ore body in a major fracture zone within the granitoid complex" (Panigrahi and Mookherjee 1997, Panigrahi et al. 2002, 2004).

2. The 2,477–2,476 Ma age reported by Panigrahi et al. (2004) most likely represents a pooled average age for a protracted period of metamorphism that took place shortly after the emplacement of the Malanjkhand granitoids, and extended to at least 2,450 Ma.

Stein et al. (2004) suggest that both the Malanjkhand granitoids and their attendant Cu–Mo–Au mineralization are 2,490 ± 8 Ma, and that the pink colouring is nothing more than the potassic alteration zone associated with formation of the ore deposit. Stein et al. (2004) attribute Re–Os ages of ~2,475 Ma and ~2,450 Ma to episodes of metamorphism and deformation at Malanjkhand, but they also note that their ~2,475 Ma age could be a mixture of 2,490 and 2,450 Ma molybdenite.

The U–Pb ages generally support deposition of zircon at ~2,475 Ma, but they do not define that event precisely (Fig. 3), nor do they exclude the possibility of a 40 m.y. metamorphic continuum. Panigrahi et al. (2004, their Fig. 2i) show a 2,490 ± 10 Ma zircon core that is pooled with younger ages from zircon rims. Two of the more precise U–Pb ages obtained by Panigrahi et al. (2004, their Fig 2b,f) appear to be from relatively unzoned portions of zircon crystals. Their ages of

2,472 ± 8 Ma and 2,475 ± 6 Ma are in agreement with Re–Os ages of 2,471 ± 9 Ma and 2,475 ± 8 Ma (replicate using new mineral separate). In summary, the U–Pb data, as presented by Panigrahi et al. (2004), blur a 40 m.y. magmatic emplacement and metamorphic history. Based on their zircon ages, there is no resolvable age information within this 40 m.y. period.

In addition, the images shown in Panigrahi et al. (2004) do not unequivocally document zircon growth solely by magmatic processes. There are numerous coupled U–Pb dating and trace element studies of zircon in high-grade metamorphic terranes of all ages (e.g. Hoskin and Black 2000; Tomaschek et al. 2003; Timmermann et al. 2004; Whitehouse and Kamber 2005). Inevitably the interpretation of zircon structure and the ensuing array of U–Pb ages encompass a range of processes, from simple magmatic crystallization, to hydrothermal growth, to transgressive replacement, to full scale in situ solid-state recrystallization. Like monazite (e.g. Bingen and van Breemen 1998), fluid-assisted recrystallization has been demonstrated for zircon as well. When fluid is present, rapid coarsening of zircon by Ostwald ripening may occur during high-grade thermal metamorphism, and addition of fluid (or anatectic melt) increases the rate of that coarsening as recorded in metamorphic rims (e.g. Ayers et al. 2003; Nemchin et al. 2001). A Cu–Mo–Au porphyry environment is by definition fluid-rich and subsequent metamorphism in the Malanjkhand region reworked earlier products of volatile-rich porphyry-style mineralization. Prolonged heating and deformation may have been responsible for coarsening of grain size in both accessory and major phases, as a means to minimize surface energy in originally porphyritic host rocks with a large range of grain sizes and predominance of fine-grained matrix. Although relict porphyritic textures are clearly visible at some locations at the Malajkhand mine, the overall coarse-grained, ductily deformed, and recrystallized nature of the hosting granitoid rocks is widespread (Fig. 1b–e).

It is unfortunate that Panigrahi et al. (2004) limited their analytical efforts to essentially one date per zircon grain, rather than dating sequential zones or paired cores and rims. Examination of reported Th/U data for the zircon analyses of Panigrahi et al. (2004) suggests open-system behaviour and a systematic change with time, although absolute values cannot be attributed to specific processes (magmatic vs metamorphic vs hydrothermal). Age information coupled with Th/U ratios has been used to provide information on the history of zircon formation. For example, a correlation between apparent age and Th/U ratio has been attributed to incomplete resetting associated with partial recrystallization of zircon in the solid-state (Hoskin and Black 2000). Even though the data of Panigrahi et al. (2004) are from different zircon grains extracted from five widely spaced Malanjkhand granitoid samples, as a first approximation we plot U–Pb ages versus Th/U ratios (Fig. 4). It can be shown that the oldest ~2,490 Ma zircons have the highest Th/U ratios indicative of magmatic values, whereas the youngest ~2,450 Ma zircons all have notably lower Th/U ratios indicative of zircon that has expelled unstable trace elements (e.g. Y, HREE, Th and P) during recrystallization (e.g. Tomaschek et al. 2003). For intermediate zircon ages (~2,485–2,470 Ma), there is the clear hint of two levels of Th/U (Fig. 4), suggesting that both primary crystallization and trace element purging through recrystallization of earlier zircon may have been occurring during the same time period in different parts of the Malanjkhand batholith. No doubt, metamorphic recrystallization of zircon would be enhanced by strain and the widespread ductile and brittle deformation of the Malanjkhand batholith and the associated Cu–Mo–Au ore body. Solid-state recrystallization and/or low Th/U metamorphic or hydrothermal overgrowths resulting from sustained metamorphism are both possibilities for the zircons shown in Panigrahi et al. (2004).

3. Panigrahi et al. (2004) review their previous Rb–Sr dating and suggest that their younger isochron date for pink granitoids (2,243 ± 212 Ma) compared to the grey granitoid (2,467 ± 38 Ma) represents the end of the hydrothermal alteration episode.

We disagree with this interpretation. First, there is no statistical difference between the two imprecise Rb–Sr isochron ages. The two ages overlap within their very large analytical errors. Second, we do not think that the hydrothermal alteration extended over a period of hundreds of millions of years. Rather, the Rb–Sr systematics were likely disturbed during younger metamorphism, as Rb (like K) displays mobile behaviour, particularly in the presence of fluid. In short, we believe that the Rb–Sr results do not offer any meaningful age data, and should not be used in this way. Much of the geochronology in this part of India has been based on poorly constrained Rb–Sr data, leading to questionable and misleading geologic interpretations, as discussed in Stein et al. (2004).

4. Panigrahi et al. (2004) suggest that zoning in the cores of zircon grains indicates a single magmatic episode of zircon growth and the small error in the pooled zircon ages points to a cogenetic population of zircon grains.

We disagree with this suggestion. The relatively small errors reported for their U–Pb ages are simply the expected statistical outcome of pooling a large number of data points with large errors (i.e. standard deviation of the mean). In doing so, a false sense of precision is achieved by “averaging” the U–Pb ages. This is inappropriately used to argue for an accurate geologic age at high precision for the pink and grey granitoids.

In complex metamorphic terranes, enormous caution should be taken when interpreting isotopic data. It has been said that it is far better to be *approximately correct*

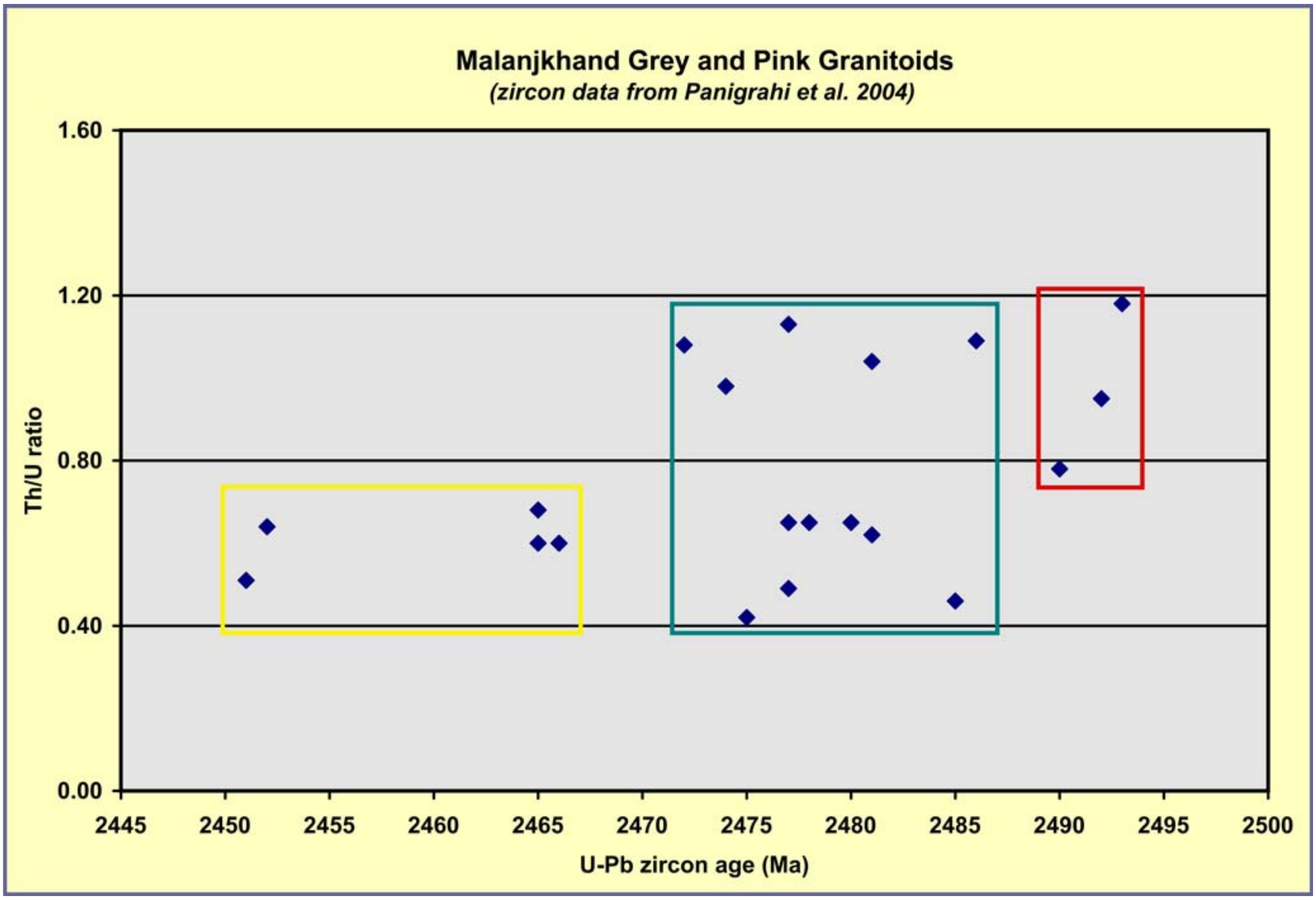

Fig. 4 Plot of U–Pb zircon ages versus corresponding Th/U ratios based on data presented in Panigrahi et al. (2004). The oldest ages (*red box*), derived from zircon cores, contain the highest Th/U ratios, indicative of magmatic crystallization. The youngest ages (*yellow box*), derived from zircon rims, contain the lowest Th/U ratios, and likely correspond to high-grade metamorphism of the Malanjkhand terrane. Intermediate ages (*green box*) contain both high and low Th/U ratios, potentially reflecting both magmatic and metamorphic derivation, likely related to locality (unfortunately zircon localities are not specified in detail in Panigrahi et al. 2004)

(accurate, but with a large and realistic uncertainty), than to be *precisely wrong* (meaningless intermediate ages with unrealistically small uncertainties derived from inappropriate pooling of data). In geology, it is accuracy that is most important, not precision, as process-oriented thinking requires a true sense of absolute time.

5. According to Panigrahi et al. (2004) the U–Pb data were obtained from five fresh representative samples (2 kg each) of Malanjkhand granitoid that were pooled into two composite samples of grey and pink colouration.

We maintain that this is poor field-to-lab procedure, particularly as the Malanjkhand batholith contains a variety of intrusive types (quartz diorite, granodiorite, quartz monzonite, granite, leucogranite) with variable alteration. The samples were taken kilometres apart (Panigrahi et al. 2004, their Fig. 1), with three pooled to create the grey-coloured composite, and two pooled to create the pink-coloured composite. The grey samples were from the batholith outside the ore body, and the pink from within the ore-bearing region of the intrusion, along the east and west margins of the ore-bearing quartz reef. By pooling samples from widely varying geographic regions, the possibility to crosscheck one grey granite sample against another is lost. In summary, sorting potassically altered rocks (pink) from less altered rocks (grey) risks mixing rock types from the outset and pooling zircons from disparate samples precludes resolution of multiple events with the U–Pb data.

6. The $^{238}U/^{206}Pb$ ratios (Panigrahi et al. 2004, their Table 1) have large one-sigma uncertainties of about 4% that are transmitted to the reported $^{206}Pb/^{238}U$ ages.

This suggests a poor U–Pb calibration and/or unstable analytical conditions, leading to marginal data, although we do not claim that the general conclusions drawn from their data set would change with improved running conditions. Still, their large analytical uncertainties may mask real geologic variations in age. Concordancy depends not only on geologic conditions, but also on analytical precision. Large uncertainties for individual U–Pb spot analyses imply intersection with concordia, even though the true age may be significantly discordant with smaller analytical uncertainties.

7. Panigrahi et al. (2004) state ‘‘the older molybdenite age is difficult to explain’’ and ‘‘the relatively large spread of the molybdenite ages remains unexplained’’.

A detailed explanation of Re–Os ages with interpretations is presented in Stein et al. (2004). The preliminary 2,494–2,492 ± 8 Ma Re–Os model ages presented in early abstracts (Zimmerman et al. 2002; Hannah et al. 2002) are only marginally distinct from the pooled $^{207}Pb/^{206}Pb$ and U–Pb concordia ages of 2,477–2,476 ± 8 Ma (Panigrahi et al. 2004), but the distinction may be highly significant. More importantly, there is no statistical difference between their, albeit incorrectly, pooled ages and our final Re–Os isochron age of 2,490 ± 8 Ma (Stein et al. 2004). Therefore, within the confines of the isotopic systematics for U–Pb and Re–Os and associated analytical uncertainties, there are no older ages requiring explanation. We acknowledge, of course, that the final isochron age was not published at the time Panigrahi et al. (2004) submitted their U–Pb work. Returning to Fig. 3, the spread in their U–Pb ages precludes resolution of any event. They show a continuum of ages, resulting from spot analyses that capture closely spaced episodes of zircon deposition, most likely associated with combinations of metamorphic or hydrothermal recrystallization and overgrowth.

In summary, the U–Pb data reported in Panigrahi et al. (2004) blur a 40 m.y. magmatic–metamorphic orogeny. The Re–Os data document calc-alkaline intrusion associated with porphyry-style Cu–Mo–Au mineralization and provide a record of protracted metamorphic reworking. In our opinion, the U–Pb ages do not define the crystallization age for the Malanjkhand grey granitoid, but average the intrusive-metamorphic history by pooling a large number of spot analyses. We maintain that the crystallization age for the Malanjkhand grey granitoid is 2,490 ± 8 Ma, as defined by the Re–Os isochron for molybdenite from an associated porphyry-style Cu–Mo–Au deposit. Older 2,490 Ma U–Pb ages for cores of zircons analyzed by Panigrahi et al. (2004) support our interpretation. Finally, we suggest that the pink colour of Malanjkhand granitoid associated with the ore deposit does not represent hundreds of millions of years of hydrothermal alteration (Panigrahi et al. 2004), but represents the geologically short-lived (< 2 m.y.) potassic alteration component of porphyry-style mineralization.

Deformation of the Malanjkhand Terrane

In January 2005, we had the unique opportunity to visit the Malanjkhand Cu–Mo–Au deposit. Detailed examination of exposures in the Malanjkhand pit and key drill core provides convincing evidence for a porphyry-style deposit that has been highly deformed, locally mylonitized, and whose stockwork has succumbed to local metamorphic remobilization (Fig. 1a–f). We have embarked on a larger dating project to better understand the metallogenic history of this economically important region along the southern margin of the Central Indian Tectonic Zone (Fig. 2).

Having established the age of 2,490 ± 8 Ma as the time of magmatism associated with porphyry-style Cu–Mo–Au mineralization at Malanjkhand (Stein et al. 2004), we report here several newly acquired Re–Os ages. Our goal is to determine the timing of other intrusive phases in the batholith and to block the end of deformation in the terrane. These data have important bearing on the early temporal history of the (proto) CITZ, as its southern boundary, the Central Indian shear zone, overprints the northwest margin of the Malanjkhand terrane (Stein et al. 2004).

We obtained three critically important samples that unequivocally illustrate occurrences of deformed versus undeformed molybdenite. Two samples are from the Malanjkhand mine, and one is from a microgranitoid phase of the Malanjkhand batholith, taken from the Devgaon Mo prospect in the central part of the Malanjkhand batholith, west of the village of Damoh (Fig. 2).

The Devgaon Mo prospect, about 15 km SSE of the Malanjkhand mine (Fig. 5a) consists of hummocky outcrop areas exposed on low knobby hills with a deep weathering profile. The Devgaon prospect is hosted in a grey to pink microgranitoid (Fig. 5b) that has been correlated with a younger, undeformed, post-mineralization microgranitoid intrusion prominently exposed in the centre of the pit at the Malanjkhand mine (Pal and Bhargava 1998; Bhargava and Pal 2000). The microgranitoid displays highly localized weak potassic, argillic, and/or sericitic–pyritic alteration. At Devgaon, molybdenite generally occurs as mm to sub-mm grains (Fig. 5c, IN05-DV1, location 21°54.118 N and 80°46.616 E). Such grains are rare and seen on only a few weathered exposures. These small grains do not provide reliable Re–Os ages (Table 1), as is typical of molybdenite derived from deeply weathered outcrop. Re loss is the presumed reason for the older ages, and the non-reproducibility for replicate ages is a clear sign of erratic isotopic disturbance.

In contrast, a few hundred metres away, abundant outcrop was broken to reveal fresh centimetre-scale, spindle-like molybdenite clots with intergrown pristine, fine-grained muscovite (Fig. 5d, IN05-DV2, location 21°54.148 N and 80°46.683 E). Prominent Fe oxide halos encircle this occurrence of Devgaon molybdenite. In a recent study, Stein (2005, see Fig. 6 therein) interpreted similar occurrences of molybdenite with Fe-oxide halos as accessory magmatic molybdenite crystallizing in late miarolitic cavities in oxidized, sulfur-poor magmas. Under these late-magmatic conditions, molybdenite is preferentially precipitated over Fe sulfides. A shortage of sulfur during subsequent deuteric alteration leaves the remaining Fe to take residency in feldspar surrounding

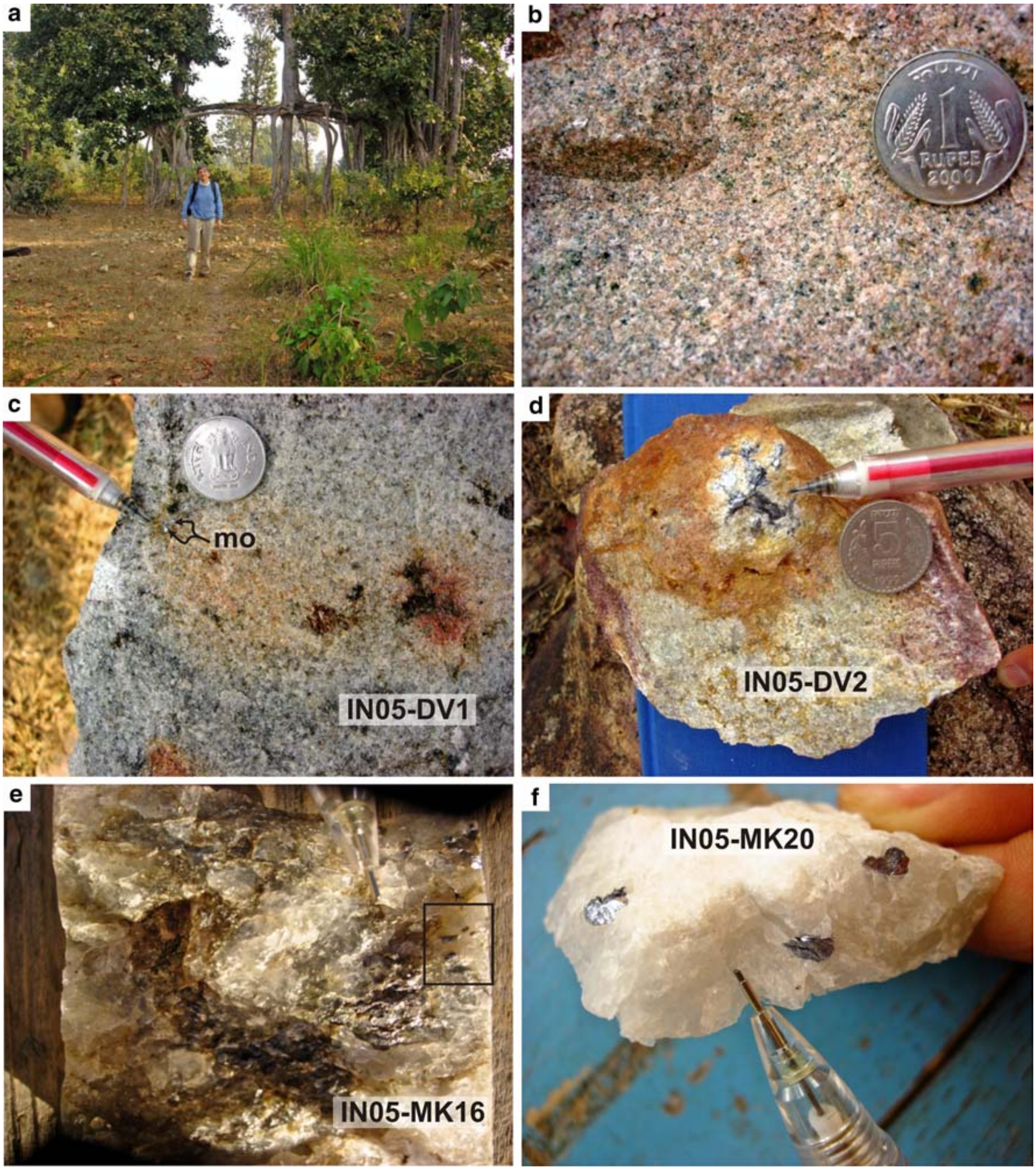

Fig. 5 a. Characteristic outcrop of the Devgaon microgranitoid, deeply weathered and vegetation-rich, with spectacular elevated banyan trees (*background*). The Devgaon microgranitoid (sometimes referred to as Devgaon aplite, e.g. Pal and Bhargava 1998) has been correlated with the post-mineralization microgranitoid body prominent in the central part of the Malanjkhand open pit. **b.** Typical fresh Devgaon microgranitoid is massive equigranular fine-grained grey to pink granite. The rupee coin is 2 cm in diameter. **c.** Disseminated molybdenite is rare, but widespread, and is often associated with primary Fe oxide halos. These small grains of molybdenite are from an exposed and weathered boulder of Devgaon microgranitoid. They yield erratically old Re–Os ages (Table 1, IN05-DV1), probably a reflection of Re loss in an environment of intensive subtropical weathering. **d.** Fresh deuterically altered Devgaon microgranitoid is derived by breaking outcrop. Abundant undeformed molybdenite as delicate spindles occurs together with pristine fine-grained muscovite. This assemblage represents late crystallization of accessory molybdenite in miarolitic pockets of the Devgaon intrusion with excess Fe taken by surrounding feldspar. The 2,468–2,466 Ma age for this molybdenite (Table 1, IN05-DV2) is the age of crystallization for this post-deformation intrusive phase in the central part of the Malanjkhand batholith. In the vicinity of the Malanjkhand mine ~15 km to the north, however, deformation of the Malanjkhand batholith continued for at least another 15 m.y. to ~2,550 Ma. **e.** Massive deformed quartz with parallel molybdenite platelets (*black box at right*) from drill core immediately north of the Malanjkhand pit (DDH 28003 343.7–344.1 m). Deformation was still going on at Malanjkhand at ~2,455 Ma (Table 1, IN05-MK16). **f.** White to translucent undeformed quartz and variably oriented molybdenite rosettes are unequivocally post-deformation (Malanjkand pit, central block, footwall, 448 level). Re–Os ages for undeformed rosettes show that deformation at the Malanjkhand mine ceased by ~2440 Ma (Table 1, IN05-MK20) the miarolitic cavities, thereby enclosing the molybdenite in a globe of Fe stain. At Devgaon, widely scattered and generally rare miarolitic cavities lined with quartz ± calcite were also observed in the vicinity of the molybdenite samples. Re–Os dating of accessory molybdenite in this setting can be used to date final crystallization of plutons. Two pristine unweathered samples from undeformed molybdenite spindles at Devgaon (IN05-DV2) are in excellent agreement and show that deformation in this central region of the Malanjkhand batholith ceased before 2,470–2,465 Ma (Table 1, Fig. 2). Age agreement based on two mineral separates from two similar occurrences at this locality is a solid test for geologic accuracy.

Although deformation ceased by 2,470–2,465 Ma in the central part of the Malanjkhand batholith, the northwest part of the batholith continued to record precipitation and deformation of molybdenite for an additional 15 to 30 m.y. Re–Os dating of two selected molybdenite occurrences from the Malanjkhand Cu–Mo–Au porphyry deposit documents deformation to at least 2,455 Ma with the cessation of deformation by ~2,440 Ma (Table 1). These younger molybdenites may have been derived by local remobilization of earlier 2,490 Ma porphyry-style mineralization that was subject to intense metamorphic reworking.

At Malanjkhand, one dated locality consists of molybdenite from an interval of highly deformed quartz seen in drill core at the northernmost Mo-rich extension of the Malanjkhand deposit (Fig. 5e, IN05-MK16). The molybdenite in this interval of splintery quartz forms millimetre platelets that are parallel to sub-parallel and show kinking and folding in cross-section. Another dated locality consists of molybdenite taken from the ore zone in the central part of the Malanjkhand pit (central block, footwall, 448 level) where active excavation is taking place (Fig. 5f, IN05-MK20). Here we sampled a seemingly rare occurrence of perfect millimetre-scale molybdenite rosettes in random orientation within a milky to translucent quartz devoid of any obvious deformation history. Both these younger molybdenite localities at the Malanjkhand mine have an affiliation with quartz reef rock, which constitutes the main ore-bearing unit.

Importantly, these Re–Os data suggest that further dating of molybdenite is likely to produce an age distribution much like that seen in the U–Pb data set of Panigrahi et al. (2004), as diagrammed in Fig. 3. Our Re–Os data are tied to well-constrained individual molybdenite samples, including replicates of specific occurrence types, thereby permitting a realistic assessment of age results in their geologic context. Whether Re–Os or U–Pb data are under consideration, the continuous versus episodic nature of metamorphism cannot be resolved within the limitations of either isotopic technique as applied to Precambrian rocks. Our understanding of orogenic processes based on incremental dating of much younger orogenies leads us to believe that punctuated episodes of deformation and metamorphism ultimately define full orogenic events.

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