FINAL TECHNICAL REPORT

TITLE: Isotopic and Chemical Studies
          of Early Crustal Metasedimentary Rocks

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AIMS OF THE PROJECT

Our aim, within the bounds of the Early Crustal Genesis Project, was the isotopic and chemical study of selected early crustal (meta)–sedimentary rocks. This was undertaken for two main reasons: firstly, until recently, most early Archean rocks so studied comprised gneisses of mafic and granitic composition, generally of high metamorphic grade, and sampled mainly from greenstone belts. Secondly, and more importantly, sediments and sedimentary processes are one of the most important pathways for the production of early upper–crustal chemical heterogeneities. Subsequent partial melting of metasediments, following high–grade metamorphism, leads to selective re–mixing of certain elements back into the earth's crust, leaving behind chemically complementary residuals.

Our understanding of the chemical evolution of the earth's early crust cannot be complete until we take into account the chemical evidence contained within the oldest (meta)–sedimentary rocks and the geochemical constraints these place on our models of crust–forming processes.

We chose Western Australia as our first field area to examine, as the Yilgarn and Pilbara Blocks comprise one of the largest and most varied Precambrian terranes. Until recently, these areas had not been investigated with the more modern isotopic techniques. Furthermore, the Western Gneiss Terrane (on the western flank of the Yilgarn Block) and the Pilbara Block are both non–greenstone in character; these types of terranes have been relatively neglected, but are of great significance in our understanding of early crustal metasediments.

To focus our efforts even further, we initially chose to examine (meta)sediments of aluminous or peraluminous character, commonly also enriched in Mg and/or Fe relative to

the more common pelitic metasediments, and at many localities, deficient in one or more of the elements Ca, Na, and K.

Work Statement

Aluminous metasediments and granitic gneisses of Western Australia

The project commenced with a 50–day field trip to the Yilgarn Block, Western Australia, by the Co–investigator S.K. Dobos in September and October of 1984. He collected over 400 samples, principally Archean metasediments, but including field–related gneisses and mafic rocks. Much of this material comprises diamond–drill core, which ensures unweathered samples for isotopic analysis; this is important since in many localities surface outcrops are too weathered for such work. (Although all the core is proprietary, we have unrestricted use of them, with freedom to publish any data derived therefrom.)

Of particular concern to the panel prior to the field trip was the possible conflict of interest with Australian groups carrying out similar work, and/or working in the same field areas. Prior to the field trip, we contacted the Western Australian Geological Survey, the Western Australian Institute of Technology isotope geochemistry group, and the Australian National University isotope geochemistry group. The directors/group leaders of all three welcomed our presence, and were very helpful to the Co–investigator on–site. Our correspondence in this matter is on file with NASA.

The samples collected during the 1984 field trip have been augmented by others collected in 1987 from Western Australia and the Northern Territory (the latter funded by Harvard University). The combined collection is now a valuable resource in the Department of Earth and Planetary Sciences, with ample first–class material for numerous isotopic and geochemical studies of both clastic and chemical early crustal sediments.

The main thrust of NAG 9–90 is the study of early crustal metasediments, with special

attention to peraluminous rocks, or rocks low in Ca and alkalis. We have concentrated our efforts on the Western Gneiss Belt of Western Australia for reasons already discussed. The progress of this work has been satisfactory, but the write—up has been delayed by the move of the Co—investigator to Australia for personal reasons. A very rough draft of a paper on these results is given in the Appendix to this report (Dobos et al., in preparation). We have also commenced a complementary paper on the major and trace—element geochemistry of these metasediments. On completion of this second manuscript, we intend to examine similar rocks from elsewhere in the Yilgarn Block, and from other Archean terranes in Australia.

Banded iron formations

During the 1984 field trip, the Co—investigator also collected metamorphosed banded iron formations and related rocks from the Yilgarn Block. Since the geologic setting of these rocks differs widely from those in the volumetrically more significant "basin—like" iron—rich sequences like the Pilbara Block, their isotopic signatures will help to constrain the Sm—Nd systematics of Fe—rich sediments in the early crust.

Our work on banded iron formations was started with NSF funds and the work was continued with funds from NAG—9—90. This work (Jacobsen and Pimentel—Klose, 1988a,b) shows that REE budget of the Archean oceans was dominated by hydrothermal circulation through mid—ocean ridges rather than by continental weathering as is the case in the Phanerozoic.

Early crustal clastic sediments of West Greenland

Most of this work was funded by NSF, but the final stages were finished with NASA support through NAG—9—90 and the NASA/NSF sponsored field trip to the early Archean

of West Greenland during the summer of 1986. One paper on the clastic sediments at Isua has been published (Jacobsen and Dymek, 1988), and suggests the presence of pre–3.8 Ga components in the Isua metasediments. Another paper on the late Archean metasediments of Rypeo is in preparation.

River waters draining Archean terranes

We collected selected Australian, Canadian and Greenland river waters for Sm–Nd and Rb–Sr isotopic analysis and REE analysis of dissolved and suspended river loads draining Archean areas. The isotopic data from these samples have been reported in papers emphasizing the present day river and ocean systems (Goldstein and Jacobsen, 1987, 1988a,b,c) and were primarily funded by NSF. However, the sample collection of rivers draining Archean areas was done during NASA sponsored field work. These data are important for calculating "average" signatures of Archean terranes, and for large–scale modeling of crustal evolution through time. Such modeling with these data is in progress.

Fiskenaesset anorthosite and aluminous metasediments

A Sm–Nd isotopic study was carried out on samples of the Fiskenaesset Anorthosite (Ashwal et al. in prep.) to constrain the igneous age of the Fiskenaesset Anorthosite. The age obtained was 2.86 ± 0.05 Ga and most likely represents the igneous crystallization age of the Fiskenaesset complex. This is an important constraint on the age of the aluminous metasediments at Fiskenaesset which we are currently studying.

Modeling of crustal growth and recycling

The available data on chemical and clastic sediments throughout earth history and continental crustal age distributions have been used to obtain improved estimates of

crustal growth and recycling rates throughout earth history (Jacobsen, 1988). The results suggest that by about 3.8 Ga ago $\approx$ 40 % of the present continental volume was present. Recycling rates were extremely high 3–4 Ga ago and declined rapidly to an insignificant value of 0.1 km^3/a during most of the Phanerozoic. The Nd model age pattern on sediments suggests a fairly high rate of growth during the Phanerozoic.

Publications

The following list comprises all the manuscripts which were produced wholly, or in part, with the help of NAG 9–90.

Ashwal, L.D., Jacobsen, S.B., Myers, J.S., Kalsbeek, F., and Goldstein, S.J., Sm–Nd age of the Fiskenaesset Anorthosite Complex, West Greenland, (in preparation).

Dobos, S.K., Jacobsen, S.B., Derry, L.A. and Goldstein, S.J., Nd and Sr isotope systematics of aluminous metasediments from the Archean of Western Australia: 1. The Western Gneiss Belt of the Yilgarn Block, (in preparation).

Goldstein, S.J. and Jacobsen, S.B., 1987: The Nd and Sr isotopic systematics of river–water dissolved material: Implications for the sources of Nd and Sr in seawater, Chem. Geol. (Isotope Geoscience Section) 66, 245–272.

Goldstein, S.J. and Jacobsen, S.B., 1988a: Nd and Sr systematics of river water suspended material: Implications for crustal evolution. Earth Planet. Sci. Lett. 87, 249–265.

Goldstein, S.J. and Jacobsen, S.B., 1988b: Rare earth elements in river waters, in press, Earth Planet. Sci. Lett. (in press).

Goldstein, S.J. and Jacobsen, S.B., 1988c: REE in the Great Whale River estuary, NW Quebec. Earth Planet. Sci. Lett. (in press).

Jacobsen, S.B. and Dymek, R.F., 1988: Nd and Sr isotope systematics of clastic

metasediments from Isua, West Greenland: Identification of Pre–3.8 Ga differentiated crustal components. J. Geophys. Res. 93, 338–354.

Jacobsen, S.B. and Pimentel–Klose, M.R., 1988a: A Nd isotopic study of the Hamersley and Michipicoten banded iron formations: The source of REE and Fe in Archean oceans. Earth Planet. Sci. Lett. 87, 29–44.

Jacobsen, S.B. and Pimentel–Klose, M.R., 1988b: Nd isotopic variations in Precambrian banded iron formations. Geophys. Res. Lett. 15, 393–396.

Jacobsen, S.B. 1988: Isotopic constraints on crustal growth and recycling, Earth Planet. Sci. Lett., Crafoord Symposium Volume (in press).

APPENDIX

Nd AND Sr ISOTOPE SYSTEMATICS OF ALUMINOUS METASEDIMENTS FROM THE ARCHEAN OF WESTERN AUSTRALIA:
I. THE WESTERN GNEISS BELT OF THE YILGARN BLOCK

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Abstract

The Western Gneiss Belt (WGB) is an elongate, high-grade non–greenstone terrane bounding the western edge of the Yilgarn Block. An upper greenschist shale–like unit from the Jack Hills area (T_{STRAT} = 2.9 Ga) in the northern part of the WGB yields an initial $\epsilon_{Nd}(T)$ = –5, T_{DM}^{Nd} = 3.61 Ga, and T_{UR}^{Sr} = 3.56 Ga. The other metasediments occur south and west of the above unit, increasing in metamorphic grade from amphibolite facies at Koolanooka and Toodyay to granulite facies at Quirading, near the southern extremity of the WGB. The majority of the samples from these localities define an Sm–Nd isochron with T = 3.16 Ga and $\epsilon_{Nd}(T)$ = –0.4 ± 0.8; T_{DM}^{Nd} model ages of these are about 3.4 Ga. Rb–Sr data define a broad trend bounded by T_{UR}^{Sr} from 3.25 to 2.67 Ga, but clustering towards the latter. Hence 3.16 Ga may reflect the age of the source rocks rather than the sedimentation or metamorphism which must have been completed by 2.67 Ga. Pelitic rocks have close to average crustal $f_{Sm/Nd}$ of –0.4, while more chemically evolved metasediments have a large range from about –0.5 to 0; in general, there is no systematic difference between these in initial ϵ_{Nd}, and they reflect broadly similar source terranes. An older group of granitoid gneisses enclosing or adjacent to the metasediments at Toodyay and Quirading yield T_{DM}^{Nd} model ages of about 3.4 Ga, while a younger group of granitic rocks yields T_{DM}^{Nd} model ages in the range 3.1 to 3.3 Ga.

REE patterns of shale–like clastic metasediments closely follow that for North American Shale Composite (NASC), and are substantially different from "Archean Shale" of McLennan and Taylor (1984). Chemically more evolved alkali and calcium poor metasediments exhibit extreme REE variability.

1. Introduction

Isotopic and geochronologic evidence indicates that by the beginning of the Proterozoic, $\approx$ 2.5 Ga ago, the continental crust was at least half its present volume. Since that time, little if any large–scale changes in the chemical composition of the sedimentary rocks have been observed. This infers a relatively constant upper crust composition since the Archean, or at least variations small enough to have been masked or buffered by sedimentary recycling and slow crustal growth. In marked contrast, both crustal growth and recycling rates appear to have been much higher in the period 3.8 to 2.8 Ga. Sediments from this period frequently differ in composition from those formed since the Archean, indicating that many Archean sediments were derived from an initially less differentiated [more mafic] and relatively rapidly evolving Archean crust.

Many fundamental questions remain concerning the timing, mechanisms, and chemical fluxes involved in this early crustal genesis; these are pertinent to our understanding of planetary evolution. As a starting point, we need to know whether the [currently] oldest terrestrial minerals, dated at 4.2 Ga, and the oldest rocks, dated at 3.8 Ga, are indeed the oldest samples preserved or whether even older material was extant, but destroyed either by late heavy bombardment or by vigorous recycling of the early crust. We need to know the compositions of the earliest rocks and their "protoliths", the mechanism of crustal recycling and the values of the chemical fluxes which accompanied it, all as functions of time. Clearly the best source of hard data for understanding early crustal genesis is the study of early crustal rocks.

Our initial aims in studying the Western Gneiss Terrain (WGT) were to determine the provenance of the (meta) sediments, especially the high–Al, high–Mg, low–alkali and low–Ca (HAMLAC) metasediments; to determine age relations and provenance of the

various granitic gneisses common throughout the WGT, and to determine temporal and chemical relations between the metasediments and the granitic and mafic/ultramafic metaigneous rocks. HAMLAC metasediments are relatively common in the Archean and Early Proterozoic, and relatively rare in the Phanerozoic. Another intent is to define the age distribution of crustal rocks in the Yilgarn and Pilbara blocks in terms of their "crustal extraction ages". Crustal residence ages of sediments will be used to constrain crustal evolution in these Archean crustal blocks. Further studies of chemical and clastic sediments in these areas should also constrain their interactions with the early ocean atmosphere system.

2. Geological setting

The Western Gneiss Terrain (WGT), of the Yilgarn Block is relatively rich in a wide range of Archean metasediments; the lithofacies is commonly shallow water marine, indicative of stable shelf condition. The WGT contrasts strongly with granitic–greenstone provinces to the east (Fig. 1); additionally it is becoming more generally accepted that the WGT is the depositional basement of the younger, eastern provinces of the Yilgarn Block [1]. Our samples from this terrain are from the Jack Hills and Koolanooka in the northern part of the WGT, and from Toodyay and Quirading, in the southern part of the WGT. This yields not only a good geographic spread, but an almost full range of metamorphic grades ranging from lower amphibolite at Koolanooka to granulite at Quirading.

3. Sample descriptions

3.1. Jack Hills sample.

#10 [JH1] fine–grained, slightly crenulated chlorite-garnet-chloritoid-sericite-quartzite; quartz comprises some 75% of the rock.

3.2. Koolanooka samples

The samples are from a sequence of lower–amphibolite grade quartzites and quartz–magnetite rocks (metamorphosed iron formation), normal pelitic metasediments, iron–rich metashales, thinly bedded siliceous volcaniclastics, and a rich assortment of assemblages corresponding to high–Al, high–Fe and/or Mg, low Ca and low–alkali bulk compositions. The sequence contains numerous mafic bands ranging from 1/2 to 10 meters in thickness; it is not possible to interpret from the field relations alone which of these were volcaniclastic mafic tuffs and which were flows or sills; detailed petrographic work indicates that some of the thinner units were probably tuffaceous. Sample #1 is an example of the latter —— it is a garnet-chlorite-cordierite-orthoamphibole-quartz-magnetite schist which occurs on a regional scale throughout the sequence in units from 10 cm to several meters thick. Sample #2 is a more normal pelitic meta–sediment comprising quartz–biotite–cordierite–plagioclase, occurring in similarly bedded units.

3.3. Toodyay samples.

Young Granitic Gneiss: #11 [TY30] A gneissic biotite granite, moderate grain size, with large elongated quartz grains and grain aggregates; unaltered.

#12 [TY31] A fine–grained, gneissic biotite–hornblende microgranite; minor alteration of mafic minerals to chlorite.

Old Granitic Gneiss: #17 [TY2] A fine–grained, deformed leucogranite with minor biotite, and trace amounts of chlorite, fresh muscovite, epidote, and magnetite altering to hematite. The occurrence of fresh muscovite and epidote, plus the deformed texture comprising well developed curviplanar grain boundaries strongly suggests that this rock has

been metamorphosed after crystallization.

Metasediments: #13 [TY17b] A coarse–grained cordierite–anthophyllite gneiss with minor biotite and traces of quartz and apatite. This rock is extensively altered along grain boundaries to fine aggregates of sericite; otherwise, the cordierite is quite fresh.

#14 [TY1] A fine–grained spinel–magnetite–orthopyroxene–orthoamphibole rock with well–developed alteration patches of sericite after cordierite; the texture is quite granulitic.

#15 [TY3] A coarse–grained orthopyroxene spinel rock with minor anthophyllite and cordierite altering to pyrophyllite and lesser amounts of chlorite along grain boundaries; there appears to be some trace high–grade chlorite; minor magnetite in patches.

#16 [TY26] A coarse–grained magnetite–cordierite–chlorite–biotite rock with minor apatite and epidote or allanite in clusters scattered through the rock. The chlorite is strongly magnesian, and it is primary. The cordierite is entirely altered to sericite and trace secondary chlorite (the latter very fine–grained).

#18 [TY10] A coarse chlorite–gedrite–biotite–cordierite–magnetite rock, with trace amounts of clinozoisite. The chlorite is primary and magnesian; the cordierite occurs in clusters of fresh grains with cores of magnetite; it is only slightly altered to sericite at the edges of the clusters.

3.4 Quirading samples

The Quirading area is in the southern part of the WGT, and is of high metamorphic grade (granulite facies). The locality is predominantly gneissic, with field evidence of a younger, somewhat less deformed granitic gneiss. The older gneiss carries deformed, non–continuous belts and lenses of chiefly aluminous and exotic metasediments, and mafic

and ultramafic granulites — outcrop is poor, and we have not seen any convincing evidence that the younger gneisses cut the metasediments and mafic granulites, though the limited field relations suggest that they should cut at least the metasediments.

Old Granitic Gneiss: Sample #3 [QB] is a 2 feldspars-quartz-biotite rock with alteration clots after orthopyroxene.

Young Granitic Gneiss: #4 [Q1] is a 2 feldspars-quartz-biotite rock, with minor orthopyroxene still preserved. From this we conclude that the granulite facies metamorphism can be no older than this young gneiss (both the old and the young gneisses can be equally labelled as charnockites).

#19

#21

Mafic rocks: Sample #6 is a 2 pyroxene–hornblende granulite (hornblende pyroxenite) with essentially no felsic minerals – it is ultramafic, with a composition that does not correspond to any common mafic igneous rock; we conclude that the protolith was probably a chemically altered mafic igneous rock prior to metamorphism. Sample #7 is a 2 pyroxene–plagioclase–minor biotite granulite with a composition similar to that of alkali basalts.

Metasediments: Sample #5 [Q12] is a cordierite-quartz-orthopyroxene granulite with trace amounts of biotite. This is a high–Al, low–Ca, low–alkali metasediment (varieties with much more biotite, corresponding to more normal pelitic metasediments have also been collected). Sample #8 [Q10] is an extremely Al–rich (altered) sapphirine–spinel–phlogopite nodule from a phlogopite– spinel–sapphirine–orthopyroxene granulite apparently flanking a narrow unit of hornblende pyroxenite; it was chosen for analysis not only because of its extreme composition, but also on the premise that it would be REE enriched.

#9

#22

#23

Young Mafic Dyke: #20.

4. Analytical procedures

Chemical separations were carried out with the procedures described by Jacobsen and Dymek [2]. The samples were spiked with ^{147}Sm, ^{150}Nd, ^{84}Sr and ^{87}Rb tracers. Spike equilibration with the sample was accomplished in TFE lined stainless steel bombs at 190° C using a mixture of HF, HNO_3, HCl and $HClO_4$. The REE and Rb and Sr were separated with a cation exchange column, using 2.5 and 4.0 N HCl as elutant. Sm and Nd were then separated from Ba and other REE using 0.2 M 2–methyllactic acid as elutant. Total chemistry blanks for Sr were 100 pg and for Nd $\approx$ 30 pg.

Mass spectrometric measurements were made on the Harvard VG Isomass 54 mass spectrometer. Sr was loaded in phosphoric acid on an oxidized Ta single filament. Nd was loaded on a Re single filament as chloride and run as NdO^+. Sm was run as Sm^+ on a Re or Ta single filament. We measured $^{87}Sr/^{86}Sr = 0.71025\pm2$ for the NBS 987 Sr standard; $^{143}Nd/^{144}Nd = 0.511130\pm10$ for the Caltech Nd Beta standard of Wasserburg et al. [3]; and $^{143}Nd/^{144}Nd = 0.511847\pm10$ for the USGS standard rock BCR–1. Weighted linear least squares fits to obtain isochron parameters were performed using the method of Williamson [4].

5. Results

5.1. Rare earth element (REE) patterns

REE patterns of two "normal" pelitic metasediments (#2 and #10) and two

HAMLAC metasediments (#1 and #5) are given in Table 4 and chondrite-normalized patterns are shown in Figs. 2 and 3, respectively. For comparison, the North American Shale Composite (NASC) REE pattern [5] typical of post-Archean shales is shown for comparison. Also shown is the average Archean shale REE pattern of Taylor and McLennan [6]. As shown the two "normal" metasediments of the WGB resemble the NASC pattern more in their LREE enrichment than the Archean shale values of Taylor and McLennan [6]. There is now an increasing amount of REE data on shales that suggest that there are no clear systematic differences between normal Archean shale REE patterns and post-Archean patterns. The apparent difference is probably because most of Taylor and McLennan's Archean shale values were based on greenstone belt shales. In contrast, the REE patterns of the two HAMLAC metasediments from the WGB (Fig. 3) do not resemble either Archean or post-Archean averages and probably were substantially fractionated relative to their crustal sources.

5.2. Model age relationships

Model ages T_{CHUR}^{Nd} can be calculated relative to the bulk Earth or CHUR curve (cf. [7–9]) and correspond to the time in the past when the $^{143}Nd/^{144}Nd$ in the sample coincided with the $^{143}Nd/^{144}Nd$ in the bulk Earth reservoir. It has however been shown by Jacobsen and Wasserburg [9] and many subsequent studies that a depleted reservoir has existed in the mantle (DM) throughout most of Earth history. It has therefore become common practice to calculate Nd model ages (T_{DM}^{Nd}) relative to such a depleted reservoir (cf. [10]) rather than the bulk earth reservoir. These depleted mantle model ages have also been called "crustal residence ages" in the same sense as McCulloch and Wasserburg [8] used T_{CHUR} ages as "provenance ages". Although the detailed evolution curve for such a

depleted mantle reservoir is not well known at present, a common approximation is to assume that it is linear starting with $\epsilon_{Nd} = 0$ at 4.55 Ga and evolving to +10 for today (i.e. the value observed in present day MORBs). For most clastic sediments such a single stage model age generally yields a good estimate of the average time of separation of their continental sources from the mantle source (i.e. the mean age of the continental source). The single stage Nd model age is given by:

$$T_{DM}^{Nd} = -\frac{1}{\lambda_{Sm}}\left[1 + \frac{(^{143}Nd/^{144}Nd)^0_{sample} - (^{143}Nd/^{144}Nd)^0_{DM}}{(^{147}Sm/^{144}Nd)^0_{sample} - (^{147}Sm/^{144}Nd)^0_{DM}} \right]$$

where $\lambda_{Sm} = 6.54 \times 10^{-12}a^{-1}$, $(^{147}Sm/^{144}Nd)^0_{DM} = 0.2136$ and $(^{143}Nd/^{144}Nd)^0_{DM} = 0.512359$ (assuming a linear DM evolution).

For Rb–Sr, the bulk Earth reference reservoir is called UR, and the Rb–Sr model age relative to the bulk earth is given by:

$$T_{UR}^{Sr} = -\frac{1}{\lambda_{Rb}}\left[1 + \frac{(^{87}Sr/^{86}Sr)^0_{sample} - (^{87}Sr/^{86}Sr)^0_{UR}}{(^{87}Rb/^{86}Sr)^0_{sample} - (^{87}Rb/^{86}Sr)^0_{UR}} \right]$$

where $\lambda_{Rb} = 1.42 \times 10^{-11}a^{-1}$, $(^{87}Rb/^{86}Sr)^0_{UR} = 0.0827$ and $(^{87}Sr/^{86}Sr)^0_{UR} = 0.7045$. A depleted mantle reference reservoir for Sr yields model ages that are essentially identical to UR model ages for the samples discussed here and are therefore not considered further. Clastic sediments normally have much higher Rb/Sr ratios than their source rocks, thus T_{UR}^{Sr} ages usually are expected to be closer to the time of sedimentation than to the mean age of the source rocks.

For chemical sediments, a two-stage Nd model age, T_{2DM}^{Nd}, is appropriate for

estimating the mean age of the continental sources of Nd since they are commonly fractionated relative to their continental sources at the time of deposition. The two-stage model can be obtained from the single stage T_{DM}^{Nd} model age by the equation:

$$T_{2DM}^{Nd} = T_{DM}^{Nd} - (T_{DM}^{Nd} - T_{STRAT}) \left[\frac{f_{cc} - f_{meas}}{f_{cc} - f_{DM}} \right]$$

where $f_{cc} = -0.45$ and $f_{DM} = 0.08529$ are the $f_{Sm/Nd}$ values of average crust and depleted mantle respectively. The two-stage model age corrects for Sm/Nd fractionation at the time of deposition of a chemical sediment and should give a better estimate of the mean age of the sources of Nd in HAMLAC sediments that have $f_{Sm/Nd}$ values very different from -0.45.

The Sm-Nd and Rb-Sr isotopic results are presented in Table 1–3 and Figs. 4–9. Model ages T_{UR}^{Sr} versus T_{DM}^{Nd} are shown in Fig 4. We note that only a couple of the samples plot close to the $T_{UR} = T_{DM}$ line. Most of the samples have younger Sr model ages than Nd model ages the exceptions are to granulite facies sample of the young granitic gneiss at Quirading and one sample of old granitic gneiss at Toodyay. The young granitic gneisses at Quirading may have anomalously high Sr model ages due to Rb loss during granulite facies metamorphism. Most of the samples have lower Sr than Nd model ages. In general large Rb/Sr fractionations occur during partial melting in the crust to form granitic rocks or during formation of sediments while only insignificant Sm/Nd fractionations occur during these processes.

Jack Hills: The metapelite sample from this locations yield ≈ 3.6 Ga nd and Sr model ages indicating that the source rocks of these sediments are as old as the oldest basement rocks exposed in the WGB around Mt. Narryer.

Koolanooka: Sample #1 is relatively unfractionated with respect to Sm/Nd, and

yields a T_{DM} model age of $\approx$ 3.9 Ga. As shown by the REE pattern for this sample it is clearly strongly fractionated from average crustal source rocks. This may indicate Sm/Nd fractionation during sediment formation rather than an unusual protolith. Sample #2 yield Nd model age of about 3.4 Ga; this sample has a typical shale REE pattern and this model age may yield a more true age for the source rocks of the Koolanooka sediments. Sr model ages for these samples are both in the range 2.5–2.7 Ga suggesting that this may be close to the time of sedimentation and/or metamorphism at Koolanooka..

Toodyay: The old granitic gneisses at Toodyay yield both Sr and Nd model ages in the range 3.3–3.6 Ga. The young granitic gneisses at Toodyay yield Sr model ages of about 2.–2.7 Ga while their Nd model ages are about 3.2 Ga. This suggest that these granitic rocks may have formed by partial melting of crust older than $\approx$ 3.2 Ga at about 2.6 Ga ago. HAMLAC sediments from Toodyay yield Sr model ages of $\approx$ 2.5 Ga, but Nd model ages in the range 3.4–3.5 Ga. This indicates very old crustal sources also for these sediment, while their time of sedimentation may be as young as 2.5 Ga.

Quirading: Old granitic gneiss from this location yield both Sr and Nd model age of $\approx$ 3.5 Ga suggesting the presence of very ancient gneisses here. The young granitic gneisses at Quirading also yield old Sr model ages in the range 3.0–3.6 Ga, while these yield Nd model ages of about 3.2 Ga. The HAMLAC sediments from Quirading yield Nd model ages in the range 3.3 –3.5 Ga, while their Sr model ages are in the range 2.6–3.1 Ga. This suggests also very old sources for these sediments, however their time of deposition is likely to be younger than 3.0 Ga.

5.3 Age constraints

The time of deposition of the Jack Hills metasediment has been dated by U-Pb on zircons to 2.9 $\bullet$ 0.2 Ga [13]. The other metasediments are constrained to have been

deposited during the time from ~ 2.67 Ga to 3.4 Ga ago [14]. The younger granitic rocks at Toodyay yielded U-Pb and Rb-Sr ages of 2.67 ± 0.05 Ga. The older granitic rocks appear from previous reports to be constrained by Rb-Sr and U-Pb to an age of 3.25 ± 0.07 Ga [14].

5.4 Isochron Relationships

The Sm-Nd data of the older granitic and mafic gneisses are shown in Fig. 5. All the data are shown relative to a T_{CHUR} reference line of 3.25 Ga. A weighted least squares fit to all the data yield T = 3.29 ± 0.32 Ga and an initial ϵ_{Nd} = +1.8 ± 4.2. The data on the granitic samples yield T = 3.61 ± 0.42 Ga and ϵ_{Nd} = 6.3 ± 6.0. The data can be compared to an age of ≈ 3.25 Ga constrained by Rb–Sr and U–Pb. McCulloch et al. [12] obtained a T = 3.21 Ga Sm–Nd isochron for the Toodyay–Northern gneisses. The Mt. Narryer data of deLaeter et al. [15] are shown for comparison. They clearly plot below the main trend in the data presented here for a larger part of the WGB and suggest that most of the gneisses in the WGB are some 0.2–0.4 Ga younger than the Mt. Narryer gneisses.

The Sm-Nd data of the younger granitic rocks of the WGB are shown in Fig. 6. The data are shown relative to a T_{CHUR} = 2.67 Ga reference line; the age suggested by U–Pb and Rb–Sr ages on these young granites. However, a weighted least squares fit to the data yield a poorly defined isochron of T = 3.37 ± 0.42 Ga with initial ϵ_{Nd} of +5.3 ± 5.7. This old age suggests that these young granites (≈ 2.7 Ga) were formed by melting of much older (>3.2 Ga) continental crust.

The Sm-Nd data of the WGB metasediments are shown in Fig. 7. A least squares fit to the sediment data yield T = 3.16 ± 0.07 Ga and ϵ_{Nd} = −0.4 ± 0.8, excluding two data points that are clearly far off the best fit line (the sapphirine nodule #8 and a chlorite–rich metasediment #18). Since this age most likely reflect source rock ages rather

than deposition ages, this suggests that the time of deposition is 3.16 Ga or younger. The origin of the sapphirine nodule is problematic: if its isotopic signature is primary, and not affected by the alteration, and if it is $\approx$ 3.2 Ga old, then its protolith then had to have a substantially positive ϵ_{Nd} of $\approx$ +4. This would allow its derivation by weathering of a depleted mafic/ultramafic rock — but in the process a high REE enrichment would have to have taken place. We infer that the metasediments may have sources that are in the range 3.1–3.6 Ga old while the Rb/Sr data discussed below suggest that their time of deposition is in the range 2.6–2.9 Ga.

The Rb-Sr data of the WGB sediments and older/younger granitic rocks are shown in Figs. 8 and 9. The Rb-Sr data show a wide scatter in the Rb-Sr isochron diagram, but mostly the data plot between T^{Sr}_{UR} reference lines of $\sim$ 2.67 Ga and 3.25 Ga. Most of the samples with very high Rb/Sr ratios are metasediments that plot close to the $T^{Sr}_{UR} = 2.67$ Ga reference line suggesting that the time of deposition of these sediments is close to this age. While Sm/Nd data for the Koolanooka samples indicate that their source rocks are >3.0 Ga, Rb/Sr data of Arriens [11] on surrounding gneisses, granitoids and quartz porphyries suggest that their ages are $\approx$ 2.5 Ga.

6. Discussion

Synthesizing our Sm/Nd data thus far we conclude that:

(i) Major crust formation took place in the WGT at about 3.2 Ga, producing both (para???) gneisses and (meta) sediments, derived from an $\epsilon_{Nd} = 0$ source not older than 3.4 Ga.

(ii) the high–Al and other clastic sediments yield no evidence for a much older continental source. While highly positive and negative ϵ_{Nd} values may occur, typical values are in the range –6 to –4, substantially lower than those of contemporaneous chemical sediments.

(iii) a younger suite of granitic and other igneous rocks was emplaced throughout the WGT between 2.7 and 3.0 Ga, but was largely derived from older rocks.

(iv) the metamorphic grades preserved regionally increase from north to south in the WGT.

(v) this regional metamorphism can be no older than the emplacement of the younger granitic rocks.

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TABLE 1.
Sm–Nd analytical results for the Western Gneiss Belt

Sample	Sm (ppm)	Nd (ppm)	$\frac{^{147}Sm}{^{144}Nd}$ [c]	$\frac{^{143}Nd}{^{144}Nd}$ [d]	$\epsilon_{Nd}(0)$
Koolanooka – Fe–, Mg– and Al–rich metasediments					
#1	2.238	7.398	0.18290	0.511551±15	− 5.78±0.29
#2	4.713	24.94	0.11425	0.510121±27	−33.72±0.53
Quirading – granitic gneisses					
#3	7.509	44.76	0.10142	0.509799±43	−40.01±0.84
#4	4.698	27.14	0.10467	0.510119±36	−33.76±0.71
#19	2.076	12.51	0.10032	0.509925±28	−37.55±0.55
#21	0.766	5.127	0.09033	0.509785±18	−40.29±0.35
Quirading – mafic and dyke rocks					
#6	3.767	19.00	0.11989	0.510429±19	−27.70±0.37
#7	1.454	6.108	0.14393	0.510664±23	−23.11±0.46
#20	8.631	39.97	0.13061	0.511542±23	− 5.96±0.45
Quirading – Fe–, Mg– and Al–rich metasediments					
#5	1.317	6.593	0.12076	0.510289±64	−30.44±1.25
#9	8.550	41.62	0.12422	0.510308±18	−30.07±0.35
#22	28.05	147.8	0.11474	0.510190±32	−32.37±0.63
#23	7.101	35.16	0.12213	0.510266±25	−30.89±0.49
#8	16.58	99.64	0.10059	0.509983±32	−36.42±0.63
Jack Hills – Fe– and Al–rich metasediment					
#10	6.012	30.59	0.11886	0.510094± 7	−34.25±0.14
Toodyay – granitic gneisses					
#11	11.07	83.70	0.07997	0.509552±22	−44.84±0.43
#12	5.217	37.59	0.08389	0.509543±13	−45.01±0.26
#17	2.061	13.92	0.08958	0.509603±14	−43.84±0.27
Toodyay – Fe–, Mg– and Al–rich metasediments					
#13	3.645	18.02	0.12232	0.510241±12	−31.38±0.24
#14	23.58	167.7	0.08497	0.509495± 7	−45.95±0.14
#15	13.50	87.79	0.09299	0.509642±28	−43.08±0.55
#16	1.747	8.602	0.12278	0.510275±18	−30.71±0.35
#18	2.066	6.447	0.19384	0.511539±11	− 6.02±0.22

a) Reported errors are 2σ of the mean.
c) Uncertainty is less than 0.1%.
d) Corrected for mass fractionation using $^{146}Nd/^{142}Nd = 0.636151$.

TABLE 2.

Rb- Sr analytical results for the Western Gneiss Belt[a]

Sample	Weight[b] (mg)	Rb (ppm)	Sr (ppm)	$\frac{^{87}Rb}{^{86}Sr}$[c]	$\frac{^{87}Sr}{^{86}Sr}$[d]	$T_{UR}^{Sr}(Ga)$[e]
Koolanooka -	Fe-, Mg- and Al- rich metasediments					
#1 (KOOL1)	201.65	1.850	3.718	1.446	0.75335± 8	2.48±0.03
#2 (KOOL2)	250.15	34.28	9.068	11.42	1.15602±16	2.75±0.03
Quirading -	granitic gneisses					
#3 (QB)	229.90	119.2	149.1	2.337	0.81572± 5	3.39±0.04
#4 (Q1)	260.74	70.58	239.5	0.856	0.74263± 6	3.39±0.04
#19 (Q5)	203.04	117.6	169.1	2.028	0.78936± 3	3.01±0.03
#21 (Q9)	197.41	60.04	218.3	0.799	0.74294± 4	3.68±0.04
Quirading -	mafic and dyke rocks					
#6 (Q7)	236.26	8.178	36.45	0.652	0.74641±11	5.01±0.07
#7 (Q8)	252.73	14.06	234.5	0.174	0.75662±12	31.7±0.53
#20 (Q6)	193.59	177.9	45.92	11.21	0.71155± 9	0.045±0.00
Quirading -	Fe-, Mg- and Al- rich metasediments					
#5 (Q12)	293.35	13.91	6.820	6.048	0.96552±28	3.02±0.03
#9 (Q14)	240.06	167.0	13.75	40.69	2.32665±11	2.76±0.03
#22 (Q11)	197.45	104.9	8.478	42.63	2.66167±40	3.17±0.03
#23 (Q17)	200.61	116.0	3.782	133.6	5.8738± 24	2.68±0.03
#8 (Q10)	261.84	2.556	3.465	2.140	0.73433±12	1.01±0.01
Jack Hills -	Fe- and Al- rich metasediment					
#10 (JH1)	258.24	28.42	39.65	2.094	0.80875± 6	3.56±0.04
Toodyay -	granitic gneisses					
#11 (TY30)	248.21	101.5	159.3	1.854	0.77307± 7	2.67±0.03
#12 (TY31)	253.61	95.31	167.3	1.657	0.76760± 3	2.77±0.03
#17 (TY2)	247.19	47.67	444.8	0.310	0.71664± 3	3.66±0.06
Toodyay -	Fe-, Mg- and Al- rich metasediments					
#13 (TY17b)	245.60	73.84	6.700	35.83	1.97719±29	2.46±0.02
#14 (TY1)	240.35	0.281	30.11	0.027	0.71240±14	-10.7±0.15
#15 (TY3)	252.42	0.365	3.042	0.348	0.73683±62	8.09±0.24
#16 (TY26)	253.23	118.1	54.85	6.375	0.94324±13	2.62±0.03
#18 (TY10)	254.76	24.60	8.088	9.096	1.05267±36	2.67±0.03

a) Reported errors are 2σ mean.
b) Weight of dissolved sample.
c) Uncertainty is less than 1.0%.
d) Corrected for mass fractionation using $^{86}Sr/^{88}Sr = 0.1194$.
e) Model age calculated using present day bulk Earth (UR) values of

$^{87}Sr/^{86}Sr=0.7045$ and $^{87}Rb/^{86}Sr=0.0827$ (DePaolo and Wasserburg, 1976).

TABLE 3.

Initial ϵ_{Nd}, $f_{Sm/Nd}$ and model ages for the Western Gneiss Belt rocks[a]

Sample	$f_{Sm/Nd}$	$\epsilon_{Nd}(T)$	T^{Nd}_{CHUR}(Ga)	T^{Nd}_{DM} (Ga)	Age(Ga)
Koolanooka	- Fe-, Mg-	and Al-rich	metasediments		
#1 (KOOL1)	-0.0702	+0.03 ± 0.52	3.25 ± 0.21	3.97 ± 0.10	3.26±0.0
#2 (KOOL2)	-0.4192	+1.00 ± 1.45	3.17 ± 0.05	3.41 ± 0.05	3.26±0.0
Quirading	- granitic	gneisses			
#3 (QB)	-0.4844	-0.02 ± 1.77	3.25 ± 0.07	3.45 ± 0.06	3.25±0.0
#4 (Q1)	-0.4679	-2.10 ± 1.35	2.84 ± 0.06	3.11 ± 0.05	2.67±0.0
#19 (Q5)	-0.4900	-4.41 ± 1.22	3.02 ± 0.05	3.25 ± 0.04	2.67±0.0
#21 (Q9)	-0.5408	-3.70 ± 1.08	2.94 ± 0.03	3.16 ± 0.02	2.67±0.0
Quirading	- mafic and	dyke rocks			
#6 (Q7)	-0.3905	+4.57 ± 1.13	2.80 ± 0.04	3.12 ± 0.03	3.25±0.0
#7 (Q8)	-0.2683	-0.97 ± 1.00	3.39 ± 0.08	3.68 ± 0.06	3.25±0.0
#20 (Q6)	-0.3360	-5.58 ± 0.46	0.70 ± 0.05	1.50 ± 0.04	0.045±0.00
Quirading	- Fe-, Mg-	and Al-rich	metasediments		
#5 (Q12)	-0.3861	+1.55 ± 2.11	3.11 ± 0.13	3.37 ± 0.11	3.26±0.0
#9 (Q14)	-0.3685	+0.45 ± 1.17	3.21 ± 0.04	3.47 ± 0.04	3.26±0.0
#22 (Q11)	-0.4167	+2.15 ± 1.54	3.06 ± 0.06	3.32 ± 0.05	3.26±0.0
#23 (Q17)	-0.3791	+0.51 ± 1.33	3.21 ± 0.06	3.46 ± 0.05	3.26±0.0
#8 (Q10)	-0.4886	+4.08 ± 1.69	2.94 ± 0.05	3.18 ± 0.05	3.26±0.0
Jack Hills	- Fe- and	Al-rich metasediment			
#10 (JH1)	-0.3957	-5.17 ± 2.23	3.41 ± 0.02	3.61 ± 0.02	2.90±0.2
Toodyay	- granitic	gneisses			
#11 (TY30)	-0.5934	-4.70 ± 1.22	2.98 ± 0.03	3.18 ± 0.03	2.67±0.0
#12 (TY31)	-0.5735	-6.23 ± 1.02	3.09 ± 0.02	3.28 ± 0.02	2.67±0.0
#17 (TY2)	-0.5446	+1.13 ± 1.30	3.17 ± 0.02	3.36 ± 0.02	3.25±0.0
Toodyay	- Fe-, Mg-	and Al-rich	metasediments		
#13 (TY17b)	-0.3781	-0.06 ± 1.07	3.27 ± 0.03	3.51 ± 0.02	3.26±0.0
#14 (TY1)	-0.5680	+1.10 ± 1.35	3.19 ± 0.01	3.37 ± 0.01	3.26±0.0
#15 (TY3)	-0.5272	+0.59 ± 1.68	3.22 ± 0.04	3.41 ± 0.04	3.26±0.0
#16 (TY26)	-0.3758	+0.41 ± 1.19	3.22 ± 0.04	3.47 ± 0.03	3.26±0.0
#18 (TY10)	-0.0145	-4.85 ± 0.33	15.6 ± 1.64	6.22 ± 0.14	3.26±0.0

a) Reported errors are 2σ mean. Model parameters calculated using present day bulk Earth (CHUR) values of $^{143}Nd/^{144}Nd = 0.511847$ and $^{147}Sm/^{144}Nd = 0.1967$ (Jacobsen and Wasserburg, 1984) and present day depleted mantle values of $(^{143}Nd/^{144}Nd)_{DM} = 0.512359$ and $(^{147}Sm/^{144}Nd)_{DM} = 0.2136$.

TABLE 4.
REE analytical results in ppm.

	Jack Hills #10	Koolanooka #1	#2	Quirading #5
La	43.2	5.76	32.0	49.8
Ce	81.6	13.7	63.6	86.7
Nd	32.4	7.96	23.4	32.4
Sm	6.18	2.32	4.43	6.09
Eu	1.25	2.27	0.940	0.685
Gd	–	2.96	4.25	4.29
Dy	4.36	3.96	4.14	2.46
Er	2.59	2.86	2.53	0.876
Yb	2.83	2.97	2.57	0.682
Lu	0.384	0.514	0.397	0.108

Figure Captions

Figure 1. Location map

Figure 2. REE patterns for Koolanooka and Jack Hills metapelites.

Figure 3. REE patterns for Koolanooka and Quirading high–Mg–Al, low Ca, low alkali metasediments.

Figure 4. T_{UR}^{Sr} versus T_{DM}^{Nd} model age diagram for the Western Gneiss Belt.
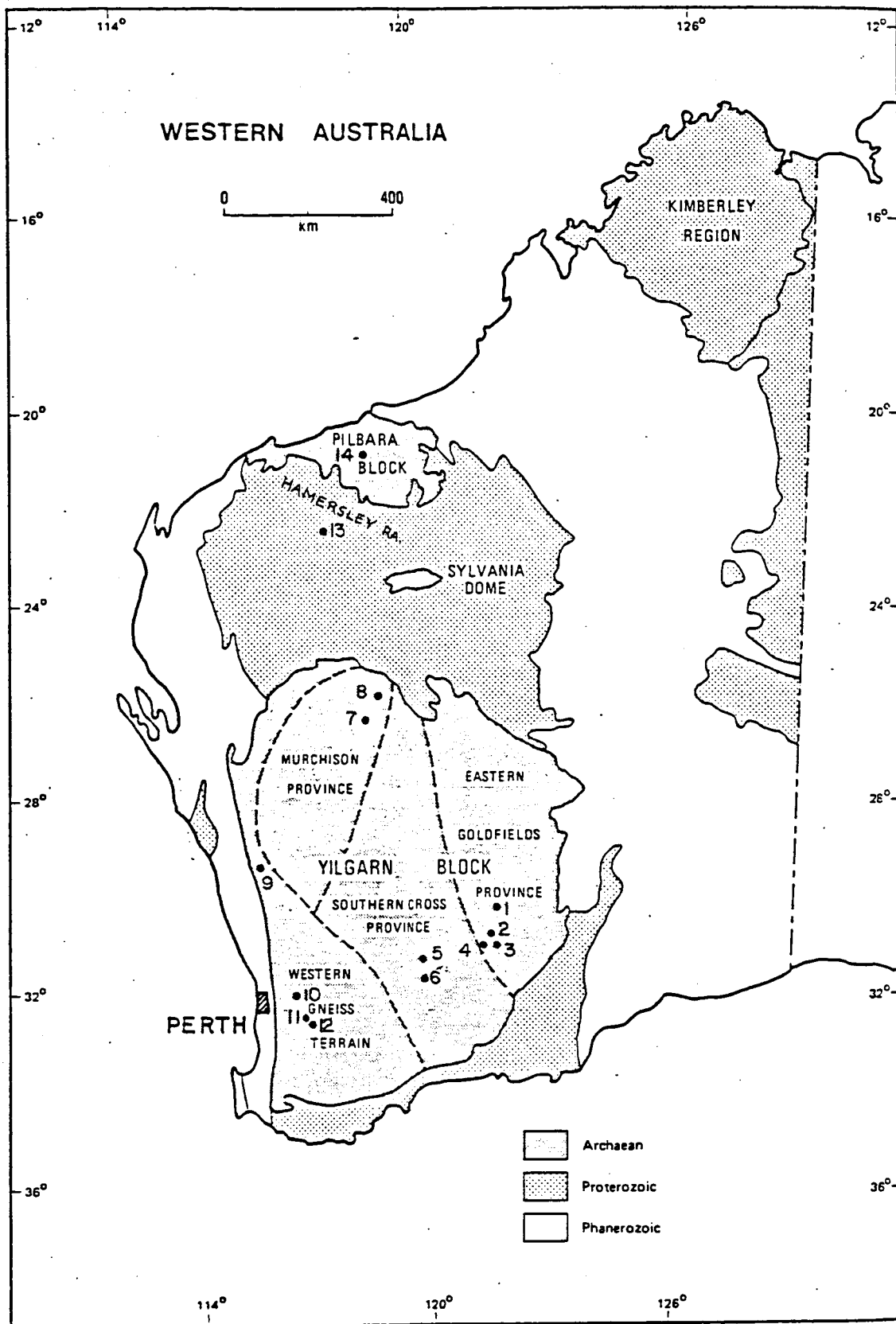
Figure 5. Sm–Nd isochron diagram for the older gneisses of the Western Gneiss Belt. Mt. Narryer data from DeLaeter et al. [15], Milly Milly to Erong data from Fletcher et al. [16], Northham and Ringa data from McCulloch et al. [12].

Figure 6. Sm–Nd isochron diagram for the younger granitic rocks of the Western Gneiss Belt. Mortigup and Monday Hill data from McCulloch et al. [12]. Quirading and Toodyay data from this work.

Figure 7. Sm–Nd isochron diagram of Western Gneiss Belt metasediments

Figure 8. Rb–Sr isochron diagram of Western Gneiss Belt metasediments.

Figure 9. Rb–Sr isochron diagram of the Western Gneiss belt.

WESTERN AUSTRALIA

0   400
km

KIMBERLEY
REGION

PILBARA
14 •
BLOCK

HAMERSLEY R↴

• 13

SYLVANIA
DOME

8 •
7 •

MURCHISON
PROVINCE

EASTERN

GOLDFIELDS

YILGARN   BLOCK

SOUTHERN CROSS
PROVINCE

PROVINCE
• 1

• 2
4 • • 3

5 •
9

6 •

WESTERN
• 10

PERTH   11 • GNEISS
• 12

TERRAIN

	Archaean
	Proterozoic
	Phanerozoic

Fig. 1

WESTERN GNEISS BELT   -   YILGARN BLOCK
METASEDIMENTS

REE SAMPLE / REE CHONDRITES

100

10

1

La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu

NASC

KOOLANOOKA 2

JACK HILLS 10

Fig. 2.

WESTERN GNEISS BELT — YILGARN BLOCK METASEDIMENTS

REE SAMPLE / REE CHONDRITES

NASC

KOOLANOOKA   1

QUIRADING   5

La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu

Figure 3.

Figure 4

WESTERN GNEISS BELT-YILGARN BLOCK
OLDER GRANITIC AND MAFIC GNEISSES

$T = 3.29 \pm 0.32$ Ga GRANITIC
$\epsilon_{Nd} = 1.8 \mp 4.2$ AND MAFIC

$T = 3.61 \pm 0.42$ Ga GRANITIC
$\epsilon_{Nd} = 6.31 \mp 6.0$ ONLY

$T_{CHUR} = 3.25$ Ga

CHUR

$^{143}Nd/^{144}Nd$

$\epsilon_{Nd}(0)$

$^{147}Sm/^{144}Nd$

MAFIC
◇ QUIRADING
◆ NORTHAM
   GRANITIC-REGRESSED
□ QUIRADING
■ TOODYAY
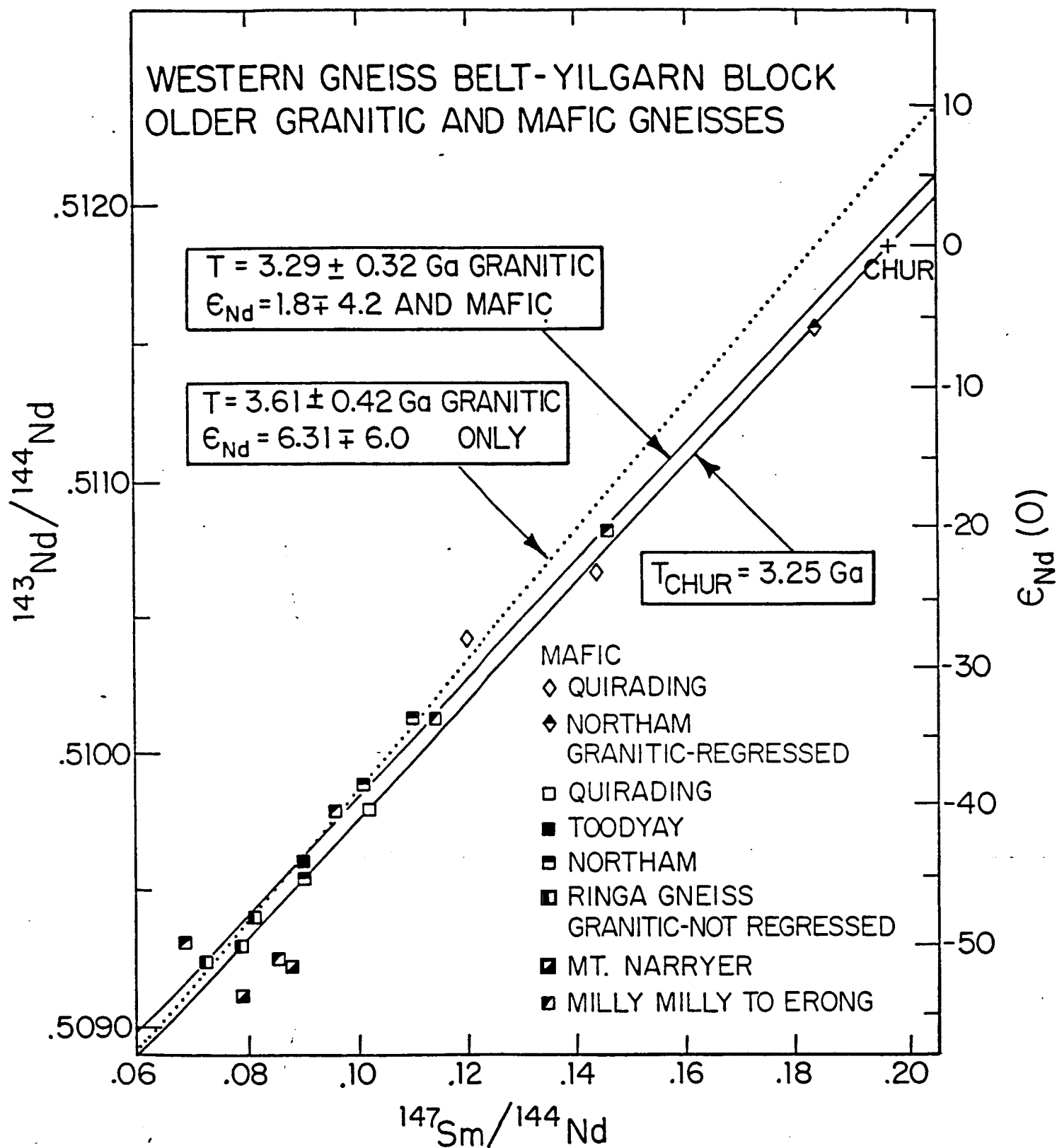◲ NORTHAM
◩ RINGA GNEISS
   GRANITIC-NOT REGRESSED
◪ MT. NARRYER
◪ MILLY MILLY TO ERONG

Figure 5

Figure 6

WESTERN GNEISS BELT-YILGARN BLOCK METASEDIMENTS

$T = 3.16 \pm 0.07 \, Ga$
$\epsilon_{Nd} = -0.4 \mp 0.8$

CHUR

○ QUIRADING
● TOODYAY
◑ KOOLANOOKA
◑ JACK HILLS

$^{143}Nd/^{144}Nd$

$\epsilon_{Nd}(O)$

$^{147}Sm/^{144}Nd$
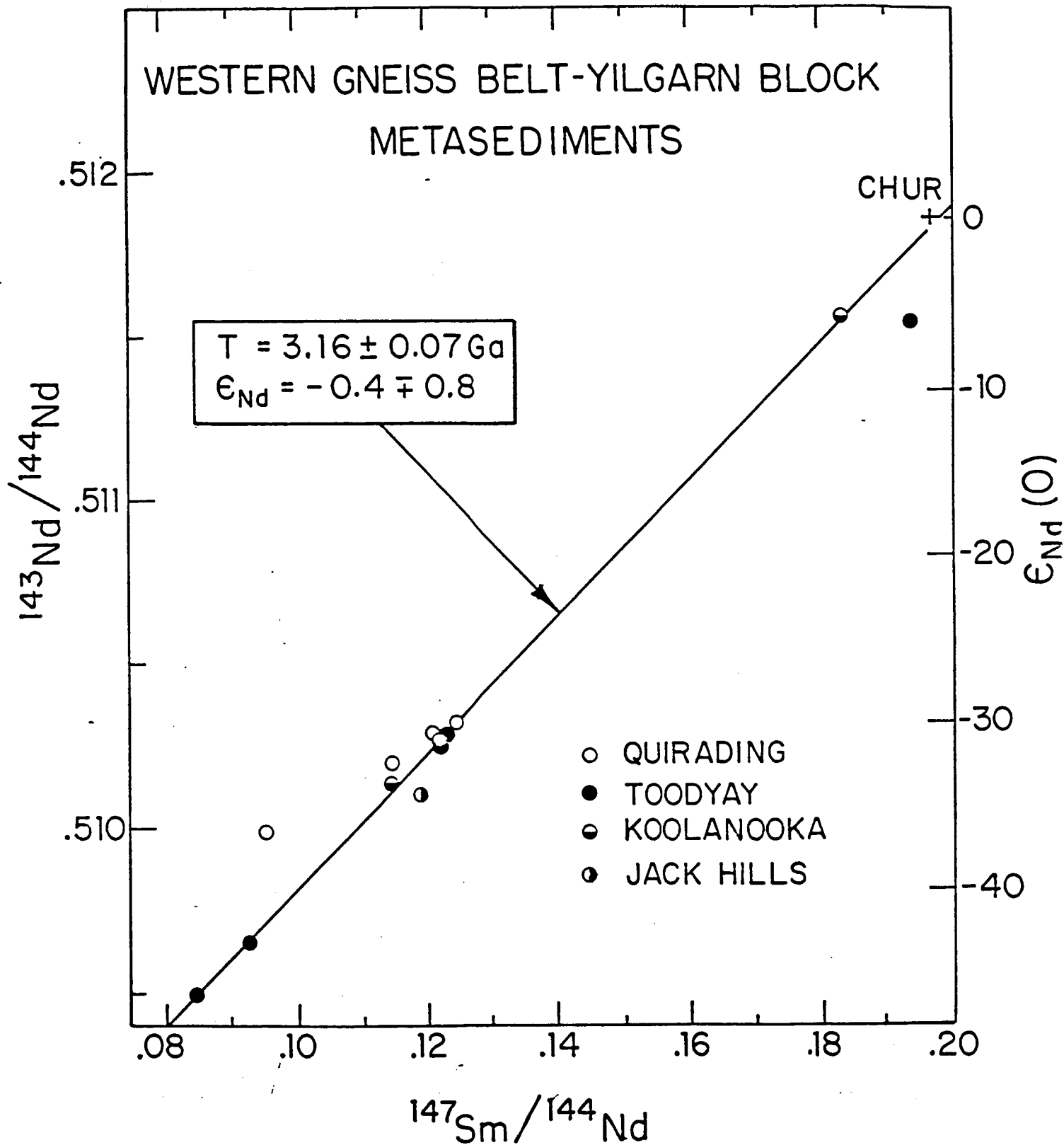
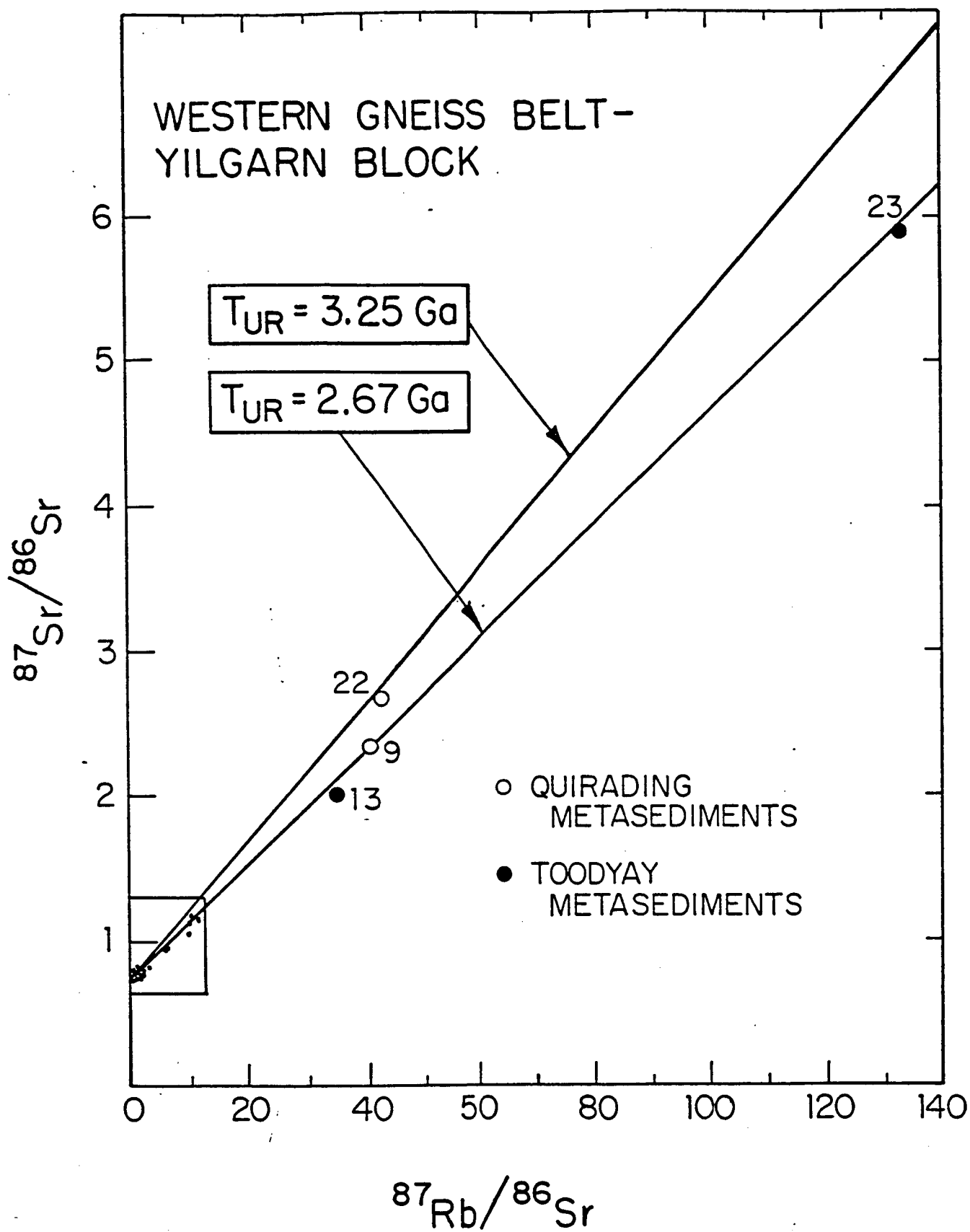Figure 7

WESTERN GNEISS BELT-
YILGARN BLOCK

$T_{UR} = 3.25\ Ga$

$T_{UR} = 2.67\ Ga$

$^{87}Sr/^{86}Sr$

$^{87}Rb/^{86}Sr$

o QUIRADING
   METASEDIMENTS

• TOODYAY
   METASEDIMENTS

8

WESTERN GNEISS BELT-YILGARN BLOCK

$T_{UR} = 3.25\,Ga$

$T_{UR} = 2.67\,Ga$

$^{87}Sr/^{86}Sr$

$^{87}Rb/^{86}Sr$

○ QUIRADING METASEDIMENTS
● TOODYAY METASEDIMENTS
◐ KOOLANOOKA METASEDIMENTS
◑ JACK HILLS METASEDIMENT
◇ QUIRADING MAFIC ROCKS
□ QUIRADING OLD GNEISS
△ QUIRADING YOUNG GRANITOIDS
■ TOODYAY OLD GNEISSES
▲ TOODYAY YOUNG GRANITOIDS

Figure 9