

The Kayelekera Uranium Deposit, northern Malawi.
Past exploration activities, economic geology and decay series disequilibrium

R. A. Bowden¹ and R. P. Shaw²

Abstract

This paper describes the work carried out by the Central Electricity Generating Board (CEGB) on the Kayelekera Uranium Deposit in Northern Malawi between 1983 and 1991. This is one of the largest Karoo-age sandstone hosted uranium deposits yet discovered. Approximately 200 boreholes, about 60% of which were fully cored, were drilled into the deposit during this evaluation. An important part of the ore reserve estimation undertaken by the CEGB at Kayelekera was gaining an understanding of the uranium decay series distribution within the deposit. Being located in a near surface environment the deposit is subject to weathering effects caused by oxidising groundwater. Three ore types are recognised, reduced facies ore, oxidised facies ore and transitional facies ore containing both oxidised and reduced material in varying proportions. Being more mobile under oxidising conditions uranium tends to be leached from the oxidised parts of the deposit and re-deposited in more reducing parts however its gamma emitting daughters tend to be less mobile in an oxidising environment leading to a marked disequilibrium between uranium and its daughters with the oxidized facies ore being depleted in uranium relative to its daughters and the reduced facies ore often showing relative enrichment.

Introduction

The Kayelekera uranium deposit is a Karoo age, sandstone hosted uranium deposit located 35km west of the town of Karonga in the far north of Malawi (Figure 1). Malawi is a relatively small landlocked country in south eastern central Africa with a total area of 118,000 km², of which some 24,000 km² is occupied by Lake Malawi. Lake Malawi, with a surface elevation of approximately 450m above sea level and depth up to 704m, is the third largest lake in Africa and occupies the southerly extension of the East African Rift Valley system.

The Kayelekera area is drained by two main river systems, the Sere and its tributaries to the north, and the Muswanga and its tributaries to the south. Both rivers join the North Rukuru River which flows into Lake Malawi just to the north of Karonga town. Kayelekera is a hilly area, generally covered by fairly open Miombo woodland. Elevations rise from about 760m in the Sere valley to about 2120m at the summit of Mususi Hill to the south west of Kayelekera.

During the period of the study, the authors both worked for the UK's Central Electricity Generating Board, then National Power and Nuclear Electric as the UK electricity supply industry was privatised in the late 1980's, RAB from 1981 to 1990 and RPS from 1984 to 1991. Between them they managed the work of evaluating the Kayelekera Uranium deposit from initial field studies, exploration drilling and ore reserve evaluation through to full mining feasibility and environmental impact studies. This paper is based on their knowledge of the deposit gained during these detailed investigations and originally recorded in unpublished CEGB reports (Bowden and Gribbin 1984; Bowden et al 1985; 1986; 1987; Bowden and Shaw 1988; Bowden et al 1989; 1990; Shaw 1991; Brown 1989; Shaw 1990a; 1990b).

The work described in this paper was undertaken at a time when uranium prices were decreasing (it stood at around US\$8 per pound U₃O₈ when the project was wound up in 1991) and global interest in exploring for uranium had decreased significantly from the uranium boom of the 1970's. Uranium is now (March 2007) about US\$85 per pound U₃O₈ having

¹ Geodec Consulting, 2928 Moggill Road, Pinjarra Hills, Brisbane, QLD 4069

² British Geological Survey, Keyworth, Nottingham, NG12 5GG, England

advanced in price, having increased from about \$45 during the last 6 months, leading to considerable renewed interest in uranium exploration over the last few years. This has included renewed interest in the Kayelekera deposit for which Paladin Resources now have Malawi Government approval to develop into a mine. While the work described is not recent the investigation of the uranium series disequilibrium present in the deposit is a comprehensive examination of the problem in a sandstone hosted deposit located in a near surface tropical environment that will be of value to the evaluation of similar deposits elsewhere.

Project History

In 1957 several samples of radioactive arkose assaying 0.02 to 0.03 %U₃O₈ were collected from Mwankimene in the North Rukuru Valley (Ray, 1975). Follow up prospecting was unsuccessful and no further work was carried out until Agip Exploration, in the course of an airborne radiometric survey in 1977 located a number of radiometric anomalies in the area. Ground follow-up led to the discovery of surface secondary uranium minerals in outcrop near Kayelekera village. Agip carried out a limited evaluation of the anomalies at Kayelekera including digging a few shallow pits and trenches but did not renew their exploration licence. BCUPO, the uranium procurement arm of the UK's Central Electricity Generating Board (CEGB) reviewed the uranium exploration potential of Africa during the late 1970's and in 1980 identified the Karoo basins of Malawi as areas with good potential for the discovery of uranium deposits. It was not until March 1983 when Malawi's new Mines and Minerals Act (Mines and Minerals Act, 1981) came into effect that CEGB were granted two Reconnaissance Licences covering the North Rukuru and Livingstonia sedimentary basins of Karoo age in Northern Malawi. The one-year Reconnaissance Licence over the Livingstonia area was renewed in April 1984 and again in April 1985 but was dropped at the end of March 1986 following discouraging results in that area. In April 1984, following a successful exploration campaign over the North Rukuru Basin and the realisation that there could be a significant deposit of uranium at Kayelekera the CEGB applied for a three-year Exclusive Prospecting Licence (EPL) covering the area of the previous Reconnaissance Licence in that area. This was renewed in April 1987 and again in April 1990. A pre-feasibility study conducted in 1986 included preliminary laboratory testing of ore samples by Davy McKee (Stockton) Ltd. This study confirmed the potential of the Kayelekera deposit and a decision was made to proceed to the full feasibility stage. As part of the feasibility study independent consultants carried out the following contributing studies:

- Preliminary Geotechnical Study - Geoffrey Walton Consultants
- Technical Feasibility Study – Wrights Engineers Limited (WEL), Vancouver
- Geostatistical Reserves Validation – Harry Parker and Ed Isaaks (Fluor Daniels)
- Geotechnical Study – Piteau Associates, Vancouver
- Safety and Health Report – Senes Consultants, Toronto
- Environmental Impact Statement – WS Atkins Environment (UK)
- Hydrological/hydrogeological Study – Steffen, Robertson and Kirsten (S.A)
- Sulphuric Acid Plant – Techpro (UK)
- Coal-fired Power Plant – British Energy International (B.E.I.)

In 1989 following the confirmation of a sizeable uranium deposit at Kayelekera negotiations were started with the Malawi Government for the grant of a Mining Licence with the intention of mining the deposit by open pit methods. However, a number of circumstances towards the end of 1989 conspired together to bring about an end to those negotiations and ultimately relinquishment of the Kayelekera licence, which lapsed in March 1992. Chief amongst these circumstances was the decision by the UK Government to privatise the CEGB; responsibility for the nuclear power generation passing in turn to National Power and then to Nuclear Electric as the industry was privatised. Neither of these operators was committed to the 'diversification of uranium supply' policy heralded by the CEGB. A second major factor

was the very significant drop in price of uranium from around US\$30/lb in the early 1980's to under US\$10/lb by the late 1980's. These economic conditions had a negative impact on the project economics and the project was placed on a minimum cost basis with limited environmental and hydrogeological data collection continuing on site during 1991 and early 1992.

In 1997/98 Balmain Resources applied for and were granted an Exclusive Prospecting Licence over 157km² covering the Kayelekera Prospect. In March 1998, Paladin Resources earned a 90% interest in the project through a farm-in agreement with Balmain Resources and in 2005 acquired the remaining 10% equity in the project. Paladin Resources have recently completed (2006) confirmation drilling and a new mining feasibility study. The deposit contains Measured/Indicated resources of 16.3 Mt at a grade of 0.09% U, equivalent to 13630 tonnes (31.1 Mlbs) of U₃O₈ (Paladin Resources 2007a). Following completion of a bankable feasibility study and an environmental impact assessment, the company applied to the Malawi Government in late 2006 for a mining licence and in February 2007 Paladin announced that they had reached a development agreement with the Malawi Government and they plan, subject to final approvals, to commence development and construction work in March/April 2007 with mine commissioning planned for September 2008 (Paladin Resources 2007b).

Exploration/Field Activities

During the 1983 field season reconnaissance prospecting comprising a regional drainage (stream sediment and water) geochemical survey and a relatively uncontrolled heliborne total count gamma-ray spectrometer survey (a carborne system mounted in the rear seat of a Jetranger helicopter flown just above tree-top height) was carried out over both licences. A small laboratory was established in the township of Karonga on the lakeside and installed with a Scintrex UA-3 pulsed uranium fluorescence analyser for analysis of uranium in water samples. Twelve anomalous areas were identified for ground follow-up. The geology at Kayelekera was mapped in detail (Figure 1) and as a major objective of the field programme was to demonstrate that the known surface mineralisation had extension in depth, a Terradex Track-EtchTM survey was carried out to test the along-strike and dip potential of the surface exposure. The result of this survey was an impressive anomaly successfully outlining the arkose scarp- subcrop over a strike length of 1000m and providing sufficient evidence to justify taking out an Exclusive Prospecting Licence and planning a drilling campaign for the next field season.

In the 1984 field season a limited drill programme was carried out using a Malawi Geological Survey drill rig. The first borehole drilled about 120 metres behind the known mineralised exposure intersected 3.2 metres of mineralisation with a grade of 0.33 %U₃O₈ at a depth of 32 metres in reduced facies arkose and was instrumental in proving the potential of the mineralisation. A total of 509.82 metres was drilled in 5 drillholes (KA01 to KA05). This drilling was supplemented by a programme of trenching in which hand dug trenches were excavated over the main scintillometer highs identified the previous year and the resulting exposed mineralisation sampled for assay purposes. For the 1985 and subsequent field seasons contract drilling crews were sourced from the UK. During the 1985 field season a total of 3993.68 metres drilling was completed outlining a deposit resource of some 7,500 tonnes contained U₃O₈.

Further drilling, totalling 3821.34 m was carried out in 1986 to complete a 50 metre x 50 metre grid and extend the margins of the deposit. The in situ resource was increased to 9300 contained tonnes U₃O₈ at a cut-off grade of 0.05% U₃O₈. In 1987 a major campaign of open-hole infill drilling totalling 7,664.82 metres was carried out to provide a 25m x 25m evaluation grid for calculation of in situ ore reserves. No drilling was carried out at Kayelekera in 1988 although 1180.10 metres of scout drilling was carried on other uranium targets in the area. Drilling was also carried out to identify limestone and coal deposits in connection with mine planning. In 1989 a total of 2017.44 metres was drilled into the deposit

and its margins for structural, hydrogeological, geotechnical and ore metallurgical testing purposes. In total 18,106.3 metres covering 213 holes were drilled into the Kayelekera uranium deposit between 1984 and 1989. Out of these 213 holes, 59% were fully cored.

Table 1: Drilling Statistics, Kayelekera Uranium Deposit and Immediate Locality

Year	Total drilled (m)	Core (m)	Open hole (m)	No. of holes	Contractor	Comments
1984	509.82	459.82	50.0	6	Malawi Geological Survey	Initial Exploration
1985	231.05	216.05	15.0	3	Malawi Geological Survey	
1985	3762.63	3106.21	656.42	36	Drillsure Ltd.	Exploration Drilling
1986	3821.34	3280.76	540.58	52	BB Drilling Ltd.	Exploration Drilling
1987	7664.82	1689.32	5995.50	88	BB Drilling Ltd.	Evaluation and Geotech Drilling
1989	2017.44	1920.54	96.9	24	BB Drilling Ltd.	Geotech, Hydrogeological and Bulk samples
1989	99.20	87.20	12.00	4	BB Drilling Ltd	Tailings Dam Geotech and Hydrogeological Studies

The Geology of the Kayelekera Deposit

Regional Setting

Northern Malawi is mainly underlain by metamorphic and igneous rocks of the pre-Karoo Malawi Basement Complex, the main components of which are gneisses and intrusives of the Misuku Belt, that form the southeastern extension of the Ubendian Mobile belt (ca 2000Ma (Schluter; 1997)) of southwestern Tanzania into Malawi. The Precambrian basement was subjected to four episodes of mainly brittle deformation in the late Precambrian and early Palaeozoic during the Irumide and Mozambique Orogenies (Ring; 1999; Schluter; 2006). A long period of erosion of the Misuku belt was interrupted in the Early Permian by the deposition of Karoo sediments upon a subdued but irregular topography initially under glacial and periglacial conditions. Faulting and subsidence accompanied Karoo sedimentation which ended with the initiation of the Gondwana erosion cycle in the Lower Jurassic. The Karoo sedimentary strata, which probably covered much of the area by the mid-Permian, now occupy several partially or totally fault bounded basins. The North Rukuru Basin is an elongate basin some 50km along strike (north-south) with a maximum width of 6.5 km (Figure 1). It contains a thick (at least 1500m) sequence of Karoo sedimentary rocks preserved in a semi-graben about 35km to the west of, and broadly parallel with, the Lake Malawi segment of the East African Rift system. The formation of the North Rukuru Basin, and the other Karoo basins of northern Malawi, preceded the development of the main East African Rift System, including the Lake Malawi Rift, by perhaps 250 million years (inception of rifting of the Lake Malawi Rift is variously assigned to the Upper Miocene (Kaufulu et al 1981) to as early, possibly, the late Jurassic (Schluter 1997)). However, the development of these graben and semi-graben basins shows that conditions of crustal extension existed in the Early Permian prior to the onset of the main rifting phase. The faulted eastern margin of the basin may have been active during sedimentation although there is no known field evidence for this. To the west the Karoo sedimentary rocks rest unconformably on the basement gneisses.

Stratigraphy of the North Rukuru Basin

The Karoo rocks of the North Rukuru Basin consist of a thick succession of clastic sediments which are divided into two distinctly different formations. These are the Basal Beds Formation consisting of diamictite (tillite) horizons with overlying flaggy sandstone and

varved shale horizons. This is overlain by a thick series of alternating arkosic sandstones and mudstones of the North Rukuru Sandstone and Shale Formation. The Basal Beds Formation rocks represent glacial and glacio-lacustrine environments whilst the North Rukuru Sandstone and Shale Formation sediments were deposited in a subsiding basin with lakes, braided and meandering river systems. The presence of diamictites associated with coal seams in the lower part of this formation, indicates periodic returns to glacial conditions during the Early Permian. The rocks of the North Rukuru Basin generally dip to the east with gradients up to 35°. Adjacent to the fault on the eastern margin of the basin, the dip is often 10° to 20° to the west as a result of faulting (Figure 1).

Stratigraphy of the Kayelekera Deposit

To facilitate the geological evaluation of the Kayelekera deposit the geologists working on the project divided the North Rukuru Sandstone and Shale Formation into informal members as a means of consistently describing the local geology. These members have not necessarily been adopted by other workers in the area or used outside the area but they serve as a means by which to understand and visualise the complex nature of the deposit. The Kayelekera uranium deposit is developed in the topmost part of the North Rukuru Sandstone and Shale Formation preserved in the basin. It lies entirely within the Kayelekera “member” which, at Kayelekera, has a maximum thickness of about 150m. Surface mapping and drill hole information identified a total of eight separate arkosic units with intervening silty mudstones and mudstones in an approximate 1:1 ratio (Figures 2 and 3). The base of the Kayelekera “member” is a mottled dark grey/chocolate brown mudstone that proved difficult to core and was unstable in the sides of boreholes. This unit is underlain by at least 70m of silty, chocolate brown mudstones with thin, discontinuous, poorly-sorted, muddy, hematitic arkose intercalations forming the top of the Muswanga Red Beds “member” at Kayelekera.

The succession is indicative of cyclic sedimentation within a broad, shallow, intermittently subsiding basin. Each cyclothem generally passes upwards from coarse reduced facies arkose through oxide-facies ‘red-bed’ mudstone into reduced facies, grey-black carbonaceous silty mudstones. Thin coaly horizons are present within some cyclothems. During the course of the delineation of the Kayelekera uranium deposit an alpha system of identifying the individual arkose horizons developed. The arkose units are labelled from R, which is the topmost arkose unit through S, T, U, V, W, X₂ and X₃ the basal arkose unit of the Kayelekera “member”. A number of other, less ubiquitous sandstone horizons were given identifiers, these are Sa, a thin arkose between R and S in the extreme south-west of the deposit; Ua, a thin discontinuous flaser-bedded sandstone just above U; and X₁ another thin flaser bedded sandstone unit just above X₂. Arkose V splits into two horizons (V1 and V2) separated by a mudstone in the southeastern part of the deposit. The intervening mudstone horizons are identified in relation to the arkose horizons above and below them e.g. the r-s mudstone lies between the R and S arkose unit (Figures 3 and 4).

Principal Lithologies

Arkose The arkose units average about 8 metres thick and are generally coarse grained and poorly sorted with a high percentage of fresh pink feldspar clasts. Mineralogical studies undertaken in 1986 (Basham and Milodowski; 1987) show that they are immature, medium to coarse grained rocks of granitic-type provenance. Approximately 50% of the clastic grains are quartz with albite/oligoclase accounting for 25% and reddened potassium feldspars, in varying relative abundances, together with muscovite and biotite comprising the bulk of the remaining 25%. In reduced-facies intersections seen in core the pink feldspars contrast strongly with the dark green pyritic, carbonaceous matrix. Individual arkose units may contain several upward fining sequences from quartz-feldspar pebble conglomerate to medium, or more rarely, fine-grained micaceous arkosic sandstone. Current bedding is common, and where observed in situ at surface indicates a consistent current direction from the southwest. Carbonaceous debris, as layers on cross-stratification surfaces, disseminations,

and as individual 'woody' elements several centimetres in length is commonly present in association with pyrite in reduced-facies arkose.

Chocolate brown 'Red-Bed' mudstone As the name implies the 'red-bed' mudstone is typically red to chocolate-brown in colour, homogenous fine-grained sediment with no discernible bedding. Pale green patchy 'reduction zones' may be present and in the lower units calcareous, concretionary nodules and calcite veining are common. These sediments appear to have accumulated in an oxygenated, subaerial environment as extensive floodplain mud flats following infill of the sedimentary basin by coarse arkosic sediments. Within the environs of the Kayelekera deposit calcareous mudstone units of this type can be traced by mapping sub-crop float of concretionary nodules weathered from the mudstone matrix.

Grey carbonaceous silty mudstone The grey carbonaceous mudstone units are more variable than the preceding red beds and comprise a range of lithotypes including light to dark grey homogenous mudstones, grey silty mudstones containing discrete quartz grains, sometimes with calcite veining, silty mudstones with multicoloured angular mud clasts, laminated bedded carbonaceous pyritic black shales, fine grained ripple cross-stratified carbonaceous sandstone and 'coal' shales.

Palynology

The Overseas Development Administration/British Geological Survey carried out a review of smaller coal basins in Africa between 1986 and 1988 (Bennett; 1989). During the course of this project a number of samples were collected from Kayelekera cores and outcrops for palynological examination. (see Bennett (1989) for details). Core samples were collected from several of the more carbonaceous horizons of the Kayelekera "member" and have been ascribed a late K3 (Kazanian) age. A sample collected from outcrop towards the base of the Karoo succession to the west of the Kayelekera deposit was ascribed a late K1 (Sakmarian) age. Unfortunately, this sampling predates the investigation of coal resources in the basal coal measures by drilling and trenching.

Structure of the Kayelekera Deposit

The Muswanga "member" of the North Rukuru Sandstone and Shale Formation is folded into gentle synclinal structures by drag against the eastern boundary fault. The Kayelekera "member" and the uranium deposit occupy the core of one of these synclinal structures with an axial trend of 330°E parallel to the eastern basement fault.

The regional structure is dominated by the Eastern Basement Fault, which strikes northwest-southeast and dips steeply to the southwest. Faults within the Karoo basin are predominantly steep normal faults trending either parallel with or normal to the Eastern Basement Fault.

The Kayelekera syncline occupies a downfaulted block bounded by normal faults trending north-northwest. A series of steep, close spaced normal faults with a combined throw in excess of 100 metres mark the eastern margin of the deposit. A transverse fault, the Chimpanji fault, cuts across this structure to the north of the deposit causing a dip reversal and the creation of a basin structure bounded by faults on its north, east and west margins. Several inclined boreholes were drilled in 1989 to evaluate the faulting in the margins of the deposit.

Joint directions in the arkose units are parallel to the three main fault directions. Jointing is more pronounced adjacent to the faults. In the deposit, the joints are often open, sometimes containing a clayey fill and form channels through which oxidising groundwaters circulate as evidenced by the fact that oxidation in transition zone arkose seen in core commonly occurs within and marginal to joints.

Mineralisation

Lenses of uranium mineralisation occur within arkose units S and T, the combined arkose-mudstone units U, V and W and the arkose units X1 to X3 to a depth of 100m. The lenses are stacked vertically along an axis approximately parallel to the synclinal axis of the fault-bounded structure (Figure 6). Mineralisation is offset, but not confined, by the fault structures however, the potential for extension of the mineralisation is restricted by the surface topography which cuts off the hosting lithologies. Most of the mineralisation is contained within the arkose units but some secondary mineralisation occurs in the mudstones immediately below the mineralised arkose particularly adjacent to the Chimpanji fault. The interpolation of arkose unit stratigraphy between drill holes is straight forward due to the excellent correlation of lithology and the presence of two coaly-shale marker horizons (between arkose units R and S and at the base of V/V2).

The mineralisation was classified into three types based on visual identification of the redox state of the hosting lithology. These are:

- reduced facies (Figure 5b)
- oxidised facies (Figure 5a)
- transition facies (mixed oxide-reduced ore) (Figure 5c)

The distribution of the different redox states in arkose units S to W is shown in Figure 7.

The uranium bearing mineral species present within the different redox facies are in correspondingly similar redox states. Coffinite ($U(Si)_4)_{0.9}(OH)_{0.4}$) is the main primary uranium mineral present in the reduced zone facies. The coffinite, often associated with organic debris and/or pyrite (FeS_2), occurs very finely intergrown with chlorite/clay which fills the interstices of the arkosic sandstones. Small quantities of extremely fine-grained uranium oxide, probably uraninite (UO_2), have been identified in some reduced and transitional zone mineralisation from all the main horizons. A uranium-titanium mineral, possibly betafite ($(CaU)_2(Ti,Nb,Ta)_2O_6(OH)$) or tanteuxenite ($(Y,Ce,Ca)(Ta,Nb,Ti)_2(O,OH)_6$) has also been identified in minor quantities. Several yellow-green secondary uranium minerals have been identified in the oxide facies from Kayelekera, all of which result from the oxidative weathering of the primary uranium minerals. The principal secondary uranium minerals are meta-autunite ($Ca(UO_2)_2[PO_4]_2 \cdot 6-8H_2O$) and boltwoodite ($(HK(UO_2)(SiO_4) \cdot 1.5(H_2O))$) with minor but ubiquitous uranophane ($CaH_2(SiO_4)_2(UO_2) \cdot 5(H_2O)$).

The uranium contained in the Kayelekera deposit was probably originally derived from the sub-aerial erosion of granitic rocks to the south-west of Kayelekera and was subsequently deposited, along with a large proportion of the eroded rock, as the arkosic sandstones and mudstones of the North Rukuru sandstone and Shales Formation. Where unaffected by surface weathering processes or oxidising groundwater circulation, the arkoses of the Kayelekera "member" are in a reduced oxidation state, preserving the organic and pyritic fraction of the rock. Under these conditions, the relatively insoluble uranium remained throughout the rock in low concentrations as a low grade protore associated with carbonaceous rich zones. Subsequently, following rift faulting and associated folding the uranium was mobilised in oxidising ground waters and redeposited as ore grade concentrations at the redox front within a preserved structural basin of reduced arkose at Kayelekera. While perhaps not conforming to all the characteristics of classic roll-front type sandstone hosted uranium deposits (see for example Dahl and Hagmaier; 1974), the Kayelekera deposit can be considered to be a variant of this deposit type. The principal difference is the fact that the basinal structure at Kayelekera has led to the accumulation of uranium in a structural low in a series of stacked arkose horizons, when compared to the classic American roll-front type of deposits that are generally formed in extensive, gently dipping strata and are rarely multi-layer deposits. The presence of carbonaceous debris and pyrite in the reduced facies arkose and the redox related mechanism of uranium mobilisation and re-deposition are similar.

Borehole geophysics and the disequilibrium problem

It was recognised by the authors (Bowden et al; 1986) early in the assessment of the Kayelekera deposit that there was a large discrepancy in some estimates of ore grade-thickness between calculation of uranium equivalent grade based on the gamma-log measurements and analytical results for uranium grade from core samples over the same intersection. It was also recognised that the discrepancy was variable in magnitude, generally greater in oxidised zones, not always in the same direction but globally for the deposit amounted to a net loss of uranium of approximately 30%.

Several possible causes for the variation were considered: -

- Errors in the chemical analysis: including sampling errors, low core recovery, sample collection errors, sample splitting errors, analytical errors.
- Errors in the gamma log estimates: calibration errors, calculation errors
- Disequilibrium between uranium and its daughter, ^{214}Bi (used by the gamma logger to estimate uranium concentration).

Routine sampling and analytical control checks showed that errors from those sources were very small compared with the identified 30% shortfall in uranium concentration and that discrepancy might arise from a combination of poor core recovery (hence non-representative sampling), gamma logging errors and disequilibrium.

Gamma Ray Logging

The first down-hole gamma logging tool used at Kayelekera was a hand-winch Mt Sopris 1000 with analog paper trace output of natural gamma emissions in cps. A new motor-winch Mt Sopris logger was purchased in 1986. The down-hole sondes were calibrated at the test borehole site in Canada to provide constants for K-factor, dead time, hole diameter and water factor and a test borehole was maintained at Kayelekera for regular calibration tests. The tail-factor method (Scott et al, 1961) was used to convert the raw gamma data to equivalent uranium grades. In this method the width of a mineralised interval is determined by measuring the amplitude of the peaks nearest to the top and bottom of the anomaly, and calculating the interval between the half-amplitude points on the log curve. Experience at Kayelekera demonstrated that this method of determining width of a mineralised interval was extremely accurate. In order to estimate the equivalent uranium grade thickness for the mineralised interval using this method the area under the gamma log curve is calculated and multiplied by correction factors for borehole diameter, the medium filling the borehole and borehole casing. The equivalent grade is obtained by dividing the grade-thickness product by the previously obtained thickness.

Although the mineralisation at Kayelekera extends over relatively thick intersections, a closer study of the nature of the mineralisation shows that it occurs as numerous fairly close spaced but discrete higher grade spikes or stringers within a wider interval of lower grade disseminated mineralisation (Figure 8a). Because of the need to provide discrete estimations of equivalent uranium grade for the different oxidation states within the same intersection and as a check on possible errors in the tail factor method we developed a new, computerised method of calculation of equivalent grade-thickness from the gamma logs was developed. The original analogue gamma log tracings were digitised at 20cm intervals and deconvolved using an approximation of the digital inverse filter proposed by Conaway (Conaway and Killeen, 1978). This method was considered more accurate than the tail factor method for the estimation of equivalent grade-thickness for thin mineralised zones and gave a digital file printout of the uranium (U_3O_8) grade every twenty centimetres down the hole (Figure 8b). At this stage no correction for the redox state of the mineralisation had been applied.

Redox classification

The recognition of a potential relationship between redox state of the arkose and the discrepancy between the gamma log equivalent grades and chemical assay grades led to greater emphasis in core logging being placed on detailed recognition and recording of the redox state of the core. In many cases it proved difficult assign a simple two-value oxidised/reduced indicator to the core as, in many instances a mixed zone with both oxide and reduced arkose were present in the same core interval (Figure 5(c)). A third core-log classification - Transition Facies was adopted, and in an attempt to provide greater control on the extent of oxidation, logging geologists were asked to assign a percentage estimate of the amount of oxidation present. This percentage subdivision of the Transition facies proved ultimately to be impracticable and the original three-division redox classification was adopted for 'correction' of the gamma log cps values.

In order to check for disequilibrium several samples selected to cover the range of redox states were sent to the Universities reactor, University of Manchester, for neutron activation analysis of the uranium decay chain. The results confirmed the presence of disequilibrium in all the daughter products of the uranium mineralisation and indicated marked variability strongly correlated with the redox state of the arkose unit (Table 2). The oxide facies mineralisation showed a strong uranium deficit compared with daughter products due to strong leaching and removal of uranium U^{238} which is soluble in a near surface oxidising environment. The reduced facies mineralisation showed a daughter product deficiency (i.e. apparent uranium enrichment compared to the gamma log estimate) probably resulting from re-deposition of leached uranium from the oxide zone. Transition mineralisation, as expected, showed both daughter product excess and deficiency. The results also showed that extremes of variation occur within short distances even within the same mineralised intersection indicating a very localised redistribution of uranium.

Table 2. Uranium Concentrations and Equivalent Uranium Concentrations

Drill Hole	From (m)	To(m)	Redox Class	^{235}U (DNM) ppm	^{238}U (NAA) ppm	$^{238}U(^{234}Th)$ ppm	$^{238}U(^{226}Ra)$ ppm	$^{238}U(^{214}Bi)$ ppm
BB125	60.5	61.0	TRANS	470±40	477±5	470±40	1200±100	990±20
BB125	63.0	63.4	REDU	2900±100	3080±30	2960±60	1600±200	1910±20
BB125	65.8	66.0	COAL	6400±300	7400±80	7400±100	4100±400	5100±100
BB118	37.9	38.1	TRANS	820±30	807±8	710±30	570±90	640±20
BB118	38.2	38.5	OXID	149±6	120±20	120±20	220±50	251±5
BB118	41.3	41.5	REDU	1430±50	1400±20	1370±40	1100±100	1150±20
BB124	16.0	16.5	OXID	66±3	58±0.6	60±20	710±70	450±20

DNM – Delayed Neutron Method

NAA – Neutron Activation Analysis

Resource estimation

The presence of high, variable disequilibrium at Kayelekera poses serious problems for the validity of any resource estimation if based even partially on the gamma log equivalent uranium grade estimates. Because of the variable disequilibrium in the Kayelekera mineralisation gamma log equivalent uranium grade estimates need to be corrected prior to using them in ore resource estimation. During the course of the evaluation of the deposit several studies were undertaken to enable the gamma log estimates of uranium equivalent concentration to be corrected for the observed disequilibrium.

Chemical Analysis

Approximately 60% of the boreholes drilled into the Kayelekera deposit between 1984 and 1991 were fully cored and all boreholes were routinely gamma logged on completion. All core intersections with gamma responses above background levels were routinely sampled for chemical analysis of uranium by XRF pressed powder pellet methods. This method was selected over XRF analysis using fused boron beads following test analyses of early samples

using both methods on cost grounds, both methods giving similar results. Cores were normally sampled over 0.5m intervals with the cores split into ½ or ¼ depending on diameter. The samples were crushed and milled on site prior to splitting and shipment of the sample splits to a UK analytical laboratory for analysis. 10% of samples were re-split to provide duplicate samples for QA/QC purposes. During the ore reserve audit by Fluor Daniels approximately 200 check samples were taken and analysed by a second laboratory, also by XRF pressed pellet methods. Approximately 25% of these samples were also verified by wet chemical determination of uranium. A number of samples were analysed for a suite of potentially economic accessories including base metals but nothing of value was identified.

CEGB Corrected Gamma Logs

The method adopted by the authors was to utilise the relationships between redox facies and uranium content as measured by XRF analytical and gamma log methods. Figure 9 shows the scatter plot and linear regression relationship between gamma log equivalent grade and assay grade for the three identified redox facies based on borehole intersections for which both estimates are available. The data used for the regression analysis was a subset of all possible data for which XRF analysis and gamma log estimates were available. The subset was defined by a) using only those drill holes which had at least 95% core recovery within the mineralised intersection, and b) the deliberate omission of highly enriched XRF values from the oxide facies data. As a further measure in applying the regression equation to correct the gamma log equivalent grades the constant term from the regression equation was dropped. The objective in taking these measures was to avoid the introduction of bias into the regression analysis either through a loss of uranium due to poor core recovery or of overestimation of uranium content due to a few high-grade samples in the oxide facies mineralisation. (Although intersections of oxide mineralisation from some samples showed no depletion at all and in some cases a marked enrichment was noted).

WEL Correction method

WEL, through their sub-consultants Fluor Daniels, in their evaluation of the uranium reserves at Kayelekera, adopted a purely statistical approach to the correction for disequilibrium. The gamma log data for a particular intersection was corrected using the average ratio of the XRF value to the deconvolved gamma log value for the nearest neighbour cored drill hole. Cross-validation using this approach gave reasonably accurate results with, most importantly, no bias.

At least four separate resource estimates were made for the Kayelekera deposit prior to 1990. A summary of the estimates for a cut-off grade of 0.05%U₃O₈ is given in Table 4.

Table 4. Summary of Ore Reserves (S, T, U, V W and X lenses)

Date of estimate	Contained tonnes U ₃ O ₈	Average Grade % U ₃ O ₈	Ore Tonnes	Resource Category*
February 1987 (CEGB)	11,681	0.187	6,246,524	Indicated
March 1989 (CEGB)	9,199	0.162	5,678,395	Measured & Indicated
1989 (WEL-Fluor)	9,465	0.146	6,482,876	Measured & Indicated
November 1989 (CEGB)	9,247	0.175	5,299,428	Measured & Indicated

* Ore reserve categories based on US Bureau of Mines guidelines for resource classification

The differences in tonnage and grade can be attributed to the different calculation methods applied. In particular the 1987 estimate was made prior to a good understanding of the effects of disequilibrium. The 1987 estimate was based primarily on the chemical grade database supplemented by corrected gamma log equivalent grade estimates where cores were not available. The correction applied to the gamma logs was based on a global regression equation derived from all samples. The variability in disequilibrium as a result of different oxidation states was not taken into account. In addition mineralisation occurring in mudstone units was included in this estimate

For the March 1989 CEGB evaluation an inverse square method of block tonnage and average grade estimation was used, this was later updated in November 1989 using a geostatistical block kriging method. In both cases the thin mudstone parting between the V_1 and V_2 arkoses was included but all other mudstone-hosted mineralisation was excluded due to its patchy nature. The mineralisation within the thin X_1 arkose was grouped with the W-X mudstone and therefore excluded from the reserves calculation.

As noted earlier the CEGB took a conservative approach to reserve estimation ensuring that errors were likely to result in under- rather than overestimation of the uranium resource at Kayelekera. Nevertheless, the closeness of the three 1989 results is an indication of the robustness of the global estimates of contained U_3O_8 .

Conclusion

The CEGB, between 1983 and 1990, discovered and delineated a significant uranium deposit at Kayelekera, northern Malawi with a conservative global resource of approximately 9000 contained tonnes of U_3O_8 . Resource calculations at Kayelekera are complicated by the presence of significant, variable secular disequilibrium between uranium and its daughters. The complication arise because geophysical gamma-logging methods of uranium grade estimation calculate an equivalent uranium grade based on a measure of the gamma emissions from a uranium daughter product on the assumption that the uranium is in secular equilibrium with the daughter products of its decay chain. At Kayelekera disequilibrium is closely associated with the redox state of the mineralisation, in particular the oxide facies mineralisation is highly depleted. This association between disequilibrium and redox facies was used by CEGB geologists to 'correct' the gamma log equivalent grade estimates.

Until recently recognition of disequilibrium in the field was dependent on the comparison of uranium analyses of core samples with gamma log equivalent grade from the same borehole intersection. At Kayelekera some 59% of all boreholes were cored and therefore the disequilibrium was readily recognised. However, the majority of exploration boreholes for sandstone hosted roll-front type uranium deposits are non-cored and it may be that disequilibrium is present to a greater extent than has been recognised, and in many more deposits than has been realised in the past. In Wyoming in the roll front deposits of the Powder River Basin it was generally believed that the disequilibrium factor varied from ~0.9 behind the redox front to ~1.1 in front, i.e., the average was ~1.0. Poor recoveries from in situ leach operations were generally attributed to operational factors rather than to errors in the reserve estimate (J. Hunter pers. comm.). In Australia exploration for Tertiary palaeochannel uranium deposits relies heavily on drilling and gamma logging in relatively unconsolidated sediments for which intact cores are not readily obtained. Examples of disequilibrium of between 20 and 25% within these deposits are now being cited in company exploration announcements as a result of the wider availability of the PFN (Prompt Fission Neutron) logging tool which enables direct measurement of uranium grade in situ within boreholes. (This tool was being developed by Mobil and Sandia Laboratories in the USA during the 1980's and was not available commercially during the CEGB investigations at Kayelekera). It is apparent therefore that in estimating uranium resources and reserves in accordance with JORC code requirements it will be necessary to investigate the presence and nature of disequilibrium effects within these types of deposit.

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Figure captions

Figure 1 – Geological map of the northern part of the North Rhukuru Basin as mapped by CEGB geologists between 1983 and 1990.

Figure 2 – Low altitude air photo showing the Kayelekera Deposit. Note access tracks for drill sites, the development of alternating grassy and wooded strips over mudstone and arkose horizons respectively, cultivated areas (pale) and the small stream draining east from the deposit into the Sere River.

Figure 3 – Generalised stratigraphic sequence of the Karoo strata in the northern North Rhukuru Basin and of the Kayelekera member hosting the Kayelekera uranium deposit.

Figure 4 – Geological map of the Kayelekera deposit.

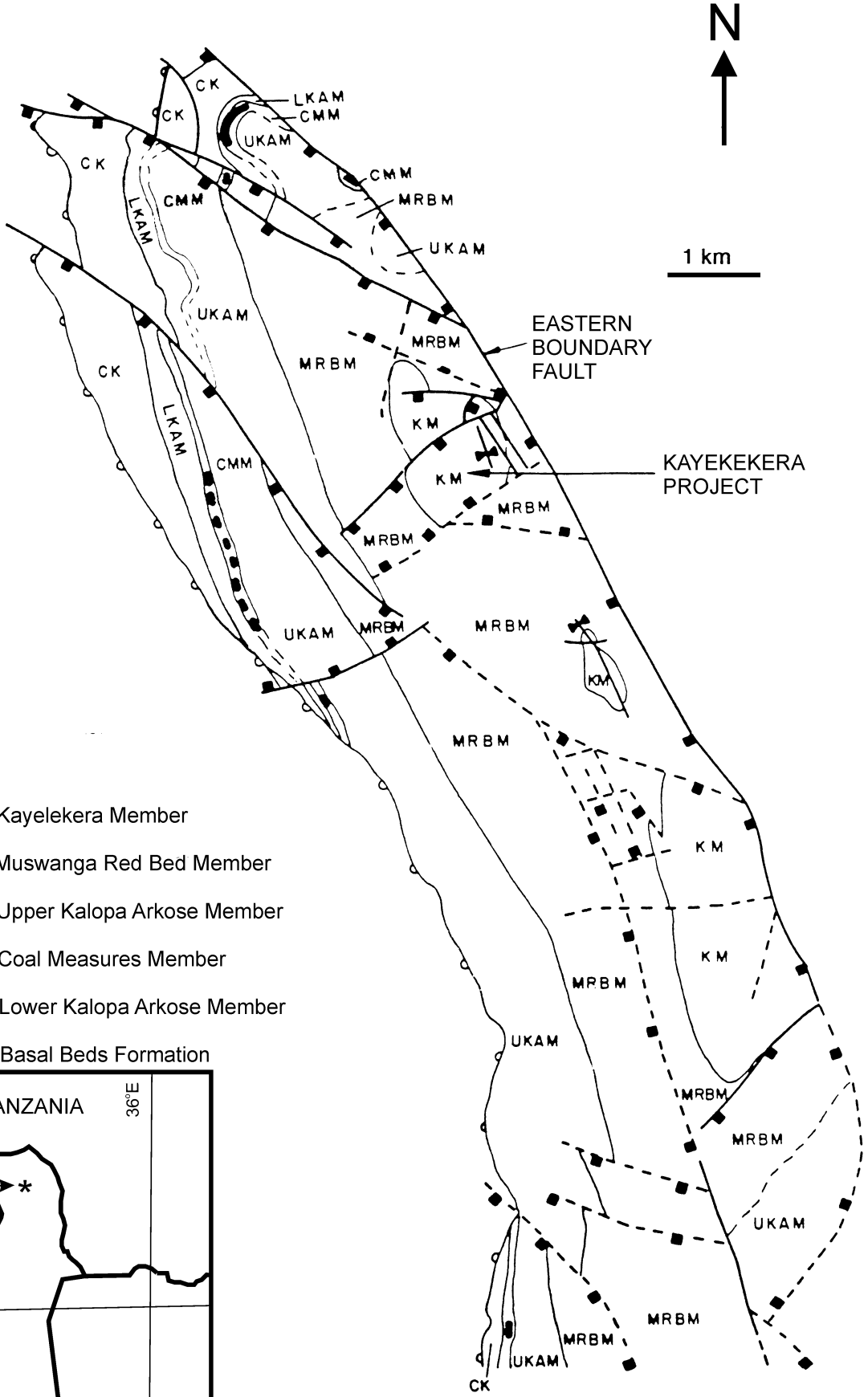
Figure 5 – Examples of oxidised, reduced and transitional facies mineralised arkose from the Kayelekera uranium deposit. a) Arkose S, oxide facies with extensive development of uranium secondary minerals (mainly autunite, boltwoodite and lesser uranophane) on a bedding plane surface, Trench 3, Kayelekera. b) Arkose W reduced facies with uranium present mainly as coffinite in sectioned core from 70.5m in drill hole BB91. c) Arkose T core sample of transition facies (partial oxidation of reduced facies arkose from 54m in drill hole BB136).

Figure 6 – Schematic cross section through the Kayelekera uranium deposit. (See Figure 4 for location). Arkose horizons are stippled, mudstones are white and uranium ore grade mineralisation black.

Figure 7 – Plan views of Arkose Lenses S, T, U, V and W showing distribution of redox zones.

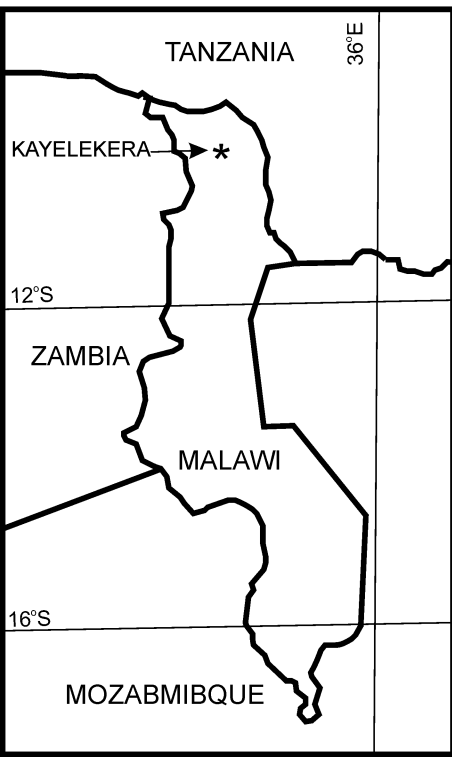
Figure 8 – a) Gamma Log, b) Deconvolved Gamma Log and c) Corrected equivalent U_3O_8 log for drill hole BB116, Kayelekera Uranium Deposit.

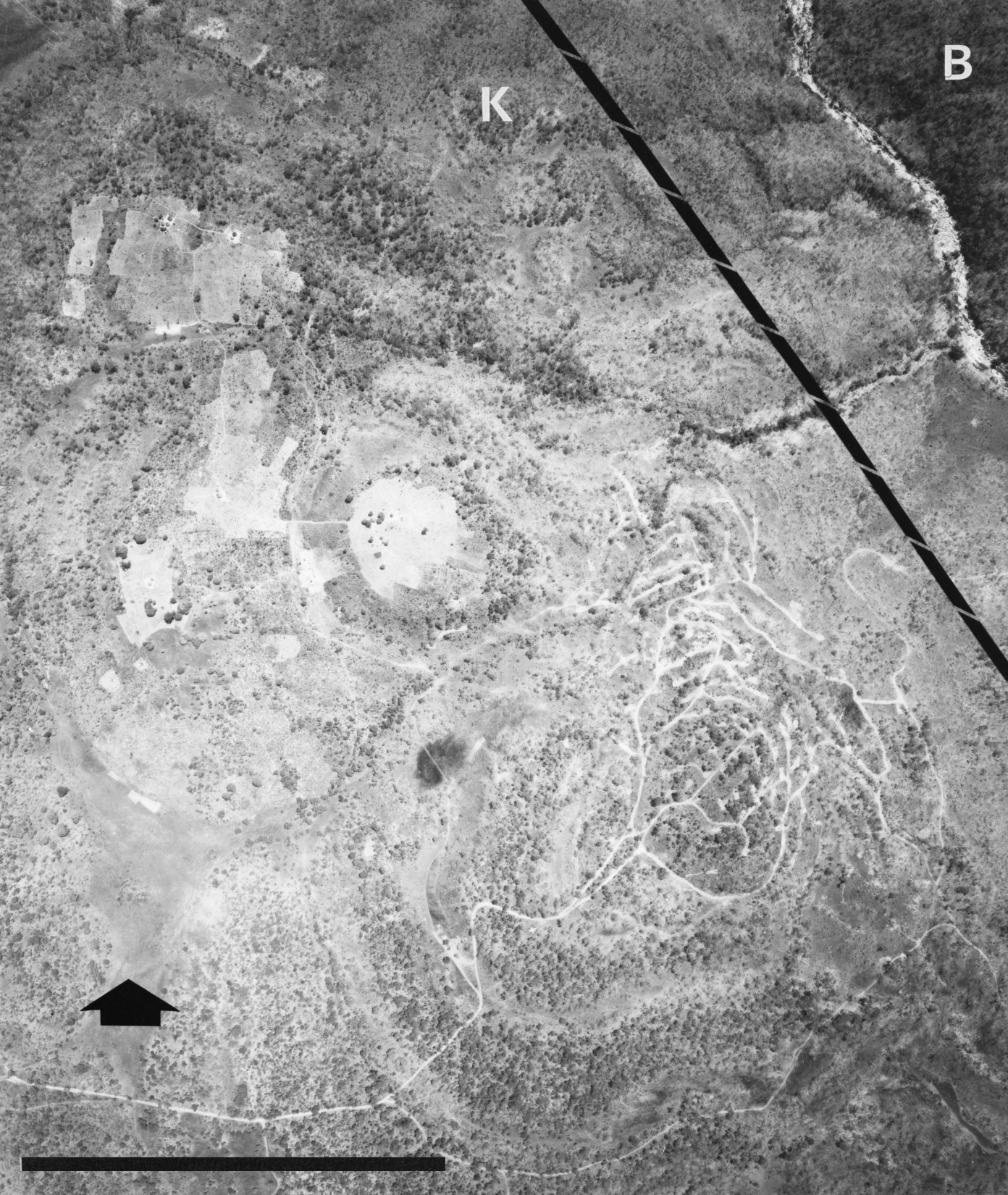
Figure 9 – Scatter plots with regression equations for correcting identified redox facies mineralisation for the effects of disequilibrium.



KEY

- KM Kayelekera Member
- MRBM Muswanga Red Bed Member
- UKAM Upper Kalopa Arkose Member
- CMM Coal Measures Member
- LKAM Lower Kalopa Arkose Member
- CK Basal Beds Formation

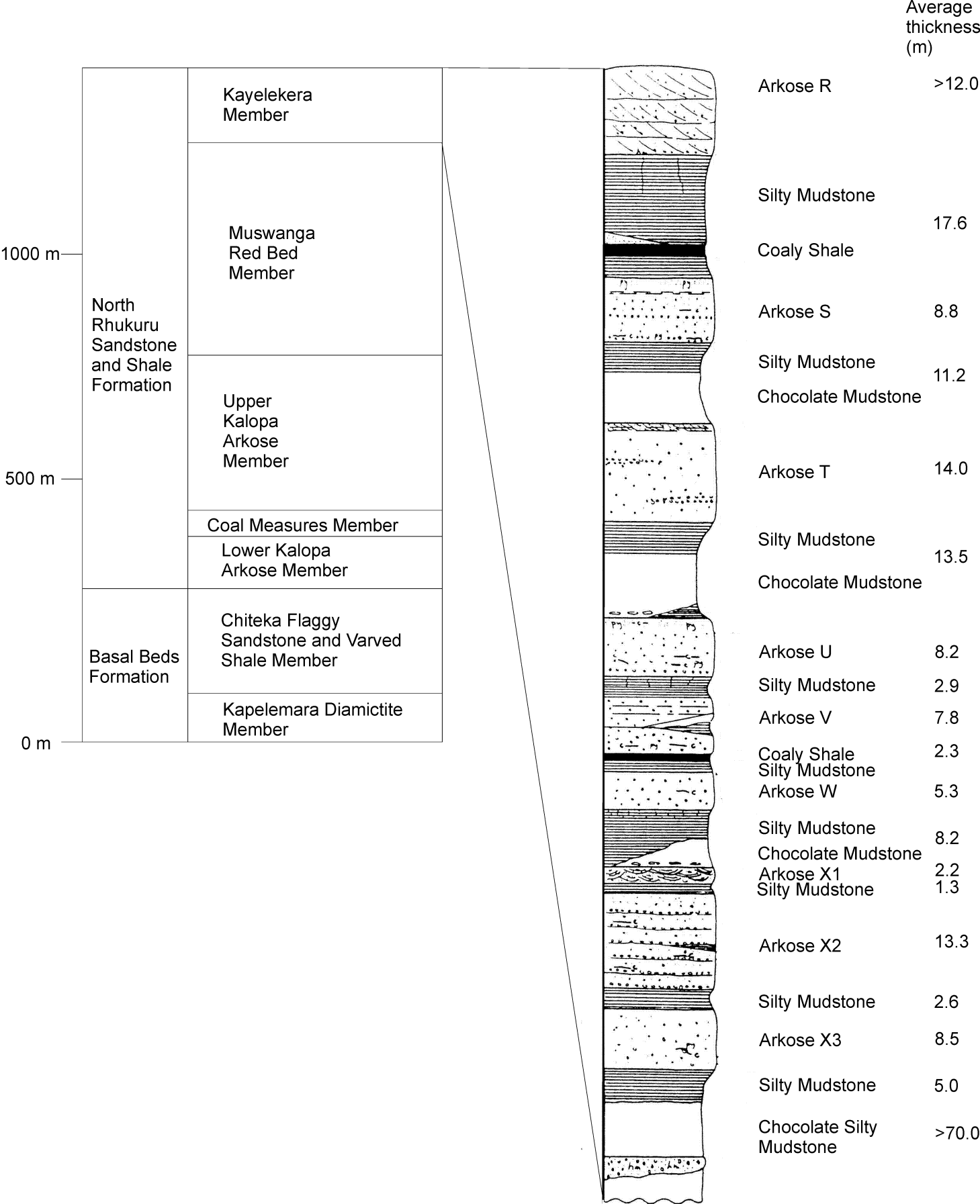


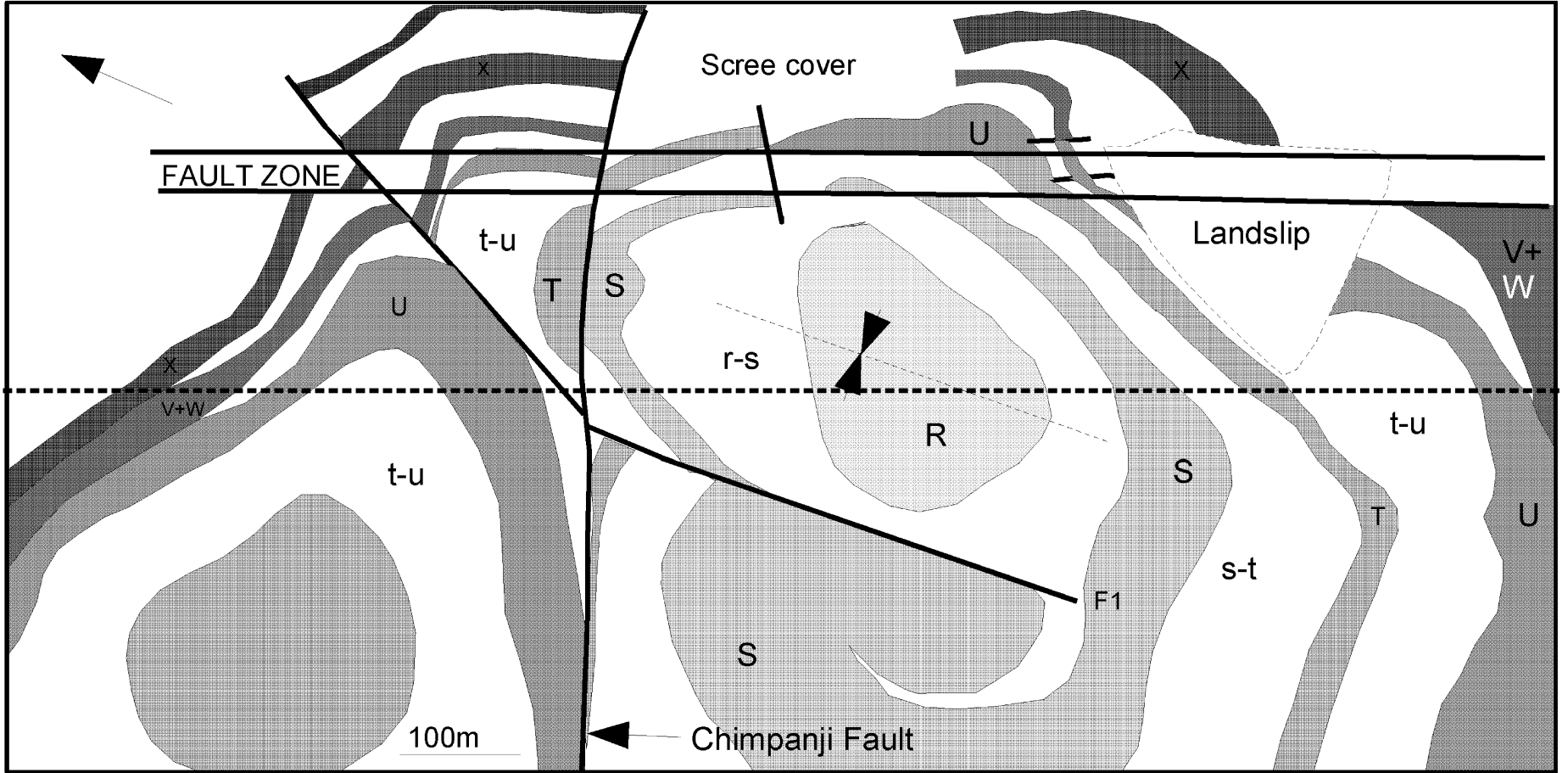


K

B







R, S, T, U, V, W, X = Arkose Units

r-s, s-t, t-u, u-v, v-w, w-x = Mudstone and silty mudstone units

----- = Line of Cross Section in Figure 6







W

E

BB40

BB69

R

DS35

DS34

DS4

DS27

S

T

U

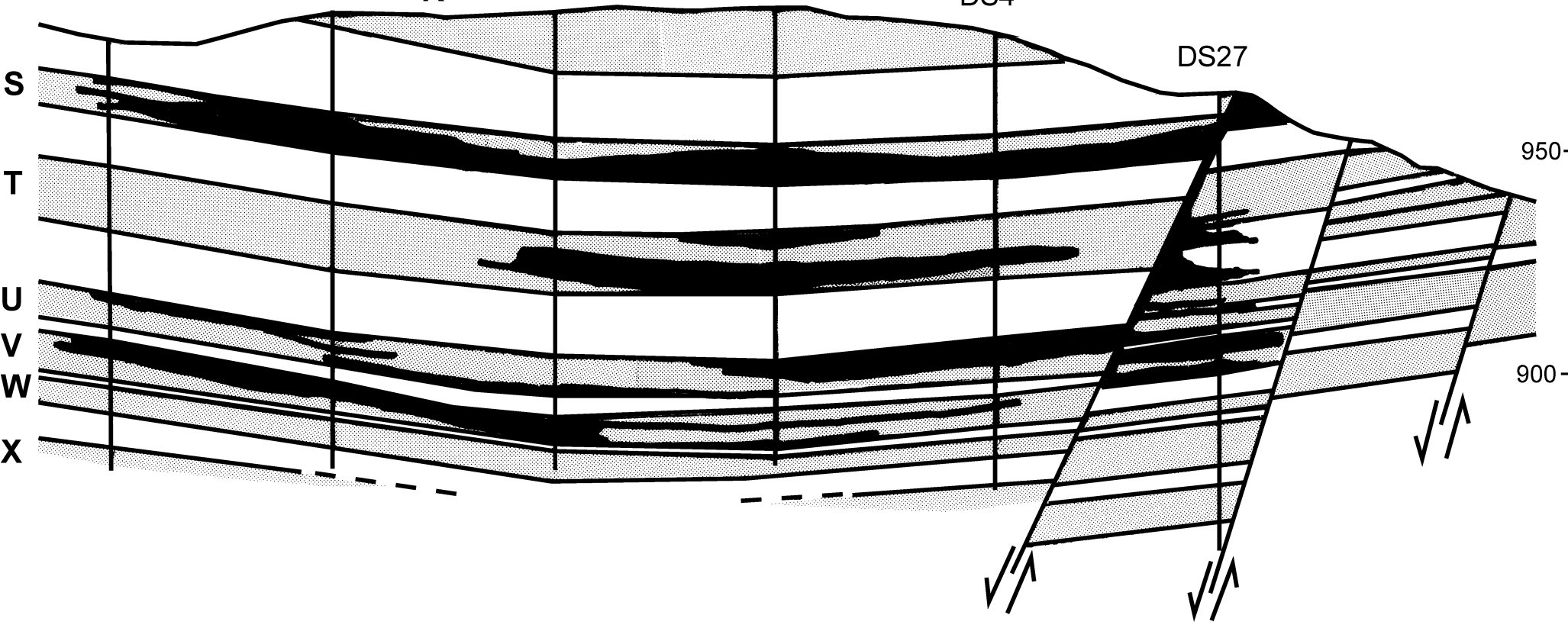
V

W

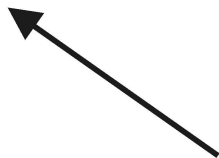
X

950

900



N



ARKOSE LENSES S, T, U, V AND W



REDUCED FACIES

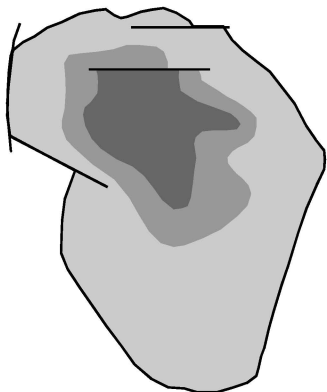


TRANSITION FACIES (MIXED RED/OX)

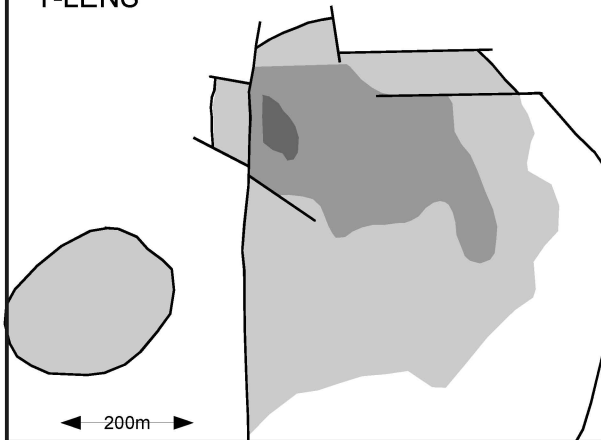


OXIDE FACIES

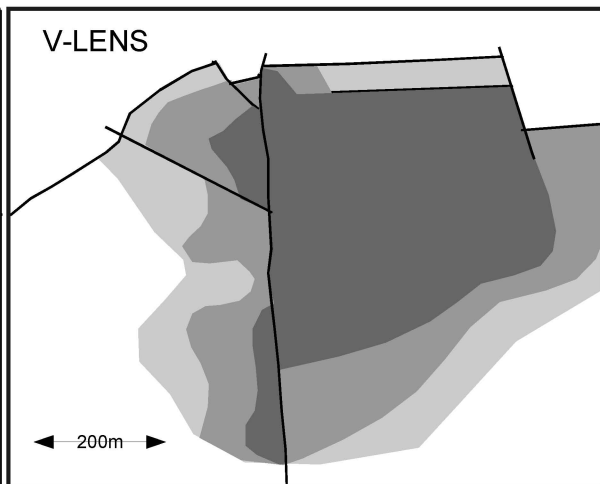
S-LENS



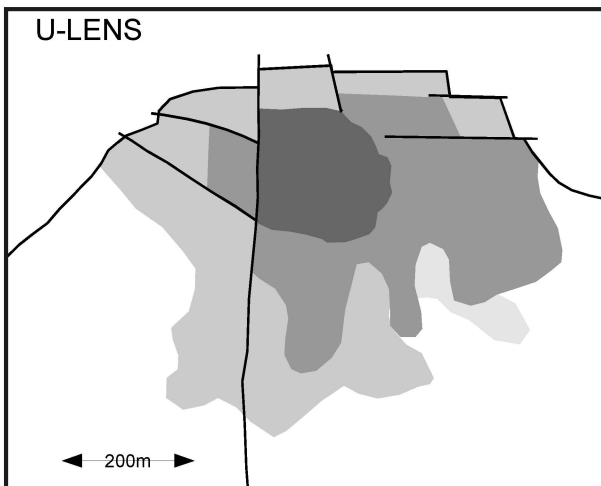
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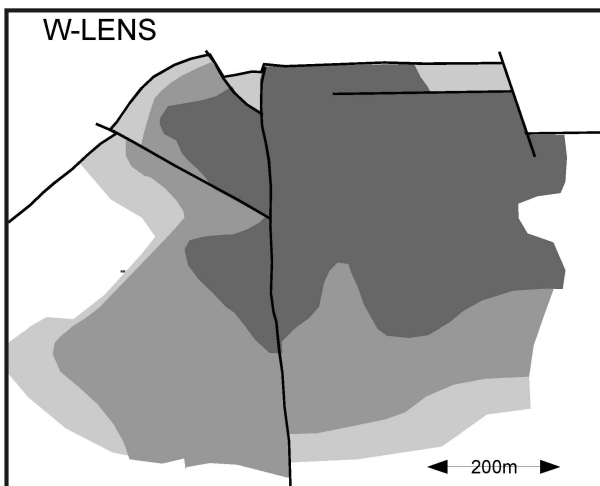
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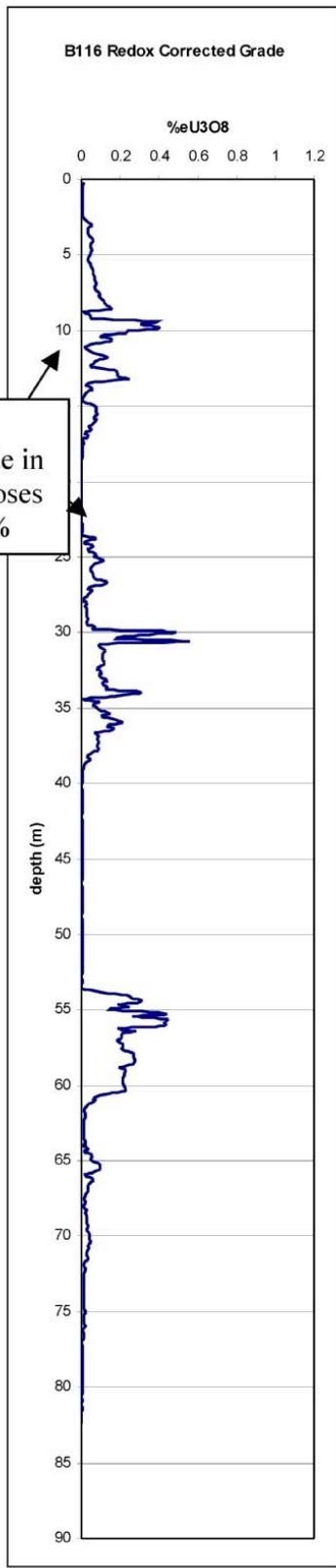
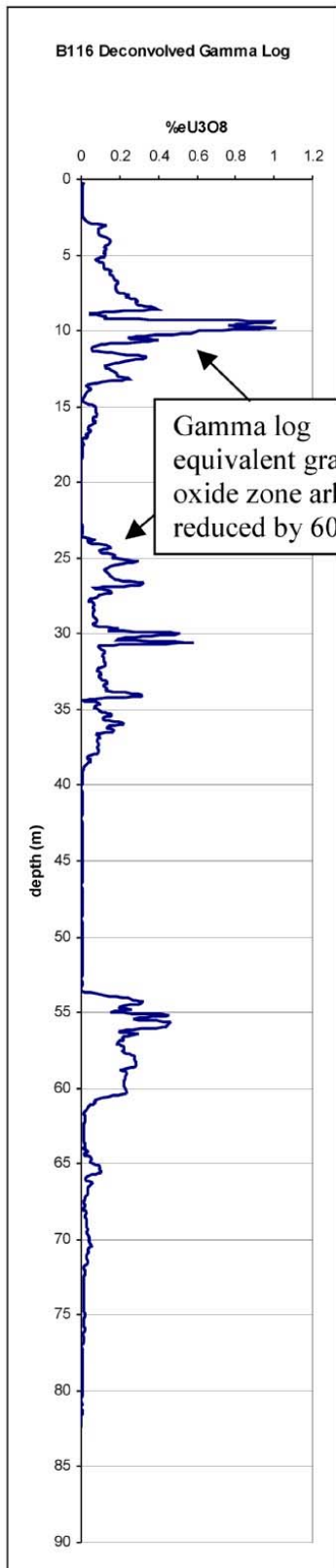
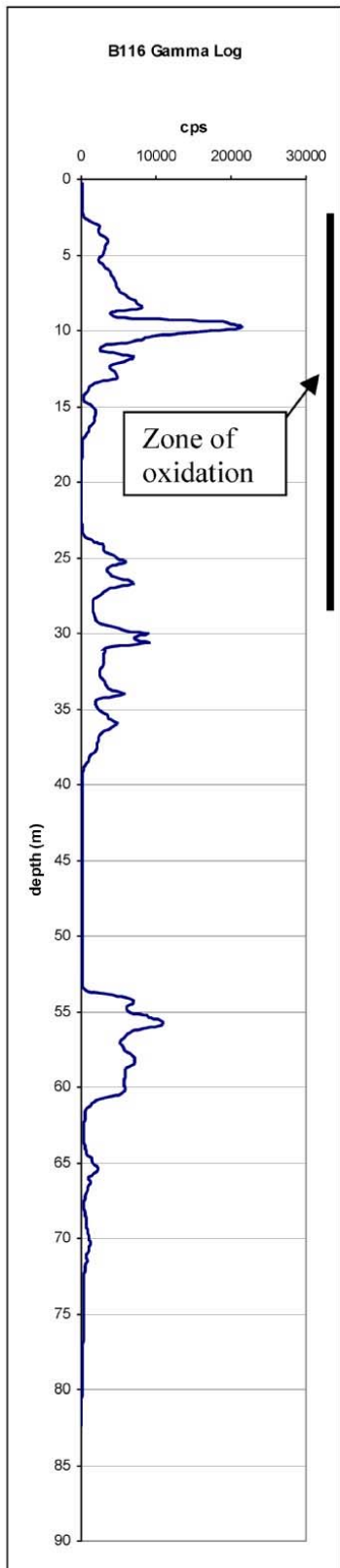


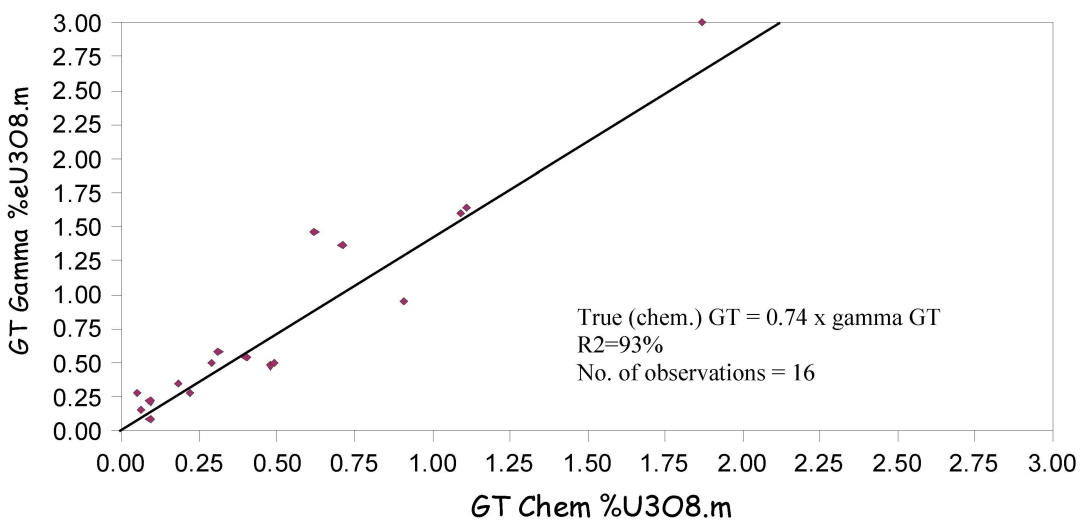
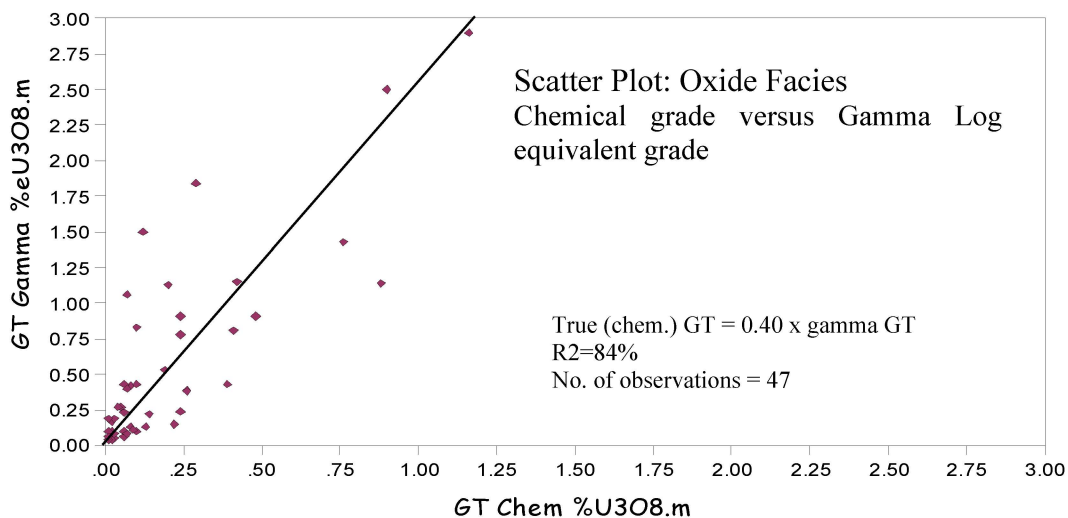
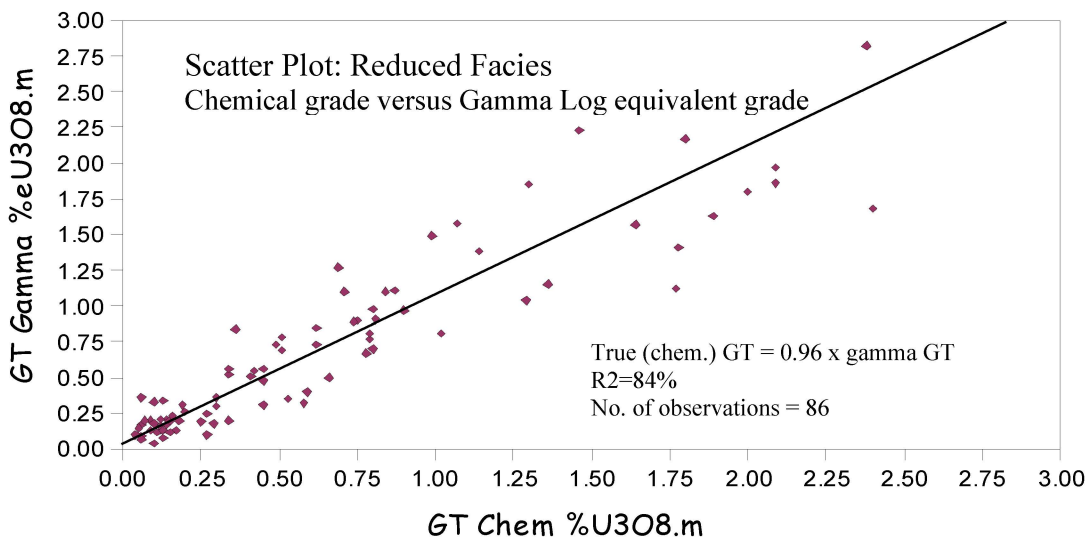
U-LENS



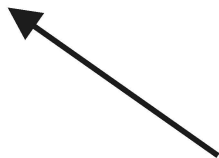
W-LENS







N



ARKOSE LENSES S, T, U, V AND W



REDUCED FACIES

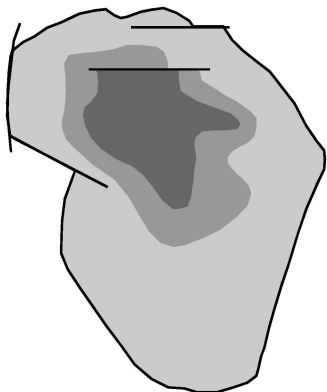


TRANSITION FACIES (MIXED RED/OX)

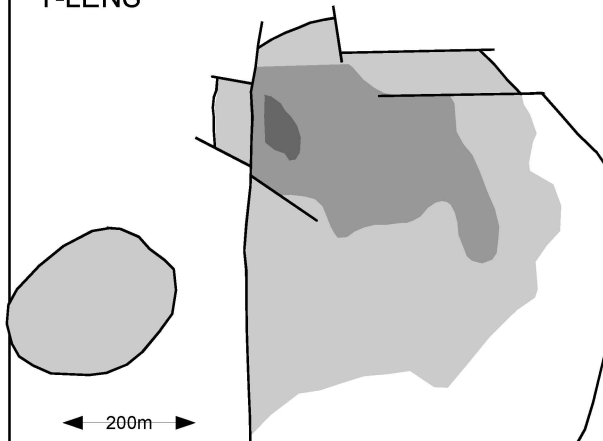


OXIDE FACIES

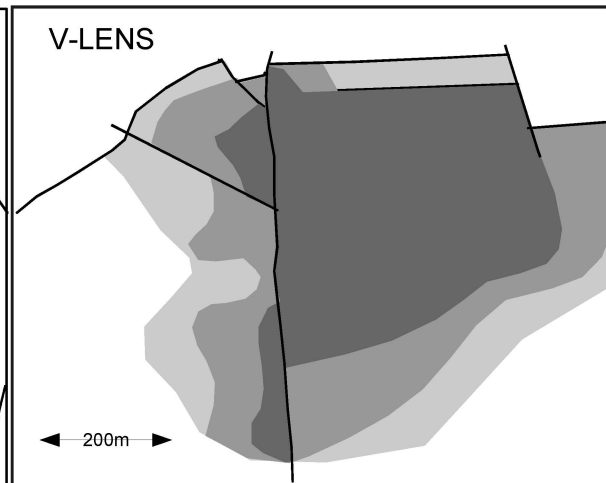
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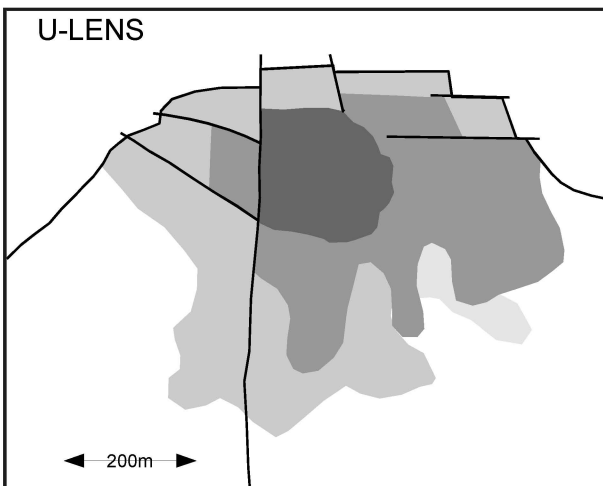
T-LENS



V-LENS



U-LENS



W-LENS

