Heavy mineral stratigraphy of the Unayzah Formation and Basal Khuff Clastics (Carboniferous to Permian) of Central Saudi Arabia

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ABSTRACT

A study of heavy mineral assemblages in the Unayzah Reservoir sandstones of central Saudi Arabia has identified successive changes in provenance signature. These define four heavy mineral units that are of regional extent and largely coincident with the four main depositional units defined by previous authors: Unayzah C, Unayzah B, Unayzah A and the Basal Khuff Clastics. Sandstone bodies with anomalous mineral signatures also occur, however, especially within the Unayzah B Member. These are attributed to local supply of sand from pre-Unayzah Paleozoic sandstones exposed on the Central Arabian Arch and on intra-basinal highs.

The stratigraphic changes in mineralogy reflect successive developments in the geography and climate of the region and in the pattern of sand sourcing and transport. The Unayzah C sands and the majority of Unayzah B sands were derived from the south but whereas the southerly derived Unayzah C sands appear to have been derived from pre-existing mature sandstones, those of Unayzah B were sourced from a wider range of rock types including crystalline basement. This contrast is interpreted as indicating that a significant hiatus may separate the two units. The Unayzah B sands are also characterised by the common presence of apatite, indicating that the source rocks were relatively unweathered. This observation is compatible with the glacial origin attributed to many of the Unayzah B sediments.

A further change in provenance signature takes place at the base the newly recognised 'un-named middle Unayzah member', equivalent to the base of Unayzah A of previous authors. This is associated with the onset of red-bed sedimentation throughout the area. Unayzah A sedimentation was terminated by a fall in sea level that led to the formation of a widespread unconformity and to the development of deeply incised valleys along the western basin margin. In most of the study area this unconformity corresponds to the base of the Khuff Formation, but in the east of the area, where the succession is more complete, it is believed to occur within the Unayzah Formation, at a level equivalent to the base of the Upper Gharif Member of Oman.

By identifying lateral and vertical changes in sand provenance, heavy mineral analysis provides an important additional tool in the stratigraphic analysis of the Permian sandstone succession of Saudi Arabia, both at the regional scale and wand at the scale of individual reservoir sandstone successions.

INTRODUCTION

Sandstones of Late Carboniferous to Permian age form important hydrocarbon reservoirs in central Saudi Arabia (**Figure 1**). The sandstones occur in the Unayzah Formation and Basal Khuff Clastics unit of the Khuff Formation. The same lithostratigraphic units are recognised in northern Saudi Arabia (wells 42–44) and have recently been identified in northern Kuwait (Tanoli et al., 2008). The equivalent succession in southeastern Saudi Arabia (wells 45–47) retains some of the stratigraphic elements of the Central Saudi Arabian succession, but has closer affinities with that of neighbouring Oman (Stephenson et al., 2003, p.484; Al-Husseini, 2004, caption to figure 3).

The first published stratigraphic study of the Permo-Carboniferous clastic succession in the subsurface was that of Ferguson and Chambers (1991). These authors applied the term Unayzah Formation, introduced for the outcrop succession by Al-Laboun (1982) and Delfour et al. (1982), to the clastic succession lying between the Hercynian Unconformity and the marine flooding surface of the Late Permian Khuff Formation. In central Saudi Arabia this succession lies unconformably on sediments of pre-Carboniferous age. An informal subdivision of the subsurface Unayzah Formation was proposed by Ferguson and Chambers (1991) and applied by McGillivray and Husseini (1992) (**Figure 2**). These authors demonstrated that sandstones occurred at three distinct stratigraphic levels, referred to as Unayzah A, B and C in descending sequence. A siltstone-dominated unit lying between the Unayzah A and Unayzah B sandstones was termed the ‘Unayzah A Siltstone’. The Unayzah A, B and C units were assigned member status within the Unayzah Formation by Al-Husseini (2004). A new informal unit, the ‘un-named middle Unayzah unit’ was recognised by Melvin and Sprague (2006) in what was the basal part of the Unayzah A succession of previous authors.

Although the Khuff Formation is dominated by limestone, a basal unit consisting of mudstone with subordinate sandstone is present throughout the study area. This unit is informally known as the ‘basal Khuff clastics’ (Ferguson and Chambers, 1991; Senalp and Al-Duaiji, 1995) or ‘Basal Khuff Clastics’ (Al-Husseini, 2004; Melvin and Sprague, 2006). It is regionally unconformable on the Unayzah Formation. Sandstones within the Basal Khuff Clastics are the youngest in the Permo-Carboniferous succession. Together, the sandstones of the Unayzah Formation and the Basal Khuff Clastics have been informally referred to as the ‘Unayzah Reservoir’ unit (e.g., Senalp and Al-Duaiji, 1995; Al-Husseini, 2004).

An entirely new lithostratigraphic scheme was proposed by Senalp and Al-Duaiji (2001), in which the subsurface Unayzah Formation was replaced with three formations: the Haradh Formation (including Unayzah B and C sandstones), the Jawb Formation (lacking reservoir sandstones), the Unayzah Formation (including Unayzah A sandstones) and the Ash-Shiqqah Formation (including sandstones of the Basal Khuff Clastics unit and some sandstones previously assigned to Unayzah A). This proposed terminology has not been adopted by subsequent authors, in part because the name Haradh Formation had already been applied to older strata in Oman (Droste, 1997 – see Al-Husseini, 2004, p. 26).

The terms Unayzah A, B and C and Basal Khuff Clastics are thus retained in the most recent publications. It should be noted, however, that their definitions and usage differ somewhat from those of Ferguson and Chambers (1991), especially in the lower part of the Unayzah Formation (Melvin and Sprague, 2006).

Biostratigraphic data for the continental Unayzah Formation succession are available for only a limited number of wells in the study area, whereas they are available for many wells in the marine Khuff Formation (Stephenson et al., 2003; Stephenson, 2004). These records have led to the establishment of a Saudi Aramco zonation scheme consisting of four palynozones, named **P1** to **P4** in order of increasing age (referred to as SA P1–P4 by Al-Husseini, 2004). The **P2** and **P4** palynozones are divisible into upper and lower subzones (**P2U**, **P2L** and **P4U**, **P4L**). The **P** zones have recently been integrated into a regional OSPZ palynomorph zonation (Stephenson et al., 2003; Stephenson, 2006). As few of the OSPZ palynozones are fully represented in the Saudi Arabian successions, the **P** zones are used as the primary biostratigraphic indicators in this paper. Palynomorph assemblages with Mid Carboniferous components (**Cm**) have also been identified in the Unayzah Formation, where they are considered to be reworked (J. Filatoff in Melvin and Sprague, 2006, p. 109).

Previously published accounts of heavy mineral assemblages in the Paleozoic sandstones of Saudi Arabia have been restricted to the outcrops that occur along the eastern margin of the Central Arabian Shield (Powers et al., 1966, p. 24–25; Vaslet, 1990, p. 38, 58; Hussain et al., 2004; Knox et al., 2006). Only Knox et al. (2006) studied the Permo-Carboniferous succession, with presentation of data from the Wajid Group (Juwayl Formation) of southwestern Saudi Arabia. The present study is thus the first to deal with the equivalent subsurface succession and provides information both on the regional palaeogeographic setting of the Permo-Carboniferous sandstones and on their stratigraphic relationships.

HEAVY MINERAL ANALYSIS

Principles

Although it is widely accepted that heavy minerals are valuable indicators of provenance, it is also apparent that the composition of an individual heavy mineral assemblage is dependent on many other factors (Morton 1985; Morton and Hallsworth 1994, 1999). These include a contrast in the size of individual minerals within the source rocks (which affects relative mineral abundance within sands of different grain size), chemical weathering (which removes minerals susceptible to oxidation or acid dissolution), transport (which leads to the hydraulic separation of minerals with differing densities and shape) and dissolution of susceptible minerals during burial diagenesis.

These processes can lead to detrital assemblages that are very different in character to those of their host rocks, with some minerals being absent and others present in very different proportions. Thus the meteoric and diagenetic dissolution of unstable minerals can reduce what were originally different and diverse assemblages to assemblages composed of relatively few ultrastable minerals (typically dominated by zircon, rutile and tourmaline). Conversely, assemblages derived from a single source rock can display substantial variation in composition because of the effects of different degrees of hydraulic sorting, weathering and burial-related dissolution. Comparison of heavy mineral assemblages using percentage data alone can therefore be highly unreliable as a means of determining provenance.

An alternative approach was proposed by Morton (1985) who recommended the use of two-component indices, which reflect the relative abundance of minerals with comparable hydraulic behaviour (i.e., comparable density and shape characteristics). These two-component indices may relate to two different minerals or to two varieties of the same minerals. A further constraint proposed by Morton (1985) was that heavy mineral analysis should be carried out on a single size fraction, thus minimizing the effects of grain size availability. The size fraction proposed was the very fine sand fraction (125–64 microns) because heavy minerals of this size can be obtained from most sandstones.

Data presentation

Four heavy mineral indices are routinely used in provenance studies: rutile:zircon, monazite:zircon, chrome-spinel:zircon, and apatite:tourmaline. These are selected because of the resistance of all the component minerals to diagenetic dissolution. They are thus equally applicable to deeply buried sands as to sands that have undergone minimal burial. Chrome-spinel is extremely scarce in the Unayzah Reservoir successions, however, and the chrome-spinel:zircon index is therefore not included in this study. Another index, the garnet:zircon index is applicable to all but the most deeply buried successions. Garnet is, however, susceptible to dissolution at depths of c. 10,000 ft (c. 3000m) and its scarcity in the Unayzah Reservoir sands of the Central Fields Area must in part be the result of burial-related dissolution. Other indices used in this study are the pink (purple) zircon index (pZi), defined by the percentage of pink (purple) zircons in the total zircon assemblage and the euhedral zircon index (eZi), defined as the percentage of zircons retaining well-preserved prism faces. Formulae for the heavy mineral indices are given in **Table 1**.

The fundamental premise of these mineral indices is that they are more or less unaffected by hydraulic sorting and thus provide a reasonably accurate reflection of the relative abundance of minerals (within the same grain size fraction) in the source rock. The mineral indices thus provide the most reliable means of relating detrital assemblages to specific source rocks and also of comparing provenance character between different sandstone bodies.

The apatite:tourmaline index (ATi) is commonly affected by the dissolution of apatite by acidic meteoric groundwater, either in the source area or in the depositional area. For this reason, ATi values may not reflect the composition of source rocks where weathering has taken place under humid climatic conditions. The index is therefore of limited value as a provenance indicator except where sediments have undergone rapid erosion, deposition and burial or where they have been deposited under arid and/or cold climatic conditions. It can, however, provide useful information on sediment maturity, since the degree of weathering is dependent not only on climate, but also on rates of erosion, transportation and deposition. In this way, variation in ATi values can reflect the sea-level history of a region (Morton and Hallsworth 1999).

A key element in the interpretation of all heavy mineral assemblages is the degree to which the mineral composition may have been inherited from pre-existing sediments. In particular, a high degree of physical and mineralogical maturity does not necessarily reflect intense weathering and prolonged transport: it can equally well reflect repeated recycling of the component sands. Fuller accounts of the concept and interpretation of heavy mineral indices are provided by Morton and Hallsworth (1999) and by Mange and Wright (2007) and references therein.

The rutile:zircon index (**RZi**) and monazite:zircon index (**MZi**) are reliable provenance indicators because all three minerals are highly stable under all conditions. However, this stability also favours recycling, such that the signature may be largely inherited from earlier sediments. Zircon is widely distributed in granites and other plutonic rocks, whereas rutile is a common constituent of regionally metamorphosed pelites and basic igneous rocks. Monazite occurs as a minor constituent of both plutonic and metamorphic rocks. The chrome-spinel:zircon index (**CZi**) is an equally reliable provenance indicator, but cannot be applied in the present study owing to the extreme scarcity of chrome spinel.

The garnet:zircon index (**GZi**) is a reliable indicator of derivation from regionally metamorphosed pelitic rocks in sandstones that have not undergone deep burial. At burial depths of more than c. 3000 m (10000 ft), however, garnet undergoes dissolution, leading to the development of progressively prominent etching of grain surfaces. In this study, etched garnets have been encountered is some western margin sections, but garnet is entirely absent from the more deeply buried successions. The garnet:zircon index cannot therefore be used for regional correlation within the study area.

The apatite:tourmaline index (**ATi**) is a potential provenance indicator, but can be strongly modified by weathering, especially under conditions of low relief and humid weathering. Apatite is a ubiquitous and abundant component of both igneous and metamorphic source rocks. Low or very low ATi values are therefore indicative of a significant degree of weathering of the primary heavy mineral assemblages.

The pink zircon index (**pZi**) indicates the percentage of pink (to purple) zircons within the entire zircon assemblage and is considered to be a reliable indicator of provenance. In the assemblages encountered in this study, the more deeply coloured pink zircons are commonly well rounded and are thus likely to be derived from pre-existing sediments. The paler pink zircons range from well rounded, probably reworked, grains to euhedral zircons that were clearly derived from local igneous or metamorphic basement rocks.

The euhedral zircon index (**eZi**) indicates the percentage of zircons with euhedral crystal form. For this purpose, the term euhedral is applied to all grains that show well-defined pyramid terminations, including those that display some abrasion of the interfacial angles. Most of the zircons thus defined are likely to be of first-cycle origin. Variation in the euhedral zircon index may reflect differing provenance as much as differing degrees of transport-related abrasion (physical maturity).

No reliable index exists to express the relative abundance of the mineral chloritoid, which typically occurs in only in trace amounts. It is, however, a useful indicator mineral since it is principally derived from alumina-rich metapelites. Little is known of the stability of chloritoid, but it appears to be stable under most weathering conditions and to be more stable than garnet under conditions of deep burial (Morton and Hallsworth, 1994, p. 245). In the Permo-Carboniferous succession of Saudi Arabia, it is largely restricted to diamictite facies, but also occurs in sandstones believed to consist of reworked diamictite material.

Applications

The primary purpose of studying heavy mineral assemblages is to identify and compare provenance signatures within sandstones. Geographic variation in the composition of assemblages is used to reconstruct palaeogeography and sand transport paths, while stratigraphic variation is used to assess changes in provenance with time. Where such changes take place more or less simultaneously, heavy mineral analysis can aid in chronostratigraphic correlation, whether on a regional scale or at the scale of an individual hydrocarbon field. This is especially useful in successions that lack good biostratigraphic control. Marked stratigraphic changes in mineral composition also contribute to interpretation of the tectonic history of a basin and its surrounding source areas.

In the Permo-Carboniferous sandstones of the study area, biostratigraphic control is very limited. Only in the marine Basal Khuff Clastics is it possible to assess variation in provenance signatures within a well-defined chronostratigraphic context. In the Unayzah Formation biostratigraphic data are sparse and of limited stratigraphic range. As a consequence, the chronostratigraphic context is much less certain and must rely on integration with observations on the occurrence of distinctive elements within the rock succession (e.g. diamictites and soil horizons).

Although the heavy mineral assemblage units identified in this study reflect long-term changes in the nature of the sand supply with time, the influx of new sand types may well have been diachronous, albeit on a limited scale. In some instances it is apparent that reworking of older sand deposits has also occurred. While they are broadly chronostratigraphic in character, therefore, the heavy mineral units should not be equated with true time zones.

Even without any clear chronostratigraphic context, heavy mineral data provide important data on the distribution of individual sandstone bodies and on the geographic and stratigraphic extent of individual depositional systems. This is especially useful in successions where coring is limited, since heavy mineral data can be obtained from both cores and ditch cuttings alike.

HEAVY MINERAL UNITS IN THE UNAYZAH AND BASAL KHUFF SANDSTONES

Initial (unpublished) heavy mineral studies on sections in and around the southern part of the Ghawar field (see Figure 1) led to the recognition of three mineral stratigraphic units, named UNZ1–3 in descending order (thus following the descending order of the Unayzah A–C lithostratigraphic scheme). Subsequent extension of the study to the west led to the identification of an additional unit at the top of the succession. The sandstones of this additional unit are restricted to the uppermost part of the Unayzah Formation and the marine Basal Khuff Clastics. To avoid unit re-numbering, this additional unit was referred to as UNZ0, with the UNZ prefix now referring to the informal ‘Unayzah Reservoir’ unit, as defined by Senalp and Duaiji (2001).

It should be noted that the units do not possess unique heavy mineral signatures. Their recognition is based on the knowledge that central Saudi Arabia experienced a series of changes in the pattern of sand influx, accompanied by changes in climatic conditions over time. As a consequence, it is not always possible to make definite unit assignments where the stratigraphic coverage is incomplete – e.g. through non-sequence, lack of sand facies or incomplete sample coverage. In such instances, correlation must rely on other information, such as lithological observations, biostratigraphic zonation or wireline log character.

The typical succession of heavy mineral assemblages is illustrated in a composite section (**Figure 3**) derived from the heavy mineral record in three wells. Typical features of the individual heavy mineral units are described below.

Unit UNZ3. This unit is typified by extremely low ATi (generally zero) values. The unit displays marked geographic variation in provenance signature (indicating the simultaneous operation of several sand dispersal systems). Provenance signatures in the central and eastern parts of the area are very consistent within any one section, indicating supply from a single source. In the west of the study area, however, the UNZ3 sandstones are characterised by highly variable MZi values, indicating mixing of low-MZi and high MZi sands.

Unit UNZ2. This unit is distinguished in most sections by the presence of significant amounts of apatite, reflected in ATi values (up to 65) that are distinctly higher than those of the UNZ3 sands (typically <1). It should be noted, however, that some UNZ2 sections also include samples with zero ATi values. The upward influx of apatite is closely associated with changes in RZi, MZi and eZi values, indicating that the UNZ2 sands are of different provenance to those of unit UNZ3. The boundary between units UNZ3 and UNZ2 is picked at a significant upward increase in ATi values or at a sharp upward increase in RZi, MZi and eZi values that occurs shortly below the increase in ATi values. The UNZ2 section in some wells in the southwest of the study area includes a unit of diamictite, characterised mineralogically by the presence of the rare mineral chloritoid.

Unit UNZ1. The UNZ1 succession as a whole is characterised by a wide variation in RZi values. The most characteristic feature is the presence of sandstones with low RZi values, very low (usually zero) ATi values and extremely low eZi values. The remainder of the UNZ1 sandstones display a wide range in RZi and ATi values. This contrast in mineral signature is the basis for subdivision of UNZ 1 into two mineralogical categories.

UNZ1A-type – characterised by low RZi values, zero ATi values and extremely low eZi values (average 0.5; 42% = 0.0);
UNZ1B-type – characterised by moderate to high RZi values, ATi values ranging from 0–55 (average 9.0) and low to moderate eZi values (average 1.5).

The UNZ1 succession typically consists of UNZ1B sandstones overlain by UNZ1A sandstones, but interdigitation of the two units is displayed in the middle and upper part of some sections. The boundary between units UNZ2 and UNZ1 is picked at a minimum in RZi values that occurs at the base of a section characterised by a progressive upward increase in RZi values. It should be noted that because there is no consistent difference between the range of the mineral signatures in the UNZ1B and UNZ2 sands, the base of unit UNZ1 is identifiable with certainty only where trends can be identified from a more or less continuous mineral record.

Unit UNZ0. This unit is characterised by relatively high eZi values (4 or more), which are generally maintained throughout the unit. The boundary between units UNZ1 and UNZ0 is picked at a sharp upward increase in eZi values, often accompanied by a change in RZi values. The UNZ0 sandstones are overlain by grey, marine mudstones of the Basal Khuff Clastics unit. Where UNZ0 sands are absent, these mudstones (or associated limestones) rest directly on UNZ1 sands.

These four heavy mineral units represent the regional evolution of sand provenance. Anomalous successions have developed locally as a result either of reworking or of sand supply from a local source. In particular, UNZ3-type sands occur locally within unit UNZ2 and sands of UNZ1A-type occur locally within the Basal Khuff Clastics.

Heavy mineral reference wells

The Late Carboniferous to Middle Permian succession of central Saudi Arabia shows considerable lateral variation, reflecting changes in facies and in structural setting. For this reason, no single section encompasses the observed range of variation in heavy mineral signatures. The heavy mineral stratigraphy is therefore illustrated with four reference sections, described below. The stratigraphic index plots for these sections include the provenance indices RZi, pZi and MZi, together with ATi and eZi, which, as explained above, may reflect both provenance and environment. Well locations are shown in Figure 1.

As noted above, successive heavy mineral units are defined by the first up-section appearance of their characteristic mineral signatures. In some instances, however, the characteristic heavy assemblages clearly occur out of the predicted sequence. Such anomalies are attributed to reworking or to the interdigitation of different sand dispersal systems. They are most apparent in unit UNZ2, where beds with zero ATi values occur within sections characterised by moderate to high ATi values. In the following illustrations, these are identified with the UNZ3 colour. It is thus important to appreciate that a sandstone unit with a UNZ3 mineral assemblage may occur within the UNZ2 stratigraphic unit.

Well 25 (Nuayyim field)

The basal sandstone unit in well 25 (**Figure 4**) is assigned to unit UNZ3 on account of its zero ATi values. Although RZi, pZi and eZi values are fairly consistent within this unit, MZi values are highly variable. The characteristic upward increase in ATi values that defines the base of unit UNZ2 has not been recorded from well 25, presumably because the relevant section is in dominantly muddy facies. The base of unit UNZ1 is taken at a low-RZi sandstone section defined by two samples, the lower of which has a high ATi value. The base of this section marks a sharp upward decrease in gamma-ray (GR) values. The overlying section shows a progressive upward increase in RZi values, culminating in an RZi peak. This is followed by a peak in ATi values. Moderate eZi values occur throughout. These features are indicative of unit UNZ1B and are characteristic of the lower part of unit UNZ1. The uppermost two UNZ1B samples are associated with low GR values and possess relatively low RZi, ATi and eZi values compared with the underlying samples. The remainder of the low-GR unit displays low RZi, ATi and eZi values, indicating unit UNZ1A. A subsequent increase in RZi values, accompanied by a slight increase in eZi values, indicates a return to UNZ1B-type assemblage. This unit differs from the underlying UNZ1B section, however, in possessing zero ATi values.

Sandstones at the top of the section are characterised by high eZi values, indicating assignment to unit UNZ0. Two separate sandstone units are present, distinguished by their differing pZi, ATi and eZi values.

The lower unit displays exceptionally high ATi values and is in continental red-bed facies. The upper unit is characterised by very high eZi and pZi values and zero ATi values. It is in marine facies, as indicated by the presence of fish debris in one sample.

From the mineralogical perspective, the section in well 25 displays the characteristics of a more or less complete Unayzah sandstone succession overlain by marine sandstones of the Basal Khuff Clastics. However, Ferguson and Chambers (1991, p. 3–4) proposed that the section from the top of the Unayzah Reservoir to c. 8770 ft represents the fill of a deep channel that was formed during the sea-level fall that terminated Unayzah A sedimentation. Renewed sedimentation was considered to have been associated with the onset of the Khuff transgression. Consequently, the Khuff Flooding Surface was placed at the base of the proposed channel fill. This cannot be verified from the heavy mineral assemblages since it is not possible to distinguish between in-situ and reworked UNZ1 sands. The only mineralogical feature that might indicate the presence of a channel is the occurrence of UNZ0 sandstones of continental facies at the top of the Unayzah Formation. This is only occurrence of such sandstones in the western margin wells, and the high eZi values indicate a genetic link with the overlying and more widespread marine UNZ0 sandstones of the Basal Khuff Clastics.

Well 7 (Wudayhi field)

The basal sandstones in well 7 (**Figure 5**) are atypical of the Unayzah Formation in possessing extremely high ATi values. Such values are encountered in Precambrian or Infracambrian sandstones of the region, but have not been encountered elsewhere in the Paleozoic succession. Since they overlie Silurian mudstones, they cannot represent an in situ Precambrian or Infracambrian succession and they may therefore represent reworking from a nearby structural high. Although this unit has been assigned to the Unayzah Formation (e.g. Melvin and Sprague, 2006), no biostratigraphic data are available to confirm this. It is therefore possible that it pre-dates the Unayzah Formation.

The lowest sandstones that can be confidently assigned to the Unayzah Formation are characterised by zero ATi values, indicating assignment to unit UNZ3. The presence of UNZ2-type sands is indicated by the first upward appearance of apatite at 14013 ft. ATi values are very low, however, and thus not reliable for defining the base of the unit. For this reason, the base of unit UNZ2 is taken at a marked upward increase in MZi values, which occurs in the sample immediately below the lowest apatite-bearing sample. They are in part associated with mudstones that contain reworked Mid Carboniferous palynomorphs of the **Cm** palynozone. A sparse assemblage of **Cm**-type has been recorded from the uppermost part of unit UNZ3 (c. 14040 ft). The associated sandstones possess slightly higher RZi values than the remainder, indicating a minor change in provenance.

The base of unit UNZ1 is taken at a minimum in RZi values, which is associated with a decrease in MZi values to zero and with a decrease in GR values. The overlying two samples show a progressive increase in RZi values. The high RZi value at 13950 ft is indicative of UNZ1B, although ATi values are extremely low. It is overlain by a unit of low-GR sandstones with low RZi values and extremely low MZi, ATi and eZi values, indicating unit UNZ1A. This is overlain by a second unit of UNZ1B-type sandstones, with moderate to high ATi values. The vertical trend in ATi values within the two UNZ1B sandstone units combined is thus comparable to that displayed in the lower UNZ1B unit of well 25. It is possible therefore that the latter unit is split in well 7 by an additional unit of UNZ1A-type sandstones.

A second, thicker, unit of UNZ1A sandstone is present at the top of the section and is overlain directly by marine mudstones of the Basal Khuff Clastics. A facies change has been recorded at c. 13777 ft (LD) that indicates an upward change from aeolian to estuarine sedimentation (O. Soliman, pers. com., 2004). The uppermost two samples thus appear to represent the basal part of the Basal Khuff Clastics. Since they are mineralogically identical to the underlying sandstones, it is likely that they represent local reworking.

The lithostratigraphic assignments shown in Figure 5 are those of Melvin and Sprague (2006, figures 7 and 24: well 7). The UNZ3 sandstones are largely equivalent to their Unayzah C Member. However, the top five samples, which display somewhat higher RZi values, lie within their Unayzah B Member, along with the high-MZi sandstones here assigned to UNZ2. The lower UNZ1B and UNZ1A units equate with their ‘un-named middle Unayzah member’, and the upper UNZ1B and UNZ1A units to their Unayzah A Member.

Well 9 (Haradh field)

The lower part of the Unayzah Formation section in well 9 (**Figure 6**) is occupied by a thick succession of sandstones with low to moderate RZi values, extremely low MZi and ATi values and low to moderate eZi values. These sandstones are assigned to unit UNZ3. A sustained upward increase in RZi values occurs at c. 14800 ft, indicating a minor change in provenance. The UNZ3 succession includes a well defined mudstone unit that contains a palynomorph assemblage dominated by Mid Carboniferous taxa. This **Cm** assemblage was originally considered to be indigenous (Owens et al., 2000), but later authors have interpreted the assemblage as reworked (Senalp and Al-Duaiji, 2001, p. 33; J. Filatoff in Al-Husseini, 2004, p. 26; J. Filatoff in Melvin and Sprague, 2006, p. 109). A comparable assemblage is recorded from the UNZ2 section in well 7 (Figure 5). No representatives of unit UNZ2 can be recognised in the well 9 section, and the UNZ3 sandstones are overlain by a siltstone-dominated section that shows an upward in increase in RZi values, culminating in an RZi peak. This feature is similar to that displayed in the basal part of unit UNZ1 in well 7 (Figure 5), and the same assignment is given to the well 9 samples. A sample from the overlying low-GR sandstone unit displays a moderate RZi value and zero ATi and eZi values. Although the RZi value in the lower sandstone is higher than normal, the zero eZi value suggests assignment to unit UNZ1A. The topmost sandstone unit is more readily assigned to unit UNZ1A on account of the very low RZi values and zero eZi values. The Unayzah sandstone section is overlain by mudstones with P2U palynofloras.

The UNZ3 sandstone section equates with the 'Haradh' Formation of Senalp and Al-Duaiji (2001, figure 19), which they considered to be overlain unconformably by the Unayzah Formation. Al-Husseini (2004, figure 9) assigned the sandstones below the Cm mudstone unit to Unayzah C and those above it to Unayzah B, as did Melvin and Sprague (2006, figure 7: well 9). The UNZ1B section falls within the 'un-named middle Unayzah member' of Melvin and Sprague (2006, figure 23: well 9). The pre-Khuff unconformity was placed at the base of the topmost sandstone by Al-Husseini (2004), whereas Senalp and Al-Duaiji (2001) placed their pre-Ash-Shiqqah unconformity at the base of the underlying mudstone unit.

Well 12 (Jawb field)

The UNZ3 section in well 12 (**Figure 7**) is characterised by uniformly low RZi values. The samples between 14556 and 14590 ft have high ATi values, indicative of unit UNZ2. The sample at 14595 ft possesses an extremely high RZi value and includes the rare mineral chloritoid. Because these provenance signatures are in marked contrast to those of the UNZ3 sandstones, this sample is included in UNZ2. This and the overlying six samples are from a diamictite unit. All of the UNZ2 samples have higher eZi values than the UNZ3 sandstones. **P4** palynofloras have been recorded throughout the diamictite section.

The unit assignment of the next four samples is uncertain because of the fragmentary nature of the record, but high RZi and ATi values between 14340 and 14390 ft indicate the upper part of UNZ1B (see Figure 3). Lower RZi, ATi and eZi values in the overlying two samples indicates assignment to UNZ1A.

The uppermost sandstones are assigned to UNZ0 on account of their high eZi values. The presence of phosphatic fish debris indicates deposition in a marine environment. **P2U** palynofloras have been recorded from the upper part of this unit and from the overlying mudstones.

The continental mudstone-dominated unit that lies between the UNZ1A and UNZ0 sandstone units is in has yield palynomorphs of the **P2L** zone. It the only section in the study area to have yielded assemblages of this type.

The UNZ3 sandstone section equates with the Haradh Formation of Senalp and Al-Duaiji (2001, figure 22), while their Jawb Formation includes unit UNZ2 and the basal part of unit UNZ1B. These authors regarded the Ash-Shiqqah Formation as absent from this section, and placed the marine UNZ0 sands identified in this study within the upper part of the Unayzah Formation. The UNZ3 sandstone section equates with the Unayzah C Member as identified by Melvin and Sprague (2006, figure 7: well 12) and the overlying UNZ2 section with the Unayzah B Member. No heavy mineral data were obtained from their 'un-named middle Unayzah member'.

CORRELATION OF HEAVY MINERAL UNITS

As discussed above, the units defined in this study are based on upward changes in provenance or environmental signatures in the heavy mineral assemblages. While it is likely that these reflect more or less synchronous changes in the sedimentary or climatic regime, the possibility of diachronism cannot be ruled out. Unfortunately, there is limited opportunity to place the units in a chronostratigraphic context. While a biostratigraphic scheme has been established for the region as a whole (Stephenson et al., 2003; Stephenson, 2004, 2006) the occurrence of the indicator palynomorphs is sporadic, so that many sections (especially in the Unayzah Formation) have no biostratigraphic control. The palaeoenvironmental analysis of the Unayzah Formation by Melvin and Sprague (2006) also has the potential for chronostratigraphic correlation, since it recognises successive distinctive lithofacies whose deposition is likely to have been more or less synchronous across the study area. For this reason, the lithostratigraphic scheme of Melvin and Sprague (2006), which takes full account of the work of previous authors, is regarded as the most widely applicable template for assessing the chronostratigraphic significance of the heavy mineral units.

Correlation of reference well sections

Three of the four reference wells described above were included in the study by Melvin and Sprague (2006). A correlation of these wells is presented in **Figure 8**.

The base of unit UNZ3, which includes the main body of sandstones with UNZ3 mineralogy, is clearly identifiable in all but well 7. As described above, this section includes a unit of sandstone that is interpreted as resulting from reworking of Precambrian or Infracambrian sandstones. We follow Melvin and Sprague (2006) in assigning this unit to the Unayzah Formation, although the possibility that it belongs to a pre-Unayzah unit cannot be ruled out.

UNZ2-type sandstones, which are characterised by moderate to high ATi values, are most clearly identifiable in well 12. They are underlain by a sample with a zero ATi value and an extremely high RZi value. This sample is included in unit UNZ2 on account of its high RZi values compared with values for the UNZ3 sandstones and the presence of chloritoid. The UNZ2-type sandstones all lie within the Unayzah B Member as identified by Melvin and Sprague (2006, figure 7). In well 7, the base of unit UNZ2 is base of unit UNZ2 is also taken at a change in provenance signature, but in this well it is taken at and upward increase in MZi rather than RZi values. The high-MZi sandstones also possess low ATi values, indicating possible reworking of high-MZi UNZ3-type sands, such as occur in well 25 (Figure 4). The base of unit UNZ2 thus defined is at a level some 35 ft (10 m) above the base of Unayzah B as defined by Melvin and Sprague (2006, figure 23). The UNZ3-type sandstones that lie within the Unayzah B Member possess higher RZi values than the underlying UNZ3 sandstones, indicating that a minor change in provenance occurred at the onset of Unayzah B sedimentation. These uppermost UNZ3 sandstones are therefore shown as passing laterally into lower part of unit UNZ2 in adjacent sections. It may be noted that both this UNZ3 section and the overlying UNZ2 section have yielded mid-Carboniferous (Cm) palynofloras, indicating that pre-Unayzah B sediments must have been exposed on one or more structural highs.

Cm palynofloras are also encountered in well 9, in a mudstone-dominated unit that occurs within the UNZ3 sandstone succession. Although this occurrence is probably quite separate from those of well 7, it is likely that they represent the same change in tectonic regime that led to the local exposure of Lower Paleozoic sediments on structural highs. The section in nearby well 33 (**Figure 9**) also possesses a well-defined mudstone unit within a succession of UNZ3-type sandstones. In this instance, however, the mudstones are barren of palynomorphs, whereas a sparse P4 assemblage has been recorded from the underlying section. Melvin and Sprague (2006, figure 23) assigned the mudstone unit in well 9 to the Unayzah B Member and the same assignment is here give to the mudstone unit in well 33. It is also likely that the overlying sandstones in both wells represent local gravity-flow deposits, as proposed by Melvin and Sprague (2006) for the sandstones in well 9.

In well 33, it is likely that the base of Unayzah B lies below the P4 occurrence in well, although there is no mineralogical evidence to support this. The sandstones that immediately overlie the mudstone unit possess ATi values indicative of unit UNZ2. In this instance, however, it is possible that the apatite has been derived from Lower Paleozoic sandstones exposed on a nearby structural high, as discussed below.

The RZi minimum that defines the base of unit UNZ1 is most clearly expressed in well 7, where it coincides with the base of the ‘un-named middle Unayzah member’ (hereafter referred to as the   member) of Melvin and Sprague (2006, figure 23). The boundary coincides with an upward change from relatively high but variable GR values to consistently low GR values. In wells 9 and 12 the base of unit UNZ1 is picked at a slightly higher level than the base of the UMU member as identified by Melvin and Sprague (2006). The wide spacing of the heavy mineral samples in these wells does not permit precise location of the base of unit UNZ1, which for practical purposes is taken at a sharp upward decrease in GR values. This gamma-ray marker appears to be widely recognisable in the more southerly sections, whereas the base of the UMU member lacks a distinctive log signature and is identifiable only in a few cored sections. There is thus a slight discrepancy between the base of unit UNZ1 thus identified and the base of the UMU member. The base of the two units may nevertheless be regarded as broadly synchronous in central and eastern parts of the study area.

The remainder of the UNZ1 succession in well 7 displays an alternation of UNZ1B and UNZ1A sandstones. The lower UNZ1B section is characterised by low ATi values and by an upward trend from very low to very high RZi values. The upper UNZ1B unit is characterised by relatively high ATi and RZi values, although the uppermost sample displays zero ATi values and low RZi values. The top of the high-ATi section is used to define an ‘ATi marker’. This occurs within the uppermost part of the UNZ1B section. The base of the upper, high-ATi unit equates with the base of the Unayzah A member (i.e. the top of the UMU member) of Melvin and Sprague (2006). The UNZ1 section in well 9 is much more expanded than in the other wells and the mineral record incomplete. Nevertheless, the lower UNZ1B unit of well 7 can be identified by its very low ATi values and the presence of an RZi peak. The lower UNZ1A sandstone of well 7 is apparently represented by a series of thin sandstones, of which only one displays typical UNZ1A mineralogy.

The upper UNZ1B unit of well 7 has not been identified in well 9 but is present in nearby well 37 (Haradh field) (see Figure 9). In well 9 it seems likely that it lies below the sandstone unit at 14000–14040 ft, since the topmost sandstone unit is assigned to the Basal Khuff Clastics (R. Price and J. Filatoff in Al-Husseini, 2004, p. 26 and figure 9). The base of Unayzah A is picked by Melvin and Sprague (2006) at c. 14075ft in well 9, but no mineral signature is available at this level. Data are similarly scarce in the lower part of the UNZ1 section in well 12. Melvin and Sprague (2006, figure 23) considered the UMU member to be very thin in this well. It should be noted, however, that the picks in both of these wells are in uncored sections and that the diagnostic sedimentological criteria are therefore lacking. The paucity of heavy mineral data in the uncored sections in these two wells is attributed to a very low sand to mud ratio, reflecting the distal setting of these wells.

Correlation of western margin sections

Correlations of wells along the western margin of the study area are illustrated in **Figures 10** and **11**.

UNZ3 sandstones are present in four of the wells illustrated in **Figure 10**. The UNZ3 sandstones show marked variations in MZi values. Those in well 7 (Wudayhi field) are very low throughout the analysed section, although it should be noted that part the UNZ3 sandstone section is unsampled. As discussed above, there is uncertainty as to the lithostratigraphic assignment of the high-ATi sandstones in well 7. They are unlike any other Unayzah sandstones and may well belong to an older formation.

In well 16 (Ghinah field) and well 17 (Hazmiyah field), high ATi values in the basal Unayzah sandstones provide definite evidence for a UNZ2 assignment. In both wells 1 and 16 the UNZ2 succession consists of a lower sand-rich division and an upper mudstone-rich division. The upper division in well 1 includes a thin unit of UNZ3-type sandstone. All three southern wells include a unit of chloritoid-bearing diamictite. In well 17 this occurs at the base of the Unayzah succession, whereas in the other two wells it occurs near the top of the unit. The lower part of the UNZ2 succession thus appears to be missing from well 17.

In well 7, UNZ2 sandstones are identified by their relatively high MZi values, which are in sharp contrast to the low values of the UNZ3 sandstones and mark a significant change in sand provenance. Three of the four high-MZi samples have slightly higher ATi values than the underlying UNZ3 sandstones, although the values are much lower than in the UNZ2 sandstones of wells 16 and 17. A thin sandstone with a UNZ3-type signature is present in the middle of the unit. In wells 18 and 25, UNZ2 sandstones cannot be identified due to lack of data. In these wells, the base of UNZ2 is picked at a sharp upward increase in GR values.

The RZi minimum that defines the base of unit UNZ1 is most clearly seen in well 7, but is identifiable also in wells 17 and 25. In all three wells, the low-RZi sample occurs shortly above an upward decrease in GR values. For correlation purposes this shift in GR values is taken as marking the base of unit UNZ1. In wells 1, 16 and 17 the GR shift occurs between 2 and 9 metres above the chloritoid-bearing diamictite.

The lower part of the UNZ1 succession in wells 17 and 25 is dominated by UNZ1B sandstones that show relatively high ATi values and a peak in RZi values. In well 7, ATi values are on average lower and the RZi peak is split by a unit of UNZ1A sandstone with low RZi values and zero ATi values. The reminder of the UNZ1 succession displays very low (mostly zero) ATi values. The ATi marker is used to indicate the top of the apatite-bearing section.

The high-ATi unit can be traced southwards as fall as well 16 (where it is represented by a single sample). In well 1 it is not present, indicating either non-deposition or pre-Khuff erosion at this site. The high-ATi unit is overlain by a unit of low-GR UNZ1A sandstones. Those of well 17 differ from the remainder in possessing high MZi values, indicating that they have a different provenance to the remainder. In well 17, the UNZ1A sandstones are overlain by a UNZ1B unit with very high RZi values. A comparable unit is present above the UNZ1A sandstones in well 25, although RZi values are lower.

UNZ0 sandstones of continental facies are present at the top of the Unayzah Formation in well 25, where they are overlain by UNZ0 sandstones that include fish debris and thus belong to the marine Basal Khuff Clastics. Marine UNZ0 sandstones are also present in wells 17 and 18. In well 18, they include three units of slightly differing mineralogy. The thin sandstone at the top of the section in well 1 has a UNZ1A mineralogy, but the presence of fish debris indicates that it also belongs to the marine Basal Khuff Clastics unit (see also Al-Husseini, 2004, figure 19).

The mineral stratigraphy presented in Figure 10 reveals a marked lateral variation in the thickness of the principal units. This variation is most apparent in units UNZ3 and UNZ2. The absence of unit UNZ3 in wells 16 and 17 is particularly striking and indicates either differential subsidence during sedimentation or differential uplift and erosion prior to deposition of UNZ2. Continuity between the UNZ3 sand units of wells 1 and 18 is indicated by the similar upward trend from moderate to low MZi values, whereas the moderate to high MZi values in the UNZ3 sands of well 25 suggest that they represent only the lower part of the UNZ succession in wells 1 and 18. Since data are lacking for part of unit UNZ3 in well 7, it is not possible to determine whether the higher MZi sands were deposited at this location also.

The UNZ2 section displays a distinct thinning from south to north, accompanied by loss of the chloritoid-bearing diamictite unit. Data for the northern wells are largely restricted to well 7, but it appears that the sandstones associated with this thinner succession are of different provenance to those in the thicker southern successions, with much lower RZi values and, at least in well 7, higher MZi values. The northward loss of the diamictite unit is most likely due to non-deposition rather that erosion at the base of unit UNZ1, since it is absent from all sections to the north and east of the Hazmiyah field. The presence in the UNZ2 sections of wells 1 and 7 of thin sandstones with UNZ3-type mineralogy indicates either reworking or continued intermittent supply of the UNZ3-type sands.

Interpretation of the upper part of the Unayzah succession is complicated by the presence of incised channels, as identified in wells 17 and 25 by Ferguson and Chambers (1991, figures 4 and 5). Both wells possess anomalous units at the top of the sandstone succession, including an additional unit of apatite-free UNZ1B sandstones. Ferguson and Chambers describe the underlying channel-fill sandstones in well 25 as being distinguished from typical Unayzah A sandstones in being less mature, while those of well 17 differ from typical UNZ1A sandstones in possessing high-MZi values. It should be noted that although the channel-fill deposits of well 17 were not recognised as such by McGillivrayand Husseini (1992) (see **Figure A6**), an incised valley fill was identified in a nearby Hazmiyah well by Senalp and Al-Duaiji (2001, figure 29). The anomalous nature of the sandstone mineralogy in this well, and the similarity of the anomalous sandstone succession to that of well 25 is here considered to provide strong support for the channel-fill interpretation proposed by Ferguson and Chambers (1991). Outside these channel fills, the UNZ1 deposits display a more consistent thickness distribution and stratigraphy than those of units UNZ2 and UNZ3. Two divisions can be recognised: a lower division characterised by moderate to high ATi values (especially in the upper part) and by an RZi peak and an upper division characterised by very zero ATi values and dominated by UNZ1A sandstones. These two units are separated by the ATi marker. The lower part of the lower division shows a progressive northward decrease in ATi values, whereas the upper part retains moderate to high values throughout. This contrast probably reflects differing degrees of mixing of high-ATi and low-ATi sands. Thickness variation in unit UNZ1 is less pronounced than in units UNZ2 and UNZ3, although the succession in well 1 is significantly thinner, probably as a result of truncation. In well 7, a UNZ1A sand unit is present in the lower division, where it appears to split the high-RZi peak.

The two channel-fill successions include a unit of UNZ1A sandstones overlain by a unit of UNZ1B sandstones. In well 25, the UNZ1B unit is overlain by a unit of continental UNZ0 sandstones. Since all these sediments are continental they are here included within the Unayzah Formation. The UNZ1A sandstones of well 25 are mineralogically indistinguishable from those in the adjacent unchannelled sections. The underlying section of low-GR sandstone was excluded from the channel fill by Ferguson and Chambers (1991) because the sandstones lack the relatively low maturity of the remainder. These apatite-bearing samples are here regarded as representing reworking of previously deposited UNZ1B sandstones and are therefore included within the channel fill. The high-MZi UNZ1A sandstones of well 17 were clearly derived from a separate source.

The UNZ1B sandstones that form the middle part of the channel fill succession in wells 17 and 25 are broadly similar in mineralogy and their association with a unit of higher GR values indicates that they are more argillaceous than the underlying UNZ1A sandstones. It seems likely, therefore, that this unit represents a period of regional aggradation. The uppermost unit of the channel fill in well 25 consists of UNZ0 sandstones with high to very high eZi values, indicating derivation from crystalline rocks exposed to the west, on the Arabian Shield. Ferguson and Chambers (1991) regarded the channel incision to have taken place during a period of sea-level fall that preceded the regional marine transgression of the Khuff Formation. They therefore placed the Khuff Flooding surface at the base of the channels. The location of the channel in well 25 was considered by Ferguson and Chambers (1991) to have been controlled by local structure. The section presented in Figure 10 supports structural control for the channelling, since both channels are associated with low points on the base Unayzah A surface.

Following the period of channel fill, marine conditions extended across the region. This was accompanied by the local deposition of marine UNZ0 sands. These are thickest in the two channelled sections, indicating that the two discrete drainage systems that produced the channels continued to supply sand to the basin after the initial Khuff transgression. This is reflected in the contrasting RZi and eZi values in the two sections. Truncation of the underlying Unayzah succession in well 1 indicates that the thin UNZ1A sandstone at the base of the Basal Khuff Clastics was probably derived from reworking of Unayzah sands exposed nearby.

The marked variation in thickness of the different units along the western margin indicates that the pattern of differential subsidence changed significantly through time. Although the thickness variation displayed by unit UNZ3 may largely reflect the infilling of a pre-existing topography (McGillivray and Husseini, 1992, caption to figure 12; Al-Husseini, 2004, p. 27; Melvin and Sprague, 2006, p. 103), the thickness variation displayed by units UNZ2 and UNZ1 must reflect differential subsidence during or shortly after UNZ2 sedimentation. Local inversion of structures is indicated by the successions in well 1, in which the thickest UNZ2–3 section is overlain by the thinnest (truncated) UNZ1 section, and in well 17, in which the thinnest UNZ2–3 section is overlain by the thickest UNZ1 section.

Wells closest to the northwestern basin margin are characterised by thin and mineralogically variable successions. These include wells 22, 3 and 29 (Figure 11). Well 22 has a relatively expanded UNZ2 succession. It differs from other sections in being dominated by a thick unit of chloritoid-bearing silty sandstone, whereas the thinner chloritoid-bearing unit in well 1 is a diamictite. It is possible that the two units are contemporaneous, but it seems more likely that unit in well 22 represents reworking of diamictite material. The chloritoid-bearing sandstone is overlain by a unit of alternating mudstone and sandstone with a highly variable gamma-ray signature. Most of the sandstones have high ATi values, indicative of UNZ2. The uppermost sandstone sample has very low ATi and RZi values, however. This sample is non-diagnostic as it could represent either a UNZ1A-type sandstone at the base of unit UNZ1 or a UNZ3-type sandstone within unit UNZ2 (as seen in well 1). Stratigraphic affinity with the underlying section is, however, indicated by its inclusion within a section characterised by P3 palynomorph assemblages, indicating that this section is younger than UNZ2 section of well 1, which is characterised by P4 assemblages. As discussed in a later section, the underlying chloritoid-bearing sandstones have heavy mineral signatures that are significantly different from those of other UNZ2 sections. This, together with their inferred derivation through reworking of diamictite, indicates that they too post-date the P4 sections encountered in wells to the south. The entire UNZ2 section in well 22 may thus represent a separate depositional phase from that of the UNZ2 (P4) succession of wells 1, 16, and 17.

The P3 assemblages in well 22 are associated with grey to pinkish grey mudstones. P3 assemblages are also associated with grey mudstones in well 29, where they rest directly on Lower Paleozoic rocks. A lack of sand precludes heavy mineral investigation of this section..

The sediments below the UNZ1A sandstone unit in well 3 are difficult to assign to the standard sequence of heavy mineral units. They display variable RZi and eZi values. The exceptionally high eZi values in two of the samples indicate contribution from crystalline basement. It is likely, therefore, that the sands in this section are of local derivation. The presence of glacially induced structures led Melvin and Sprague (2006) to assign the entire section to the Unayzah B Member. Since P3 palynofloras have been recorded from nearby well 23 (not studied for heavy minerals), the absence of P3 assemblages in this section may well be the result of subsequent channel incision.

The UNZ1 sections of wells 1, 22 and 29 lack substantial UNZ1A sandstone successions. As discussed above, the high-ATi UNZ1B section appears to be absent from well 1, but it is present at the top of the UNZ1 succession in well 22 and in the lower part of the succession in well 29. This indicates a strong north–south variation in the pattern of relative subsidence during the deposition of unit UNZ1 (UMU and Unayzah A members).

According to (Melvin and Sprague, 2006, figure 23) the UNZ1A sandstones in well 3 lie above the pre-Khuff unconformity and truncate the underlying succession. They are here interpreted as occurring within an incised valley fill. Sparse P2 assemblages have been recorded from a thin siltstone within this sandstone section. The UNZ1A sandstones are overlain by sandstones with relatively high eZi values (UNZ0-type) at the base and at the top. They are associated with P2U assemblages. The presence of fish debris in the upper UNZ0 sandstone section indicates marine facies of the basal Khuff Clastics. UNZ0 sandstones are also present in the Basal Khuff Clastics unit of well 29.

Studied sections closest to the Arabian Shield are those of wells 19, 20 and 21 (see Figure 1). Data for well 19 are restricted to a cored section in the Unayzah Formation that includes two sandstone units of UNZ1A mineralogy (**Figure A8A**). This provides evidence for a minimum southward extension of the UNZ1A sands and supports the explanation that their absence in well 1 is due to erosion beneath the pre-Khuff unconformity. Wells 20 and 21 display UNZ0 sands resting directly on basement (**Figure A8B, C**). The sandstones of both wells are assigned to the marine Basal Khuff Clastics.

Western margin to basin correlation

A well correlation from the western margin to the east of the study area is presented in **Figure 12**.

The UNZ3 sands in this section show marked variation in thickness, with the thickest sections occurring in wells close to the southern limit of the Ghawar field. In the three western sections, UNZ3 sandstones are present within unit UNZ2. The association in two of these wells with reworked mid Carboniferous (Cm) palynofloras indicates that these occurrences are due to local reworking of UNZ3 or older sandstones from nearby structural highs. As discussed above, the uppermost part of unit UNZ3 in well 7 was assigned by Melvin and Sprague (2006) to Unayzah B, indicating that these sands may also be reworked. The UNZ3 sandstones in well 6 (Ghazal field) display highly variable MZi values, indicating an alternation of sand supply from two sources. The remainder of the sections display extremely low MZi values. Wells 12 (Jawb field), 39 (Tinat field) and 40 (Tukhman field) display very consistent mineral index values, with RZi values lower that those of the three western wells. UNZ3 sands thus appear to have been supplied from three different source rocks.

Unit UNZ2 sections with the characteristic moderate to high ATi values are restricted to wells 39 and 12, indicating that these sections were outside the area of substantial reworking of UNZ3 sands. In both instances, the UNZ2 sands are associated with P4 palynofloras. The absence of **P4** assemblages in the other four wells may reflect the dominance of sediment reworked from unit UNZ3 or perhaps older formations. Unit UNZ1 shows a progressive west –east reduction in the proportion of UNZ1A sand, indicating that the source of these sands lay to the west.

The succession established for unit UNZ1 in well 7 (Wudayhi field) is not identifiable in its entirety in any of the wells included in this correlation panel. The lower UNZ1B section, with its low ATi values and characteristic RZi peak appears to be present in well 9 (Haradh field), but cannot be traced further to the east because of lack of data and scarcity of sand. The upper UNZ1B unit, characterised by high ATi and RZi values, has not been identified in well 9, but its likely position may be inferred from the its location in nearby well 37 (Haradh field), as shown in Figure 9. The unit is well defined further east (well 12) and the very top of the unit, including the ATi marker, is present in well 40. It thus appears that where mineral recovery and stratigraphic completeness permit, the fourfold division of unit UNZ1 established in well 7 is potentially recognizable over much of the study area

The UNZ1A succession in well 6 is difficult to interpret on heavy mineral data alone. The distinct high-RZi peak may correlate with that in the lower part of the UNZ1 succession in well 9. However, Melvin and Sprague (2006) assign this section to the Unayzah A Member, which would indicate correlation with the upper, apatite-bearing UNZ1B unit of well 7. Only two samples have been studied within the high-GR UNZ1B section of well 6, one of which did not yield a valid apatite/tourmaline count. Correlation with the upper unit of well 7 cannot therefore be ruled out on mineralogical criteria. For this reason, we have followed the lithostratigraphic assignments of Melvin and Sprague (2006). These indicate that the Unayzah B Member is absent from this well.

In wells 39 and 40 the upper UNZ1A sandstones of the standard UNZ1 succession are overlain by a mudstone-rich unit with UNZ1B-type sandstones. The same unit believed to be present also in wells 9 and 12. It is overlain by a unit of UNZ1A-type sandstones that show pronounced thinning to the southeast. In wells 39 and 40 this uppermost UNZ1A sandstone unit is overlain by UNZ0 sandstones of continental facies. No heavy mineral data are available for the equivalent interval in well 12, but it is believed also to be in continental facies and has yielded palynomorph assemblages of the P2L zone, indicting correlation with the Upper Gharif Formation of Oman. As discussed in a later section, the base of the uppermost UNZ1A sandstone is believed to represent the unconformity associated with the base of the Upper Gharif Formation. Sandstones are largely absent from the overlying Basal Khuff Clastics unit but three thin marine sandstones of UNZ0 type are present in well 12.

Northern and eastern Saudi Arabia

Heavy mineral analysis has been carried out on several wells that lie outside the study area, including wells 42, and 44 in the north, wells 45, 46 and 47 to the east, and wells 48 and 49 to the south (see Figure 1, inset). As might be expected from their wide geographic separation, provenance signatures in these wells are significantly different from those of central Saudi Arabian sections. Some elements of the heavy mineral units described above are, however, identifiable. High eZi values, similar to those of the UNZ0 sandstones of this study, have been found in the uppermost part of the Unayzah Reservoir succession in wells 42, 44, 45 and 46. In the former two wells, these constitute the lower part of the Basal Khuff Clastics. In the latter two wells, they are associated with continental facies and are thus comparable to those of well 40. Data for the lower part of the succession are available only for wells 45, 46, 48 and 49. In wells 45, 46, and 48 sandstones with relatively high ATi values suggest correlation with unit UNZ2. The current data set is, however, too limited to determine whether the mineral stratigraphy established for central Saudi Arabia is fully applicable to sections to the east and south. The cored section in well 49 consists almost entirely of chloritoid-bearing diamictite, again indicating correlation with unit UNZ2.

RELATIONSHIP BETWEEN MINERAL UNITS AND LITHOSTRATIGRAPHIC SUBDIVISIONS

The heavy mineral data presented in this paper have established that there is broad agreement between the heavy mineral units identified in this study and the lithostratigraphic scheme established for the Unayzah Formation by Melvin and Sprague (2006). This is summarised in **Figure 13**. It has proved less easy to establish a consistent correlation with the lithostratigraphic schemes of earlier publications (Ferguson and Chambers, 1991; McGillivrayand Husseini, 1992; Senalp and Al-Duaiji, 1995; Senalp and Al-Duaiji 2001; Al-Husseini, 2004). All published lithostratigraphic assignments relating to the analysed wells are, however, shown on stratigraphic plots. These include plots for the four reference wells (Figures 4 to 7), for well 1 (Figure 14) and for the for wells 3, 4, 5, 6, 17, 18, 20, and 22 (Appendix figures A1, A2, A3, A4, A6, A7 and A8, respectively).

As discussed in the text relating to correlation of the reference wells (Figure 8), the key tie points in the correlation between the heavy mineral units and the lithostratigraphic scheme of Melvin and Sprague (2006) are (1) the base of unit UNZ2, which generally equates with the Unayzah B/C boundary, and (2) the base of unit UNZ1, which is at or close to the base of the ‘un-named middle Unayzah’ member. Exceptions can mostly be explained by the occurrence of locally derived sand units (as where UNZ3-type sands occur within the basal part of the unit Unayzah B in well 7: Figure 5), by lithostratigraphic assignments that have been made in uncored sections thus lack the diagnostic lithofacies criteria, or by inadequate heavy mineral sample coverage. The most serious such discrepancies between the have been encountered in well 1 (**Figure 14**), which has already been illustrated in two of the correlation panels (Figures 10 and 11). These discrepancies are discussed in more detail here.

The bulk of the succession in well 1 is characterised by apatite-bearing sandstones. In the section below 6050 ft, however, apatite values are very low, indicating assignment to unit UNZ3. This is in accordance the assignment of this section to the Unayzah C Member by Melvin and Sprague (2006), although it should be noted that the section is largely uncored.

The section between 5935 and 6040 ft, where most samples display moderate to high ATi values, is assigned to unit UNZ2. The upper part of this interval is occupied by diamictite, which is elsewhere characteristic of the Unayzah B Member. In this instance, however, the diamictite unit was placed by Melvin and Sprague (2006, figure 23) at the base of the UMU member. The diamictite unit is chloritoid-bearing and thus similar to the diamictite units of nearby wells 16 and 17. In all three wells, the diamictites are associated with typical UNZ2 signatures and with P4 palynomorph assemblages. In wells 1 and 16 a more specific assignment to the P4U zone (upper OSPZ2) can be made. Chloritoid-bearing diamictite is also associated with P4 palynofloras in well 49, far to the southwest (see Figure 1 and Figure A11). In well 12, in the southeast of the study area, a chloritoid-bearing sample at the base of the diamictite unit occurs just below a section with P4 assemblages, and falls with Unayzah B as identified by Melvin and Sprague (2006, figure 23). For these reasons, it is here proposed that the chloritoid-bearing diamictite in well 1 should be included within the Unayzah B Member and that the base of the UMU member is at c. 5925 ft (log depth), corresponding to an upward change from grey mudstone facies to red-brown alluvial facies.

UNZ1 sandstones of well 1 indicate assignment to UNZ1B, with the trend of upward-increasing RZi values indicating correlation with the lower UNZ1B unit of well 7 (and, by correlation, well 9). This interpretation is compatible with the assignment by Melvin and Sprague (2006) of the entire UNZ1 section in well 1 section to the UMU member. The basal UNZ1B sample in well 1 is distinctive in possessing a high ATi value. A similar feature is seen in well 25 (see Figure 4), indicating that an additional, high-ATi, sandstone unit is present at the base of unit UNZ1 in some southwestern wells. As discussed in a subsequent section, these two sandstones have distinctive compositions that suggest reworking of Unayzah B diamictites similar to those in well 49.

The study by Melvin and Sprague (2006) did not extend to the Basal Khuff Clastics or to the continental deposits that fill the incised valleys along the western margin. The continental valley-fill deposits were excluded from the Unayzah Formation by Ferguson and Chambers (1991), who placed them in the Khuff Formation, and by Senalp and Al-Duaiji (2001), who placed them in their newly defined Ash-Shiqqah Formation. These assignments were based on information obtained from cored sections, whereas many of the sections included in this study are uncored and thus lack the data required to recognise the presence of an incised valley fill. To maintain internal consistency, therefore, all continental sandstones have been included within the Unayzah Formation in this paper, with the Khuff marine flooding surface being identified either by the presence of fish debris within the sandstones or by the occurrence of P2U palynomorph assemblages. The section overlying the marine flooding surface and below the Khuff D carbonates is assigned to the Basal Khuff Clastics.

SAND PROVENANCE

In the following account, sand provenance is discussed in terms of the lithostratigraphic scheme of Melvin and Sprague (2006). For this reason the data plots are restricted to sections in which correlation between the heavy mineral units and the lithostratigraphic units are fully established or can be confidently inferred. Variations in mineral signature between and within the stratigraphic units are presented in the form of two-component mineral-index cross-plots.

From the heavy mineral profiles presented in preceding sections, it is evident that significant changes in provenance took place over time. These are primarily reflected in RZi and MZi values (**Figure 15**). The most profound change took place at the end of Unayzah B sedimentation, with the loss in western wells of sandstones with higher MZi values . The few exceptions are in the Unayzah A successions of wells 16 and 17, where the presence of high-MZi sands probably represents local reworking of Unayzah C sands. Associated with this loss of high-MZi values is the development of a bimodal distribution of RZi values, with the UNZ1B sandstones characterised by high RZi values and the UNZ1A sandstones by low RZi values.. The UNZ0 sands, which occur in both continental (Unayzah) and marine (Khuff) successions, display very low RZi values throughout.

Additional information on provenance can be gained from the stratigraphic variation in eZi values (**Figure 16**). The relatively high eZi values that characterise the UNZ0 sandstones have been discussed above, and attributed to a significant contribution from basement rocks exposed to the west (Arabian Shield) and to the southeast. These contrast strongly with values for the UNZ1A sandstones, which are believed to be derived from pre-Unayzah Paleozoic sandstones, and those for the UNZ1B sandstones, which are believed to have a southern source. A more subtle contrast is seen between the Unayzah C and Unayzah B sandstones, with the latter showing an increased proportion of sands with a relatively high eZi to RZi ratio. These sands plot within the range for the UNZ0 sandstones and (with the exception of one sample from well 33) possess a similar geographic distribution, i.e. along the western margin and in the far east and south of the study area. By inference, the basement source rocks that provided the UNZ0 sands were also exposed during Unayzah B sedimentation. The sample from well 33, which possesses the highest eZi value, is also characterised by a high ATi value (see Figure 9) and may have been derived from unweathered basement rocks exposed on a nearby intrabasinal high.

Unayzah C Member

To facilitate description of the geographic variation in heavy mineral signatures in the Unayzah C and B members, the wells are grouped into seven areas (**Figure 17**).

The most striking feature of the UNZ3 sandstones of the Unayzah C Member is the east to west variation in RZi and MZi values, as illustrated in cross-plots between the two indices (**Figure 18**). MZi values are highest in western wells while RZi values are highest in the wells of the southeast-central part of the study area (including the south Haradh area).

The highest MZi values have been recorded from the wells in the west central area (Nuayyim, Ghazal and Abu Shidad fields) (Figure 18a). MZi values are significantly lower in the Wudayhi field and in well 5, as they are in wells along the western margin (Figure 18c). This lowering of the MZi values is attributed to mixing of the high-MZi sand population with a low-MZi, low-RZi sand population.

When traced eastwards into the southeast central area, sand compositions show a progressive decrease in MZi values and an increase in average RZi values (Figure 18b). MZi values are also low in the eastern and southern areas (Figure 18d), but here the low MZi values are associated with low RZi values.

This lateral variation in provenance signature indicates that the Unayzah C sands were derived from several sources, whose location can be inferred from the geographic variation in MZi and RZi values. Since the highest MZi values are found in west central wells, but not in the western wells, the high-MZi sands were most probably derived from the southwest (**Figure 19a**). As indicated by Knox et al. (2007), this is in agreement with the occurrence of comparable high-MZi sandstones in the Juwayl Formation of the Wajid outcrop area (see Figure 1). In the Unayzah C sandstones, the highest MZi values, and therefore the likely route of northward sand influx, follow a line from well 25, via well 26 to wells 6, 27 and 28. Continued transport to the north, up to the western flank of the Ghawar structure, is indicated by the occurrence of sands with low to moderate MZi values in well 5.

Additional information on the pattern of sand dispersal is revealed by variation in RZi values within the low-MZi sandstone samples (**Figure 19b**). Low-MZi sands with RZi values greater than 15 occur only in the southeast-central area. Elsewhere, the majority of low-MZi sands display RZi values between 2 and 12. The principal influx of low-RZi, low-MZi sands appears to have been from the southeast, as indicated by the thick low-RZi sandstone successions in wells 12 and 40. The higher RZi values in the UNZ3 sandstones of wells 11, 39 and 38 appear to reflect mixing of these very low-RZi sands with high RZi sands derived from the southwest. Sands with moderate RZi values appear to have entered the basin from the south (via well 41).

Sands with very low to moderate RZi values entered the basin from several sources along the western and northwestern margins of the basin, indicating derivation from the southeastern flank of the Central Arabian Arch. Lower Paleozoic sandstones, as encountered in the Hawtah and Dilam fields, possess similar RZi and MZi values (**Figure 20a, c**) and probably sourced the low-RZi Unayzah C sands.

Since none of the sands around the margins of the study area possess high RZi values, the occurrence of the highest RZi values in the southeast central area is anomalous. It seems most likely that these sandstones were derived from erosion of older Palaeozoic sands located on a nearby intrabasinal structural high. Data from the Ghawar structure (**Figure 20b, d**) indicate that Devonian sandstones are the most likely source, since they have higher RZi values than the pre-Devonian sandstones. The source of these sands may have been on the Ghawar structure itself, but in view of the regional pattern of northward transport, the source is perhaps more likely to have been a structural high located to the south of the Ghawar field.

The Unayzah C sandstones thus appear to have been largely derived from source areas to the south, with local contributions from the western margin and from an intra-basinal high located close to the south Ghawar area. The location of the southern source areas is unknown, but the highly quartzose nature of the sandstones indicates derivation from mature Paleozoic sandstones. The scarcity of apatite in the UNZ3 sands is likely to have been inherited from the source sandstones, since the Unayzah C sediments are believed to have been rapidly deposited under cold climatic conditions that would have been unfavourable to significant chemical weathering (Al-Husseini, 2004; Melvin and Sprague, 2006).

Unayzah B Member.

A comparison of RZi and MZi values for Unayzah B and Unayzah C sandstones (**Figure 21**) shows that the east to west contrast in MZi values that characterises the Unayzah C sandstones continues into the Unayzah B sandstones. Within individual areas, however, it apparent that there are significant differences in composition between the sets of sandstones. This indicates that most Unayzah B sands cannot have been derived by reworking of Unayzah C sands, but must represent fresh sand influx from several distinct sources.

Unayzah B sandstones in the west-central and northwest-central parts of the study area (Figure 21a) possess a similar range in MZi values to the associated Unayzah C sandstones, but possess a lower average RZi values, indicating derivation from a more restricted source. The wide range in MZi values and the lower average RZi values in the suggest that the sandstones must represent a new sand influx rather than reworking of Unayzah C sands (which would lead to a greater degree of homogenization). The relatively low MZi values in sandstones of the Nuayyim field indicate mixing with low-MZi sands, probably derived from Lower Paleozoic sandstones exposed to the west. This suggests that the main northward transport path of the high-MZi sands lay to the east of the Nuayyim field. It is likely that the two low-MZi samples from the Wudayhi field also represent mixing with low-MZi sandstones.

The relatively high RZi values that characterise the Unayzah C sandstones of the southeast-central area (Figure 21b) are not evident in the Unayzah B sandstones. This indicates that the high-RZi source that existed during Unayzah C sedimentation no longer operated and that the Unayzah B sands are unlikely to have been derived through reworking of nearby Unayzah C sandstones. The Unayzah B sandstones of well

33 (Shaden field) are distinctive in possessing lower RZi values than the remainder. The source of these sandstones is discussed further below.

In most western margin wells (Figure 21c) the Unayzah B sandstones possess compositions similar to those of the associated Unayzah C sandstones, and are similarly interpreted as resulting from the mixing of moderate to high MZi sands sourced from the southwest with low-MZi sands sourced from Lower Paleozoic sandstones exposed to the west. In well 3, all the sands are of low-MZi type, indicating that the high-MZi sands did not reach that location.

All but one of the Unayzah B sandstones of well 22 (Hilwah field) plot in an entirely separate field from the remainder of the western margin sandstones. These sandstones are chloritoid-bearing and, as discussed in an earlier section, probably originated by reworking of diamictite sand components. This interpretation is supported by the close similarity in composition between eight of the sandstone samples and four of the diamictite samples in wells to the south (wells 1 and 17). One sample, from the top of the well 22 section, differs in possessing very low RZi values. This sandstone was probably derived from lower Paleozoic sandstones exposed to the west. The diamictite samples from well 16 plot closer to the main group of Unayzah B sandstones, as do the diamictite samples of well 49, far to the southwest. It thus appears that at least two distinct diamictite types are present, presumably representing separate influxes of sediment-laden ice. It is not clear whether these represent separate periods of ice influx or the development of separate streams of floating ice during a single phase of ice influx. The latter seems more likely, however, in view of the similarity in age (lower P4U zone) of the diamictites in wells 1 and 16 (see Figure 10).

The Unayzah B sandstones of southeastern and southern wells (Figure 21d) mostly have higher MZi and RZi values than the associated Unayzah C sandstones, indicating a change in source.

Plots of RZi against ATi values (**Figure 22**) demonstrate that the bulk of the Unayzah B sandstones are of UNZ2-type, with ATi values greater than 1. This provides confirmation that that the most of the Unayzah B sandstones cannot have been derived through the reworking of Unayzah C sands but must represent new sand influx. Sandstones that lack UNZ2-type signatures occur in western margin wells (especially well 3) and in wells in the southeast-central part of the study area, where they form relatively thick sandstone bodies (e.g. wells 9 and 33: Figure 9). Those in the west were probably derived from Lower Paleozoic sandstones exposed to the west. Those in southeast-central wells cannot have been derived from the south, where all the sands are of UNZ2 type. They are therefore believed to be of local derivation, which is compatible with their interpretation by (Melvin and Sprague, 2006) as sublacustrine gravity-flow deposits. A plot of RZi/MZi values for individual wells in this area (**Figure 23**) shows that they possess distinctly different provenance signatures. The sandstones of well 9 have signatures similar to Devonian sandstones of the Ghawar area (Figure 20b) and were therefore most likely derived from Upper Paleozoic sandstones. This is supported by the occurrence of Cm palynofloras in the underlying mudstones. Those of wells 10 and 33 display significantly lower RZi values and were most probably derived from Lower Paleozoic sandstones (see Figure 20d). The relatively high proportion of apatite-bearing sandstones in wells 10 and 33 may be inherited from Lower Paleozoic succession, which includes a higher proportion of apatite-bearing sandstones than the Devonian succession (**Figure 24**).

A plot of MZi against ATi values for the Unayzah B sandstones (**Figure 25**) shows that sandstones with the highest MZi values possess very low ATi values, while sandstones with very high ATi values possess very low MZi values. Sandstones with both low MZi and ATi values are also present. This pattern is interpreted as representing the mixing of three end-member sand types. (1) Sands with very low MZi values (0–2) and ATi values less than 1. These were probably derived from nearby Lower Paleozoic sandstones. (2) Sands with very low MZi values and ATi values ranging from 1 to 55. These compositions are lacking in the Unayzah C Member and the sandstones are therefore interpreted as representing a new sand influx associated with the onset of Unayzah B sedimentation. Since the high-ATi sandstones are most prominent in southern wells (Figure 22) the influx is presumed to have been from the south. (3) Sandstones with MZi values ranging from 2 to 9 and ATi values less than 1. These have MZi and ATi values similar to those of the UNZ3-type Unayzah C sands of southwestern and northwest central wells and could represent either continued supply of sand from the same southwesterly source or reworking of Unayzah C sands. Reworking seems unlikely for the Unayzah B sands of the Wudayhi field and well 5, however, since they possess significantly lower average RZi values than the underlying Unayzah C sands. They also display a much wider range in MZi values than would be expected to result from reworking (and hence homogenization) of Unayzah C sands. They are therefore interpreted as representing renewed influx of moderate to high MZi sands during Unayzah B sedimentation.

It thus seems likely that Unayzah B sand sedimentation was dominated over much of the region by continued supply of far-travelled, low-RZi, high-MZi sands (UNZ3-type) from the southwest (**Figure 26a**), coupled with a new supply of far-travelled sands with low to moderate RZi values and moderate to high ATi values (UNZ2-type) sands from the south (**Figure 26b**). As during Unayzah C sedimentation, eastward influxes of low-MZi UNZ3-type (apatite-free) sands occurred along the western margin of the basin. Sands with high RZi values (well 22) also occur locally in western margin wells and sands with very high RZi values have been recorded from wells 12 and 41. These presumably represent further minor influxes from the south. The complex pattern of sand supply in the western margin area is a reflection of the localised distribution of different stratigraphic units within the Unayzah B succession (see Figure 10) as well as the interaction between three separate sand influxes.

The influx of high-MZi sands extended northwards to the western margin of the Ghawar structure, reaching at least as far as well 5. The sediments of well 5 have been shown to consist almost wholly of massive diamictite (Melvin and Sprague, 2006, p. 140), indicating that the high-MZi sands were transported northwards by floating ice. It may be noted that the diamictite lacks chloritoid and has lower MZi values and lower average ATi values than the chloritoid-being diamictite of wells along the western margin. The diamictite of well 5 is therefore of separate provenance. The anomalously thick accumulation of southerly derived sediment in well 5 may have resulted from an accumulation of ice at that location, perhaps within an embayment closed to the north. Conversely, the absence of Unayzah B diamictite in nearby wells indicates that they lay outside the area of ice accumulation.

The complexity of sand supply displayed by the Unayzah B succession is undoubtedly related in part to the wide range of depositional facies represented. These include fluvial sandstones, glaciolacustrine gravity-flow sandstones, aeolian sandstones and various types of mud-rich diamictite (Melvin and Sprague, 2006, figure 17). This range in facies indicates the potential for interplay between deposition of sediments of distant and local derivation. As discussed above, the development of intrabasinal structural highs may have been responsible for the variable development of sand bodies in the southeast-central part of the study area.

Unayzah A and ‘un-named middle Unayzah’ members. Sand compositions in these two member fall into three distinct groups: the low-RZi sands of UNZ1A (**Figure 27a**), the generally high-RZi sands of UNZ1B (**Figure 27b**),) and the highly localised high-MZi sands (**Figure 27a**).

The UNZ1A sands, which are associated with low-GR sandstone units, display very consistent index values compared with those of unit UNZ1B or indeed any other Unayzah sandstones, being characterised by low to very low RZi values and, with one exception (well 17), by very low to zero MZi values (**Figure 27a**). They also possess extremely low ATi values (**Figure 27c**). Their typically low eZi values suggest derivation from pre-existing mature sandstones, coupled with abrasion during aeolian transport. A comparison of index values of those obtained for pre-Permian sandstones of the region indicates that the UNZ1A sandstones were probably derived from Lower Paleozoic formations, particularly the low-MZi Saq Formation (see Figure 20c). Such sandstones form an extensive Permian subcrop around the flanks of the Central Arabian Arch (see McGillivray and Husseini, 1992, figure 9; Abu-Ali and Littke, 2005, figure 1). This provenance is compatible with the prevailing eastward wind direction inferred from cross-bedding in the aeolian UNZ1A sandstones (Heine et al., 2006) and with the regional decrease in UNZ1A sandstone thickness to the southeast (Figure 12).

It seems unlikely that the UNZ1A-type sands of Unayzah A were far travelled, since minor geographic and stratigraphic variations in RZi values indicate a lack of homogenization of sand compositions. Some of the UNZ1A sandstones are aeolian and were presumably brought into the area by prevailing winds from the west. Others are of fluvial origin and were brought into the area by streams draining the Central Arabian Arch. The occurrence of very low eZi values in the fluvial sandstones suggests that they may have been derived by reworking of previously deposited aeolian sands.

The UNZ1B sandstones are associated with mudstone-dominated successions that represent deposition in extensive playa lakes and with in fluvial settings. They are characterised by a wide range in RZi values (**Figure 27b**), with an average RZi value higher than in any other of the Permian sandstones. Since none of the pre-Permian sandstones of the region display such high RZi values (see Figure 20), the high-RZi UNZ1B sands must have been derived from a distant source, probably to the south. Many of the UNZ1B sandstones display moderate to high ATi values (**Figure 27d**), representing the peak in ATi values displayed in the lower part of the UNZ1 succession. MZi values in the UNZ1B sandstones are generally low (**Figure 27b**), but four samples from wells 16 and 17 possess higher than normal values, indicating minor input from the high-MZi sand source that supplied the high-MZi UNZ1A sands in the incised valley fill of well 17 (see below).

The standard (pre-incision) UNZ1 succession is therefore seen as representing an interplay between regionally distributed high-RZi (UNZ1B) sands supplied from the south and low-RZi (UNZ1A) sands supplied from the west. Variation in RZi values within the UNZ1 succession may be seen as reflecting variation in the relative input from these two sources. Since the UNZ1B sandstones are associated with more mudstone-rich sections, it seems likely that they represent periods of relatively high lake level and reduced fluvial or aeolian sand influx.

Samples with distinctively high ATi values are present at the base of the UNZ1 section in wells 1 and 25. They plot very close to the diamictites of well 49 (see Figure 22) and thus probably represent the reworking of distant Unayzah B equivalents during the earliest stages of UMU member sedimentation.

Unayzah A sandstones associated with pre-Khuff incised valley fills are mostly indistinguishable mineralogically from the laterally extensive sandstone units. The UNZ1A sands of wells 3, 6 and 25 (see Figures 10–12) are thus likely to have been derived either by reworking of previously deposited UNZ1A sands or by continued sand supply from the same source rocks. In well 17, however, the high-MZi values indicate derivation from a different, presumably local source. The UNZ1B sandstones that occur within the incised valleys are associated with relatively muddy units. They were probably deposited when a rise in base level led to drowning of the Unayzah or pre-Unayzah outcrops that had previously supplied the UNZ1A sands. They are presumed to represent renewed sand influx from a southerly source.

Continental UNZ0 sands are present only in wells 25 and 40 (see Figures 10 and 12). The relative abundance of euhedral zircons indicates increased sand supply from crystalline basement rocks. These sandstones are associated with mudstone-dominated successions, indicating that the increased proportion of basement-derived sand was associated with a reduction in sand supply. This is attributed to a rise in lake level causing inundation of the low-lying Lower Paleozoic outcrops that had previously sourced the UNZ1A-type sands. The relationship between these continental UNZ0 sands and the marine UNZ0 sandstones of the Basal Khuff Clastics is discussed in the following section.

The mineralogy of the Unayzah sandstones that underlie the basal Khuff unconformity is shown in **Figure 28**, along with the inferred provenance for all sands of the Unayzah and un-named middle Unayzah members.

Basal Khuff Clastics. Sandstones within the Basal Khuff Clastics commonly possess UNZ0 (high-eZi) signatures. UNZ0 sandstones are for the most part restricted to western marginal sections, but are also recorded from sections in the south and east of the study area (**Figure 29**). The high eZi values indicate that their source rocks included a significant component of crystalline basement rocks. The UNZ0 sandstones that occur along the western margin of the basin were clearly derived from the adjacent Arabian Shield. Although no heavy mineral data are available from present-day exposures on the Shield, samples from nearby shallow subsurface basement sections have yielded zero RZi and MZi values and strongly contrasting pZi values (**Figure 30a, b**). These few subsurface samples are unlikely to be representative of the full range of potential source rocks on the Shield. Nevertheless, the very low RZi values displayed by the UNZ0 sandstones in the north and west (**Figure 30c**) indicate that basement rocks made a substantial contribution to the UNZ0 sands. The unusually high pZi values recorded from one of the UNZ0 units in well 25 can also be matched with one of the basement samples (**Figure 30b, d**). The UNZ0 sandstones of southern and eastern wells (**Figure 30 e, f**) were probably also derived in part from basement rocks, although the source area is not known.

There is no substantial difference between the compositions of the marine and continental sandstones in the two areas, indicating that no substantial change in palaeogeography occurred between the latest phase of Unayzah A sedimentation (including filling of incised valleys) and the onset of marine Basal Khuff Clastics sedimentation.

The continental sandstones of well 25 possess very high ATi values, similar to that obtained from a single data point for the basement rocks in well 18 (**Figure 31a, b**). These high values indicate derivation from unweathered source rocks. The very low (mostly zero) ATi values for the remainder of the UNZ0 sandstones, including the marine sandstones of well 25, indicates that these were derived from deeply weathered basement rocks.

UNZ1A sandstones that occur within the Basal Khuff Clastics in wells 1 and 4 (Figures 14, A2) were probably derived by reworking of Unayzah A sands or from pre-Unayzah sandstones exposed on local structural highs.

RELATIONSHIP BETWEEN HEAVY MINERAL UNITS AND DEPOSITIONAL PHASES

The lithostratigraphic subdivisions of Melvin and Sprague (2006) are based on the recognition of successive changes in lithofacies within the Unayzah Formation. Each of the members that they defined was thus associated with a specific environmental setting: the Unayzah C Member with deposition on an extensive glaciofluvial outwash braidplain, the Unayzah B Member to deposition within glacial push-moraines, ice-proximal outwash fans and ice-distal glacial lakes, the un-named middle Unayzah member to deposition on low-lying alluvial floodplains, and the Unayzah A Member to deposition under relatively arid conditions in aeolian dune fields and ephemeral rivers. A correlation between heavy mineral signatures and specific depositional environments is beyond the scope of this paper, but the following general observations may be made.

The Unayzah C Member is characterised by monotonous successions of quartzose sandstone, which is for the most part reflected in equally monotonous heavy mineral profiles. The only exception to this is in the western part of area, where southerly-derived high-MZi sandstones interfinger with southwesterly-derived low-MZi sandstones. A key feature of the Unayzah C sandstones is the scarcity of apatite, reflected in the extremely low ATi values, whereas the majority of Unayzah B sandstones are of apatite-bearing, UNZ2 type (Figure 22). Such a strong contrast can have only two explanations: (1) derivation from different source rocks or (2) derivation from the same source rock but under very different climatic conditions. It is generally agreed (e.g., Senalp and Al-Duaiji, 2001; Al-Husseini, 2004; Melvin and Sprague, 2006) that both the Unayzah C and Unayzah B sands were deposited under cold conditions. The absence of apatite in the Unayzah C sandstones cannot therefore be attributed to weathering since apatite is relatively stable under cold conditions and under conditions of rapid erosion and deposition (Morton and Hallsworth, 1999; Mange and Wright, 2007 and references therein). Accordingly, for these sandstones to represent glacial outwash deposits, as proposed by Senalp and Al-Duaiji (2001), Al-Husseini (2004) and Melvin and Sprague (2006), they would have to have been derived from a separate glacier system from the one that supplied the UNZ2 diamictites of the Unayzah B member. Since both the Unayzah C and Unayzah B sediments appear to have been derived from sources to the south, this does not seem likely. The interpretation favoured here is that deposition of the Unayzah C sands preceded the onset of glaciation in the Arabian region and represents a cold-climate pluvial phase. Under such a climatic regime, rapid erosion of deeply weathered pre-Unayzah Paleozoic sandstones exposed to the south of the Peninsular region would have led to the development of a major northward-flowing braided fluvial system, with the thickest sand accumulations taking place in topographic lows on the eroded pre-Unayzah surface (McGillivrayand Husseini, 1992).

The relatively complex mineralogy displayed by the Unayzah B sands reflects of the diverse nature of the component lithofacies, as described by Melvin and Sprague (2006). While the sampling for this study was not focused on individual lithofacies, it is apparent that the glacigenic diamictite deposits are characterised by UNZ2-type sands supplied from the south, whereas the lacustrine gravity-flow deposits (including those of wells 9 and 10) are typically composed of UNZ3-type sands. The latter were probably derived from pre-Unayzah sandstones exposed on nearby structural highs.

The Unayzah A/B boundary was interpreted by Melvin and Sprague (2006) as disconformable, and marking a long-term shift to drier conditions within the depositional area. A lowered lake level at this time may have been responsible for an increase sand supply from the Central Arabian Arch, reflected in the low RZi values that define the base of unit UNZ1 and that appears to mark the base of the UMU member. The subsequent upward increase in RZi and ATi values is interpreted as indicating an increase in the supply of sands from the south, probably in response to a rising lake level. The data are insufficient to establish whether the base of the Unayzah A Member is associated with a distinctive heavy mineral signature, but the upward increase in ATi values within the UNZ1B section may reflect a drier climate, and hence less meteoric leaching, within the source area. The apparently abrupt loss of apatite in the uppermost part of the UNZ1B succession (at the ATi marker) may reflect a change to a more humid climate, although this appears to be at odds with the occurrence of aeolian facies in the overlying UNZ1A sandstones. Possible explanations are (1) that a brief period of more humid climatic conditions preceded the onset of widespread UNZ1A sand deposition or (2) that base of the main UNZ1A sand unit marks a hiatus and that the low-ATi UNZ1B section was originally thicker.

The UNZ1A sandstones that overlie the ATi marker form a semicontinuous sheet over most of the study area. During this time, sediment supply was dominantly from Lower Paleozoic sandstones exposed to the west. Although the bulk of the sands are in fluvial or aeolian facies, sedimentological studies have shown that in several sections UNZ1A-type sandstones occur within incised valley fills and thus represent a separate phase of sedimentation. No different in heavy mineral signatures is apparent, however.

The occurrence of UNZ1A-type sandstones within incised valley fills and a the base of some Basal Khuff Clastics sections means that that it is not possible to identify a clear-cut mineral stratigraphy for the youngest part of the Permian sandstone succession. Heavy mineral signatures do, however, serve to distinguish between the UNZ1A-type sands, representing continued supply or reworking of Unayzah A sands, and UNZ0-type sandstones, which include material derived from crystalline basement rocks. They also revealed the distinctive nature of the mineral succession within the continental incised valley fills of wells 17 and 25 (Figure 10), in particular the presence of continental UNZ0-type. A comparable continental succession (with UNZ1A sandstones overlain by continental UNZ0 sandstones in well 25. Comparable continental UNZ0-type sandstones are present at the top of the Unayzah succession in wells 39 and 40, in the east of the study area (see Figure 12). It is possible that these widely separated successions represent the same period of regional aggradation whose deposits are preserved only in incised valleys (in the west) and areas of greatest subsidence (in the east).

The incised valley fill of well 3 (Dilam field) differs from those of wells 17 and 25 in lacking UNZIB-type sands. The UNZ1A-type sands are overlain by sands with eZi values intermediate between those of UNZ1A and UNZ0, indicating that the switch from UNZ1A-type sand supply to UNZ0-type sand supply was more gradual than in well 25.

Within the marine Basal Khuff Clastics, heavy mineral signatures allow the mapping out of the basement-derived UNZ0-type sandstone derived in the west and southeast of the study area (Figure 29). The increase in the proportion of basement-sourced sands is believed to reflect reduction in the area of exposure of pre-Unayzah Paleozoic sandstones in response to rising sea level.

Most of the UNZ0 sandstones have extremely low ATi values, indicating that the basement source rock must have been deeply weathered. This may indicate a continuation of the more humid climate that led to the disappearance of apatite from the UNZ1B-type sandstones, including those within the incised valley fills of wells 17 and 25. The one exception is the occurrence of very high ATi values in the continental UNZ0 sandstones of well 25. A possible explanation of this anomaly is that these sands were sourced locally from an unweathered basement source that had become exposed during the valley incision.

RELATIONSHIP BETWEEN MINERAL UNITS AND PALYNOZONES

A summary of the relationship between the heavy mineral units and the palynomorph biozonation is shown in **Figure 32**.

The oldest palynozone, P4, is associated with heavy mineral unit UNZ2, which is broadly equivalent to Unayzah B. The apparent exception in well 1 is believed to be due to incorrect lithostratigraphic assignment, as discussed above). Within the study area, the P4 assemblages mostly belong to the upper division of the zone (P4U). P4L assemblages have been recorded only in the basal part of the zone in well 12, where they are interpreted as reworked. It is also possible that the sparse P4 assemblages of wells 1 and 33 belong to the P4L zone, though the assemblages are too poor to be certain. The only certain in-situ records of the P4L zone are in well 48 immediately south of the study area and in well 49, 500 km to the south. In well 49 (see **Figure A11**) the P4 assemblages are associated with over 900 m of chloritoid-bearing diamictite that has a typical UNZ2 signature. These observations indicate that the entire P4 zone is associated with the Unayzah B Member and that over most of the study area the succession is incomplete, with only the upper part of the member (P4U zone) being represented. Since the marked contrast in mineralogy between units UNZ3 and UNZ2 appears to preclude lateral passage between the two, it seems that a substantial hiatus, spanning the entire P4L interval, exists over most of the study area, as shown on Figure 32. The duration of deposition of the Unayzah C sands is uncertain, but in view of the high-energy nature of the fluvial sands and their remarkable uniformity, it is quite likely that they were deposited in a relatively short period of time.

P3 assemblages have been reported from five wells in study area, of which four have been studied for heavy minerals. The only section to yield good heavy mineral data is that of well 22, in which the P3 zone is mostly associated with UNZ2-type sands. The P3 mudstones extend northwards from well 22 onto the eastern extension of the Central Arabian Arch (**Figure 33**), where they rest directly on Lower Paleozoic sediments. This indicates that they were deposited at a time of high sea level. P3 assemblages have also been recognised in well 43, some 700 km farther to the northwest. A notable feature of the distributions of the P3 and P4 records is that they are mutually exclusive. No section has been found that includes both P3 and P4 sections. While the absence of P4 sections beneath the P3 sections can be explained by non-deposition prior to transgression of marginal areas, the absence of P3 assemblages in the more basinal areas is less easy to explain. The P3 assemblages cannot be lateral equivalents of the P4 assemblages since comparable assemblages in Oman (OSP3b-4 and OSP2, respectively) are clearly separated in time (Stephenson et al., 2003).

Melvin and Sprague (2006, p. 144) state that P3 assemblages are associated with 'Unayzah A depositional facies'. In well 22, however, they occur in mudstones that are dominantly grey, with minor salmon-pink coloration. Further to the north, in wells 4, 29, and 30 (**Figure A2),** P3 assemblages are associated with dark grey mudstones. In all of these wells, the top of the P3 interval coincides with an upward change from grey to red sediments, which Melvin and Sprague (2006, p. 143) identify as characterizing the base of the UMU member. It is may be for this reason that the P3 mudstones of well 4 were assigned by Melvin and Sprague (2006, figures 8, 23) to the Unayzah B Member.

The P3 sediments examined in this study thus appear to lie between P4 sediments assigned to the Unayzah B Member and red-bed sediments typical of the UMU member. As the contrast in climatic signature indicates a separation in time between the P3 and P4 depositional phases, the P3 sediments are here placed above the unconformity that Melvin and Sprague (2006) recognise at the top of the Unayzah B Member, but below the base of the UMU member as currently defined. This interpretation implies that a lake existed to the northwest of the study area, extending as far south as well 22. Exposure of Unayzah B sediments to the south of well 22 is implied by the occurrence of UNZ2-type assemblages in all but the uppermost part of the P3 section in the well 22. It is likely that the underlying chloritoid-bearing sands (interpreted as having been derived from chloritoid-bearing Unayzah B diamictite) were also deposited during this phase of sedimentation. As noted above, these sandstones have a mineralogy that is very different from that of nearby Unayzah B sandstones (see Figures 21, 22) and were probably derived from diamictites exposed to the south of the study area.

The occurrence of UNZ1-type assemblages at the top of the P3 section may represent a transition to the provenance pattern of the UMU member, with sand derived from Lower Paleozoic sandstones exposed to the west.

Within the study area, P2L assemblages have been encountered only in well 12, where they are associated with continental mudstones that include thin sandstones of UNZ0 type. The assemblages are similar to those reported from Rawakib-1 (well 46 of this study), which were assigned to the OSPZ5 zone by Stephenson et al. (2003, p. 482). P2U assemblages are widely associated with the marine transgressive deposits of the Basal Khuff Clastics.

DISCUSSION

The stratigraphic synthesis presented in Figure 32 shows the Late Carboniferous to Permian succession of central Saudi Arabia to be highly incomplete compared with that of Oman. Assignment of the Unayzah C Member to the lower and middle parts of the OSPZ1 zone is based on the absence or near absence of the P4L zone within the study area. The certain records of the P4L zone are to the south of the study area, with the P4L section reaching over 700 m 49. In well 48, P4L sandstones of UNZ2-type overlie sandstones with the characteristic UNZ3 signature. This demonstrates that the boundary between unit UNZ3 (Unayzah C Member) and unit UNZ2 (Unayzah B Member) is not diachronous. The absence of the P4L zone over most of central Saudi Arabia must therefore be ascribed to non-sequence.

Interpretation of the Unayzah C Member as pre-glacial dates as within the OSPZ1 palynozone. It may well be equivalent to the braidplain sediments of the Al Khlata P9 production zone (see Osterloff et al., 2004, figure 2), which are also dominated by mature sandstones.

The next significant hiatus is that identified by Melvin and Sprague (2006) between the Unayzah B Member and the UMU member. Resumption of sedimentation following this hiatus appears to have started in the northwest of the region, with the establishment of the ‘P3 lake’. The remainder of the area appears to have been non-depositional at this time, with northward reworking of Unayzah B sediments. The age of the P3 sediments is uncertain, because although the P3 assemblages have are some elements in common with those of the Oman succession, there is no direct match. This led Stephenson et al. (2003) to place the P3 zone within the OSPZ3b–OSPZ3c–OSPZ4 zonal range. This spans the interval of the Haushi Limestone of Oman , which is dated as OSPZ3c (Stephenson, 2008) and which has been shown on faunal grounds to be Late Sakmarian age (Angiolini et al., 2006; Stephenson et al., 2008). In the absence of definitive correlation of the P3 zone with the OSPZ zones, the P3 sediments are here tentatively correlated with the Haushi Limestone, since both units clearly represent a period of high sea-level stand. The P3 section is accordingly shown as Late Sakmarian in age on Figure 32. The UMU member is accordingly shown as earliest Artinskian, the age given to the basal Middle Gharif Member of subsurface Oman (Stephenson et al., 2008, Figure 2b).

The third significant hiatus within the Permian clastic succession is represented by an unconformity that has been identified throughout the study area. This is generally referred to as the ‘pre-Khuff unconformity’ as in most sections it corresponds to the base of the Basal Khuff Clastics. In the western margin area, however, the base of the Khuff Formation has been picked at the base of a series of deeply incised valley fills (e.g. Ferguson and Chambers, 1991; Melvin and Sprague, 2006). The sediments within these fills are dominantly continental and in wells 3 and 25 display an upward transition from sandstones of UNZ1-type (probably derived from Lower Paleozoic sandstones) to sandstones of UNZ0-type (derived mainly from crystalline basement). This is interpreted as marking the progressive indundation of the lower-lying Paleozoic outcrops, with exposure becoming increasingly restricted to basement uplands. The same progression is seen in wells in the east of the study area, with thin UNZ1A sands overlain by continental, mudstone-dominated sediments with minor UNZ0-type sandstones. In well 12, the mudstone-dominated sediments have yielded P2L (OSPZ5) assemblages, indicating equivalence with the Upper Member of the Gharif Formation of subsurface Oman. The Upper Gharif Member is conformably overlain by the Khuff Formation (OSPZ6 zone), but rests unconformably on the Middle Gharif Member. The unconformity surface includes incised channels 2–3 km wide and up to 20 or possibly as much as 50 m deep (Osterloff et al., 2004, p. 114). As illustrated by Osterloff et al. (2004, figures 3, 5, *et seq*.) the Upper Gharif Member is relatively sand-rich and rests on (or incises) a widespread mudstone unit that forms the uppermost part of the Middle Gharif Member. By analogy, the equivalent, presumably unconformable, boundary in the east of the study area most likely lies at the base of the thin UNZ1A sandstone unit that occurs beneath the UNZ0 unit in wells 29 and 40 and is inferred to underlie the P2L section in well 12 (see Figure 12). This UNZ1A sandstone unit overlies a mudstone-rich UNZ1B section that may equate with the mudstone unit at the top of the Middle Gharif Member. The UNZ1A sand unit is thickest in well 9 and thins rapidly to the southeast, indicating that the sands most originated through reworking of Unayzah A sections exposed to the west and north.

In the east of the study area, therefore, the base of the Khuff Formation may well be conformable, as in Oman, with any regional unconformity generated some 10 million years before the Khuff marine transgression, at the end of Middle Gharif sedimentation. This implies that the incised channels identified in western margin sections also developed long before the Khuff transgression and that their continental fills are time-equivalent to the Upper Gharif succession of Oman. This interpretation is supported by the complex provenance history displayed by the channel fills, which implies accumulation over an extended period of time. It may therefore be inappropriate to apply the term ‘pre-Khuff unconformity’ to the channel incision surface

CONCLUSIONS

Heavy mineral analysis has provided new insights into the stratigraphy of the sandstone succession in the Unayzah Formation and Basal Khuff Clastics of central Saudi Arabia. The heavy mineral assemblages reveal stratigraphic trends related to changes in sea level, climate and tectonic setting, together with geographic trends that reflect different directions of sand influx. The marked changes in regional provenance signature associated with the base of the Unayzah B and un-named middle Unayzah members support the proposal of Melvin and Sprague (2006) for a hiatuses at both levels. The heavy mineral record across the boundary between the Unayzah Formation and the basal Khuff Clastics is more complex, mainly because of erosion and local channelling associated with a fall in sea level that is believed to have taken place some 10 Ma before the Khuff transgression. The associated unconformity is believed to equate with that at the base of the Upper Gharif Formation in Oman.

The heavy mineral units defined in this paper are not consistently chronostratigraphic in nature since they reflect the effects of local sand influx as well as changes in regional sand supply. It is therefore only though integration with sedimentological and biostratigraphic data that the full stratigraphic significance of the heavy mineral data is revealed. Through such integration, heavy mineral data can be used to assist stratigraphic correlation, especially in sections that are uncored or lack biostratigraphic data.

Although this study has focused on the central Saudi Arabia, limited evidence indicates that comparable stratigraphic changes in heavy mineral assemblages occur within the Permian sandstone successions to the north and east. Provenance signatures in these areas are different from those encountered in central Saudi Arabia, but it seems that the mineral successions reflect the same series of tectonic, climatic and sea-level events.

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References

Al-Husseini, M.I. 2004. Pre-Unayzah unconformity, Saudi Arabia. In: M. I. Al-Husseini (Ed.), Carboniferous, Permian and Early Triassic Arabian stratigraphy. GeoArabia Special Publication No. 3, Gulf Petrolink, Bahrain, p. 15–59.

Al-Husseini, M.I. 2006. Permian Arabian tectonostratigraphy chart. GeoArabia, v. 11, no. 4, 95–103.

Al-Laboun, A.A. 1982. The subsurface stratigraphy of the pre-Khuff formations in Central and northwestern Arabia. PhD dissertation, King Abdulaziz University, Jiddah, 102 pp.

Delfour, J.R., R. Dhellemmes, P. Elsass, D. Vaslet, J. Brosse, Y. de Nindre and O. Dottin. 1982. Explanatory notes to the Geologic map of the ad-Dawadimi Quadrangle, sheet 24g. Jiddah, Ministry of Petroleum and Mineral Resources.

Droste, H.H.J. 1997. Stratigraphy of the Lower Paleozoic Haima Supergroup of Oman. GeoArabia, v. 2, no. 4, p. 419–472.

El-Khayal, A.A. and R.H. Wagner 1985. Upper Permian stratigraphy and megafloras of Saudi Arabia: palaeogeographic and climatic implications. Dixième Congrès International de Stratigraphie et de Géologie du Carbonifère, Madrid 1983, Compte Rendu, v. 3, p. 175-194.

Ferguson, G.S. and T.M. Chambers 1991. Subsurface stratigraphy, depositional history, and reservoir development of the Early-to-Late Permian Unayzah Formation in central Saudi Arabia. Proceedings of the 7th Society of Petroleum Engineers Middle East Oil Show, Bahrain, SPE Paper 21394, p. 487–496.

Filatoff, J., M.A. Miller, R. Rahmani and S. Franks 2003. Paleozoic palynostratigraphy, sedimentology and petrography. Saudi Aramco, GLTSD Special Report no. 43 (unpublished).

Hussain, M., L.O. Bababola and M. Hariri 2004. Heavy minerals in the Wajid Sandstone from Abha-Khamis Mushayt area, southwestern Saudi Arabia: implications on provenance and regional tectonic setting. GeoArabia, v. 9, no. 4, p. 77-102.

Heine, C.J., J. Wilkins, J. Melvin, B. Wallick and J. Cole 2004. Geostatistical distribution of eolian facies using a modern analog as a modeling template, Permian Unayzah Formation, Tinat field, Saudi Arabia (Abstract). GeoArabia, v. 9, no. 1, p. 77.

Knox, R.W.O'B., J. Filatoff and J.D. Cocker 2007. Stratigraphic evolution of heavy mineral provenance signatures in the sandstones of the Wajid group (Cambrian to Permian), southwestern Saudi Arabia. GeoArabia, v. 12, no. 4, p. 65–96.

Mange, M. and Wright, D. 2007. Heavy minerals in use. Developments in Sedimentology 58, 1328 pp.

McGillivray, J.G. and M.I. Husseini 1992. The Palaeozoic petroleum geology of central Arabia. American Association of Petroleum Geology, v. 76, pp. 1473–1490.

Melvin, J. & R.A. Sprague 2006. Advances in Arabian stratigraphy: origin and stratigraphic architecture of glaciogenic sediments in Permian-Carboniferous lower Unayzah sandstones, eastern central Saudi Arabia. GeoArabia, v. 11, no. 4, p. 105–152.

Morton, A.C. 1985. A new approach to provenance studies: electron microprobe analysis of detrital garnets from Middle Jurassic sandstones of the Northern North Sea. Sedimentology, v. 32, pp. 553–566.

Morton, A.C. and C.R. Hallsworth 1994. Identifying provenance-specific features of detrital heavy mineral assemblages in sandstones. Sedimentary Geology, v. 90, pp. 241–256.

Morton, A.C. and C.R. Hallsworth 1999. Processes controlling the composition of detrital heavy mineral assemblages in sandstones. Sedimentary geology, v. 124, pp. 3–29.

Owens, B., J. Filatoff, G. Clayton and S. Al-Hajri 2000. Evidence of mid-Carboniferous miospore assemblages from Central Saudi Arabia. In: S. Al-Hajri and B. Owens (Eds), Stratigraphic palynology of the Palaeozoic of Saudi Arabia. GeoArabia Special Publication No. 1, Gulf Petrolink, Bahrain, p. 154–167.

Powers, R.W., L.F. Ramirez, C.D. Redmon and E.L. Elberg Jr. 1966. Geology of the Arabian Peninsula: Sedimentary Geology of Saudi Arabia. United States Geological Survey, Professional Paper 560D, 147 p.

Senalp, M. and A. Al-Duaiji 1995. Stratigraphy and sedimentation of the Unayzah reservoir, central Saudi Arabia. In: M.I. Al-Husseini, (Ed.) Middle East Petroleum Geosciences Conference, GEO’94, Gulf PetroLink, Bahrain, v. 2, p. 837–847.

Senalp, M. and A. Al-Duaiji 2001. Sequence stratigraphy of the ’Unayzah Reservoir in Central Saudi Arabia. Saudi Aramco Journal of Technology, Summer 2001, p. 20–43.

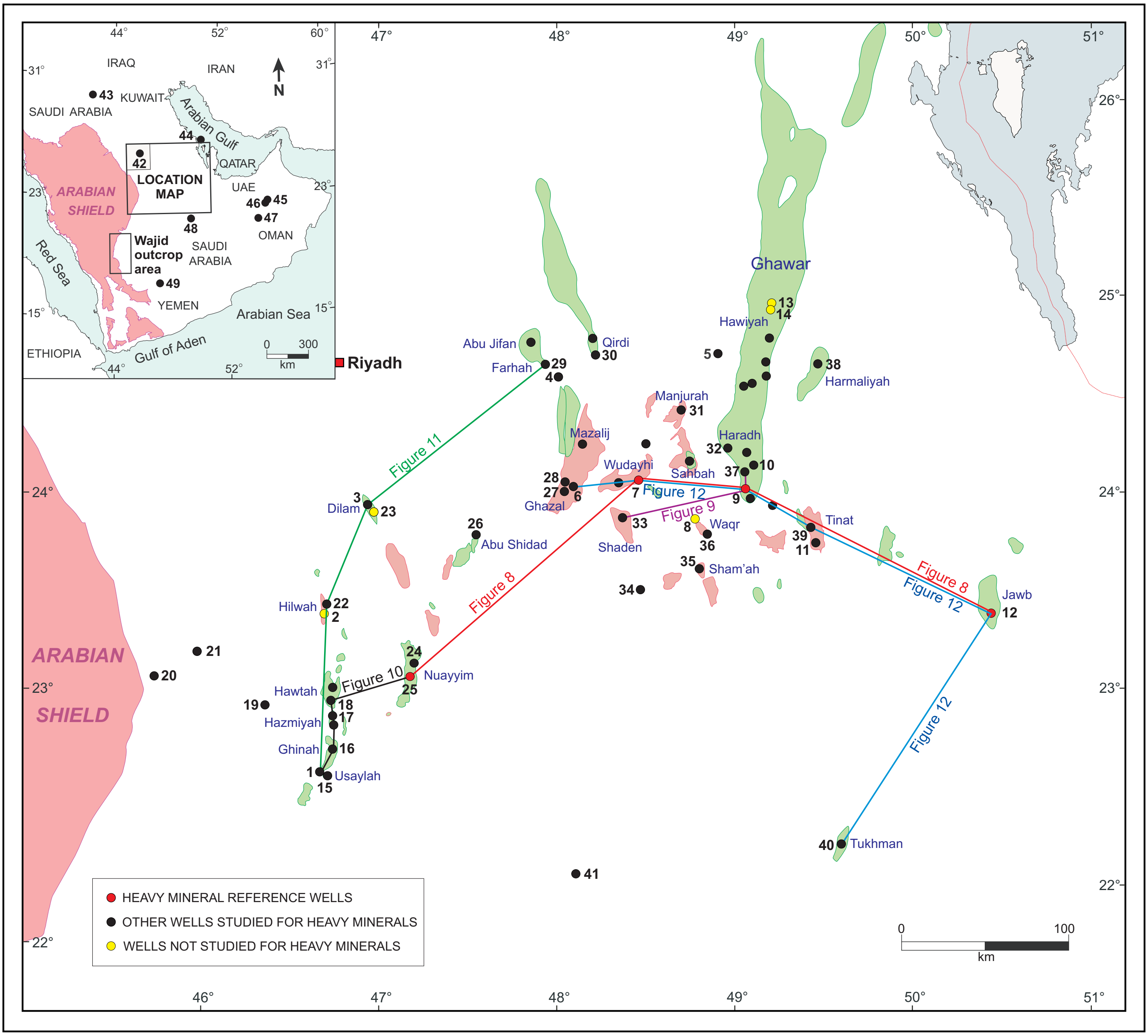
Stephenson, M. H. 2004. Early Permian spores from Oman and Saudi Arabia. . In: M.I. Al-Husseini (Ed.), Carboniferous, Permian and Early Triassic Arabian stratigraphy. In: GeoArabia Special Publication 3, Gulf PetroLink, Bahrain, p. 185–215.

Stephenson, M.H. 2006. Stratigraphic note: Update of the standard Arabian Permian palynological biozonation; definition and description of OSPZ5 and 6: GeoArabia, v. 11, no. 3, 173–178.

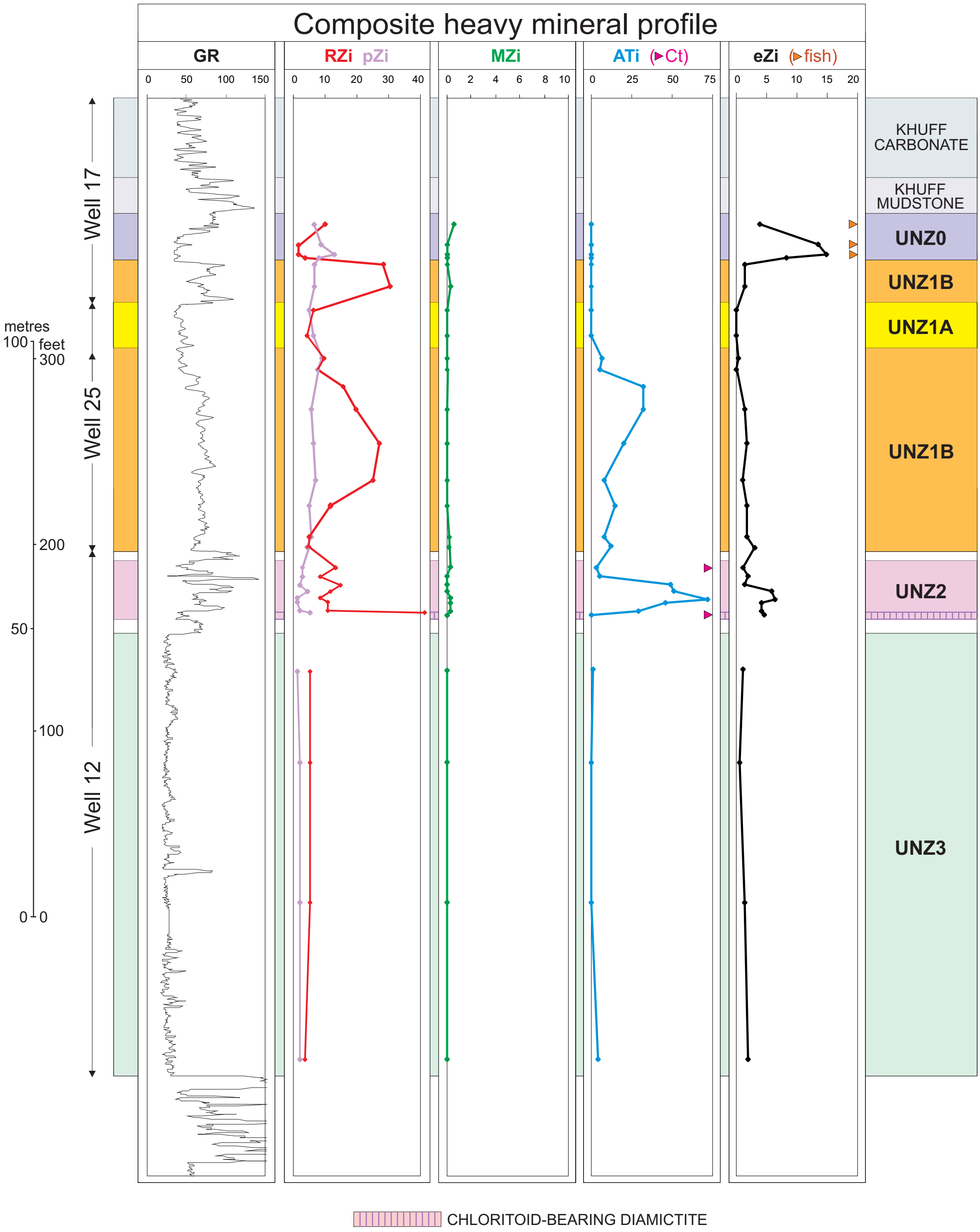
Stephenson, M.H., P.L. Osterloff and J. Filatoff 2003. Palynological biozonation of the Permian of Oman and Saudi Arabia: progress and challenges. GeoArabia, v. 8, no. 3, p. 467–496.

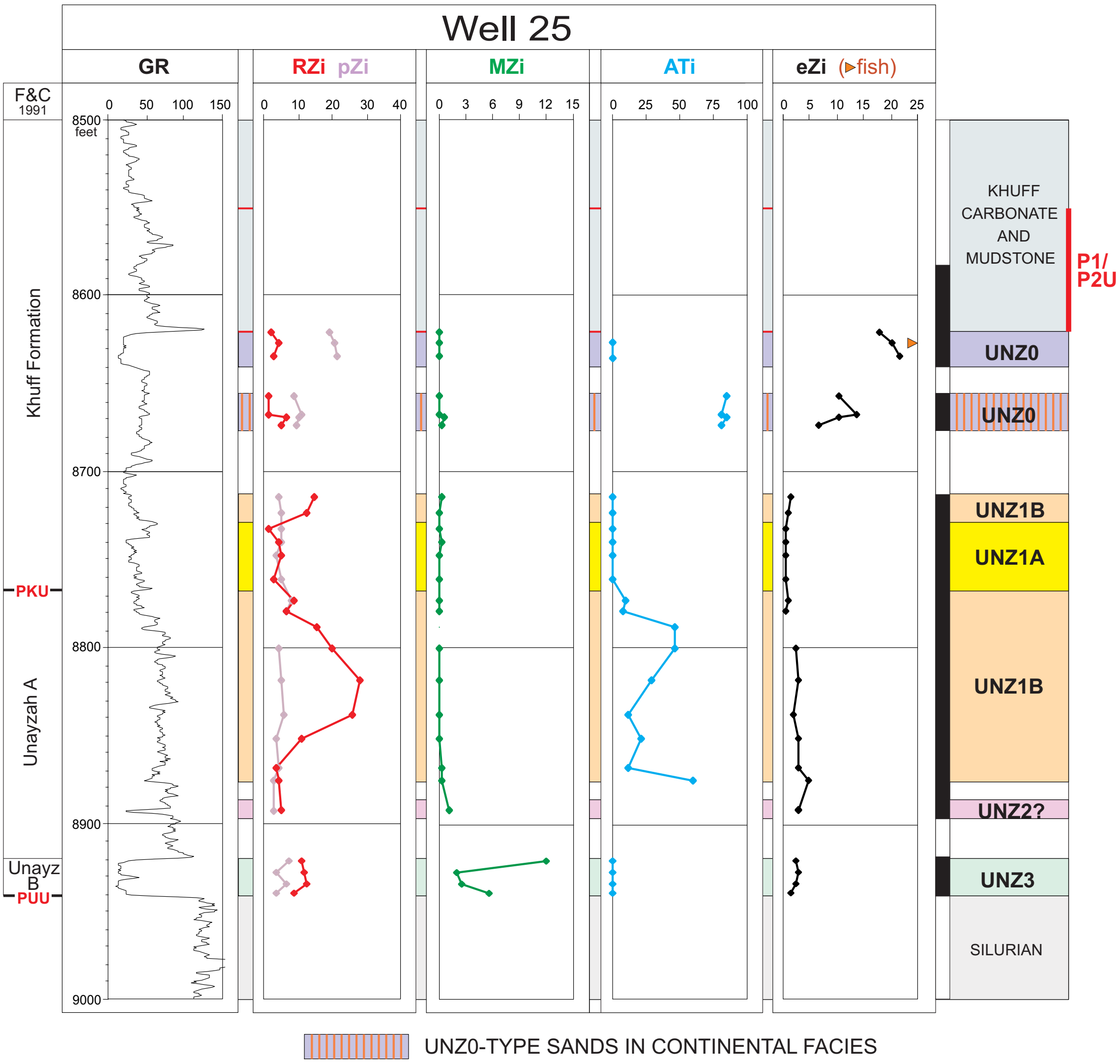
Tanoli, S.K., R. Husain and A.A. Sajer 2008. Facies in the Unayzah Formation and the Basal Khuff Clastics in subsurface, northern Kuwait. GeoArabia, v. 13, no. 4, p. 15–40.

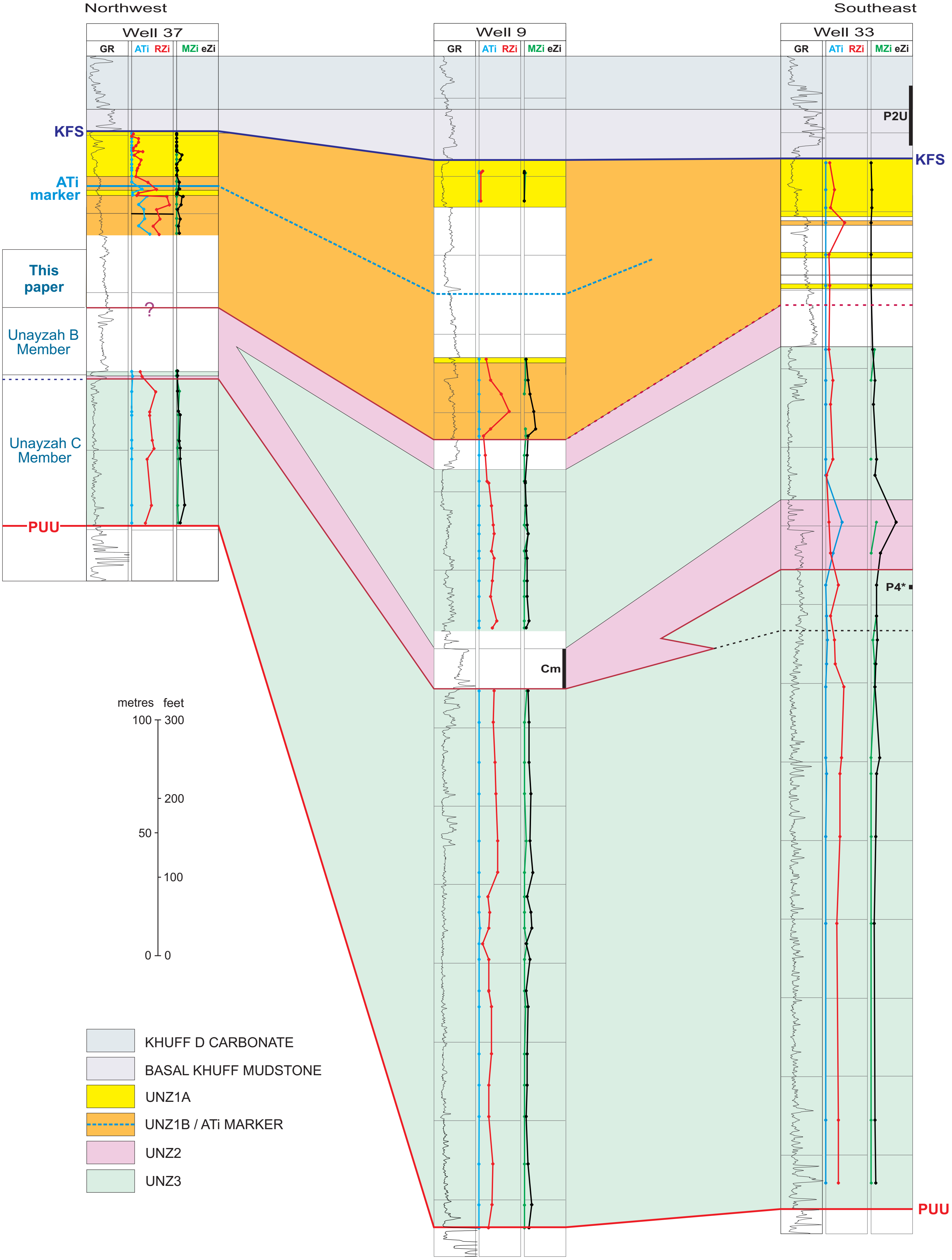
Vaslet, D. 1990. Le Paléozoïque (anté-Permien supérieur) d’Arabie Saoudite. Histoire géologique de la bordure occidentale de la plate-forme arabe. Document du BRGM, no. 191, 209 p.

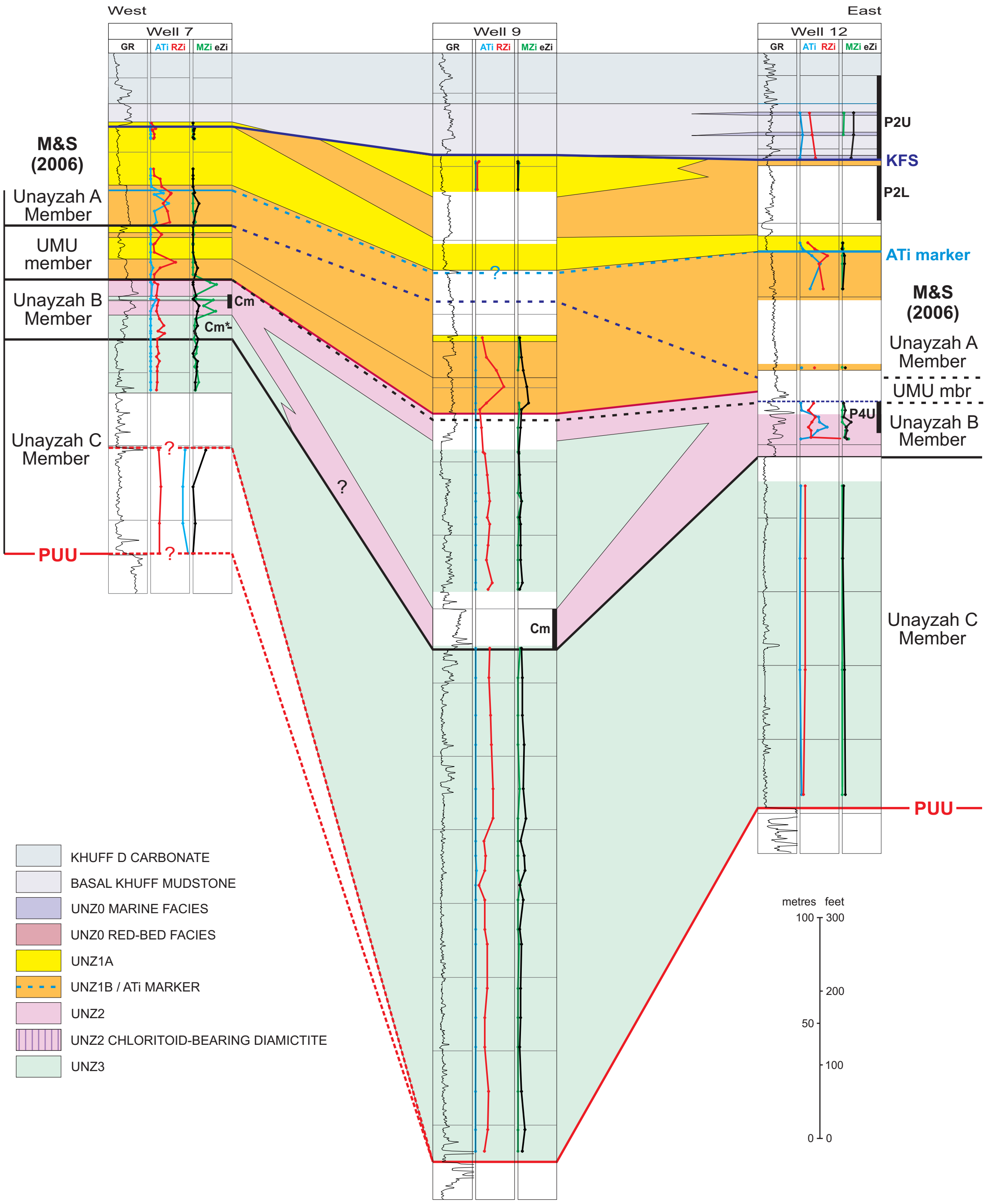

LOCATION MAP
IRAQ
IRAN
KUWAIT
SAUDI ARABIA
Arabian Gulf
QATAR
UAE
OMAN
ARABIAN SHIELD
Red Sea
Wajid outcrop area
YEMEN
Arabian Sea
ETHIOPIA
Gulf of Aden
N
0 300 km
44° 52° 60°
31° 23° 15°
42 43 44 45 46 47 48 49
Riyadh
Ghawar
Hawiyah
Haradh
Harmaliyah
Abu Jifan
Farhah
Qirdi
Manjurah
Mazalij
Wudayhi
Sahbah
Ghazal
Dilam
Abu Shidad
Shaden
Waqr
Sham'ah
Tinat
Jawb
Tukhman
Hilwah
Hawtah
Hazmiyah
Ghinah
Usaylah
Nuayyim
ARABIAN SHIELD
Figure 8
Figure 9
Figure 10
Figure 11
Figure 12
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41
46° 47° 48° 49° 50° 51°
22° 23° 24° 25° 26°
0 100 km
● HEAVY MINERAL REFERENCE WELLS
● OTHER WELLS STUDIED FOR HEAVY MINERALS
● WELLS NOT STUDIED FOR HEAVY MINERALS

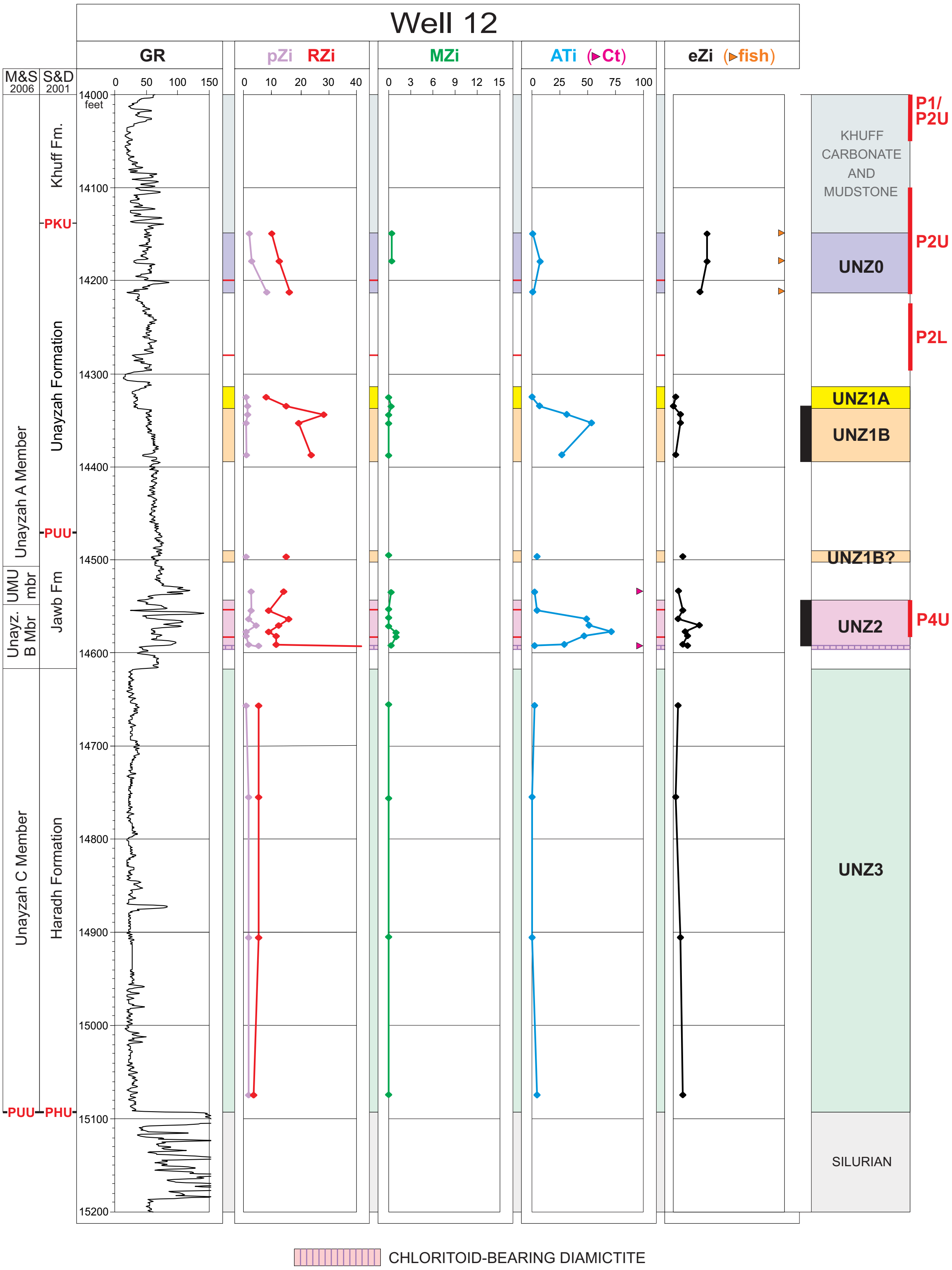
Ma	Stage	Ferguson & Chambers (1991)		Al-Husseini (2004)		**Melvin & Sprague (2006)**	Senalp & Al-Duaiji (2001)	
	CAPITANIAN	**KHUFF FORMATION (part)**	Khuff D	Khuff-D Member	SA P1		KHUFF FORMATION	
			BKC	BKC	SA P2	BKC	ASH-SHIQQAH FM	UNAYZAH RESERVOIR
	WORDIAN ROADIAN KUNGURIAN	PRE-KHUFF UNCONFORMITY					PRE-ASH-SHIQQAH UNCONFORMITY	
	ARTINSKIAN	**UNAYZAH FORMATION**	Unayzah A	Upper Unayzah-A Sub-member		**Unayzah A Member**	UNAYZAH FORMATION	
				Lower Unayzah-A Sub-member	SA P3	**‘un-named middle Unayzah member’**		
	SAKMARIAN		Unayzah B	Unayzah-B Member	SA P4	**Unayzah B Member**	JAWB FORMATION	
	ASSELIAN LATE CARBONIFEROUS		Unayzah C	Unayzah-C Member		**Unayzah C Member**	HARADH FORMATION	
		PRE-UNAYZAH UNCONFORMITY					PRE-HARADH UNCONFORMITY	

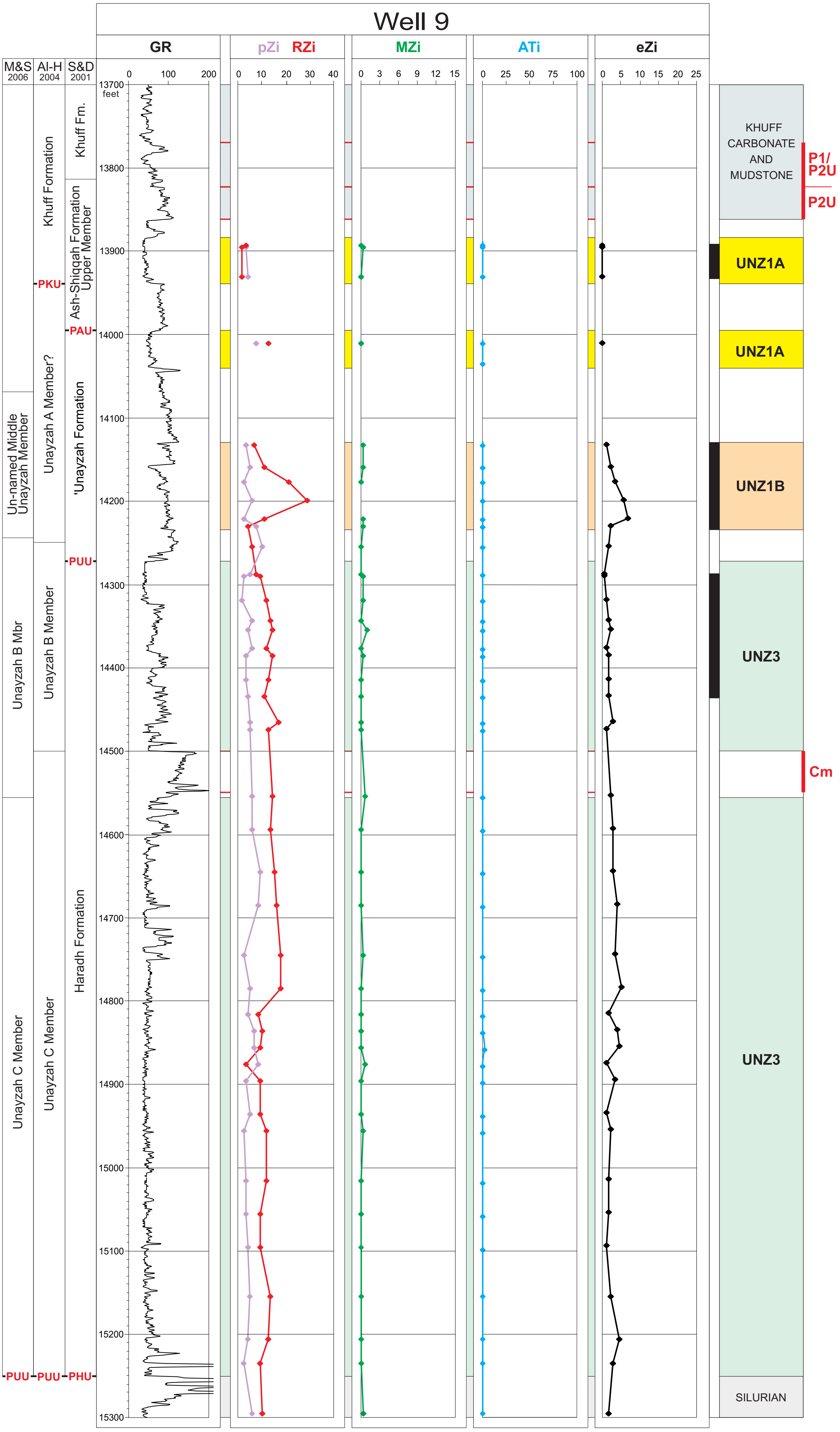

Composite heavy mineral profile
GR
0 50 100 150
RZi pZi
0 10 20 30 40
MZi
0 2 4 6 8 10
ATi (▶Ct)
0 25 50 75
eZi (▶fish)
0 5 10 15 20
metres
feet
100
300
200
50
100
0
0
Well 17
Well 25
Well 12
KHUFF CARBONATE
KHUFF MUDSTONE
UNZ0
UNZ1B
UNZ1A
UNZ1B
UNZ2
UNZ3
CHLORITOID-BEARING DIAMICTITE

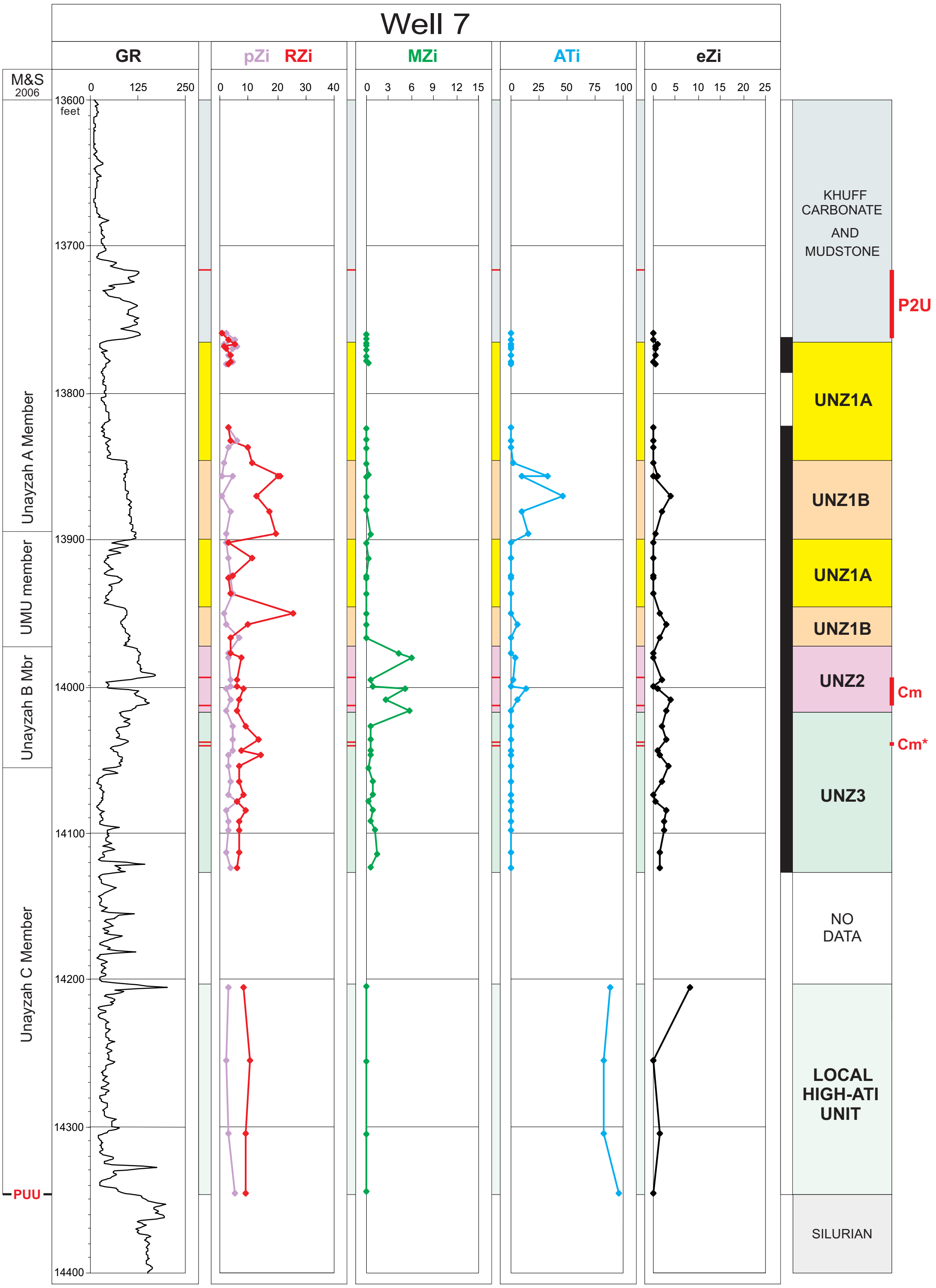

Well 25
GR
RZi pZi
MZi
ATi
eZi (▸fish)
F&C 1991
0 50 100 150
0 10 20 30 40
0 3 6 9 12 15
0 25 50 75 100
0 5 10 15 20 25
8500 feet
8600
8700
8800
8900
9000
Khuff Formation
PKU
Unayzah A
Unayz B
PUU
KHUFF CARBONATE AND MUDSTONE
P1/ P2U
UNZ0
UNZ0
UNZ1B
UNZ1A
UNZ1B
UNZ2?
UNZ3
SILURIAN
UNZ0-TYPE SANDS IN CONTINENTAL FACIES

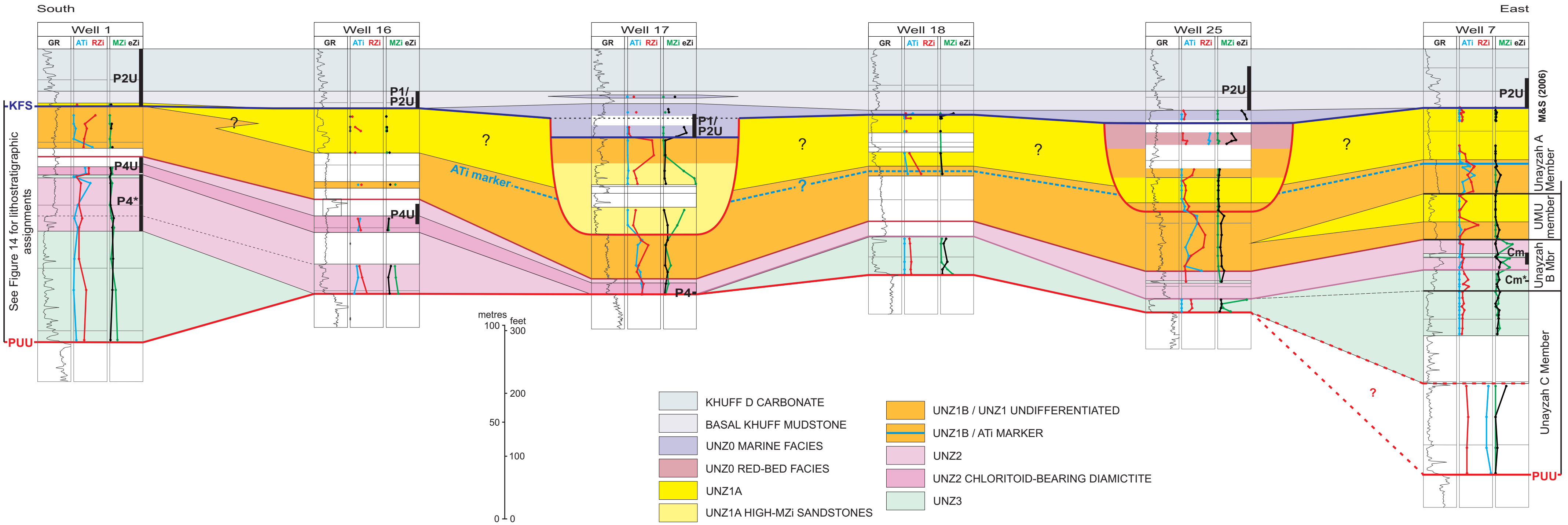

Northwest
Southeast
Well 37
Well 9
Well 33
GR
ATi
RZi
MZi
eZi
KFS
ATi marker
This paper
?
Unayzah B Member
Unayzah C Member
PUU
P2U
KFS
P4*
Cm
PUU
metres
feet
100
300
200
50
100
0
0
KHUFF D CARBONATE
BASAL KHUFF MUDSTONE
UNZ1A
UNZ1B / ATi MARKER
UNZ2
UNZ3

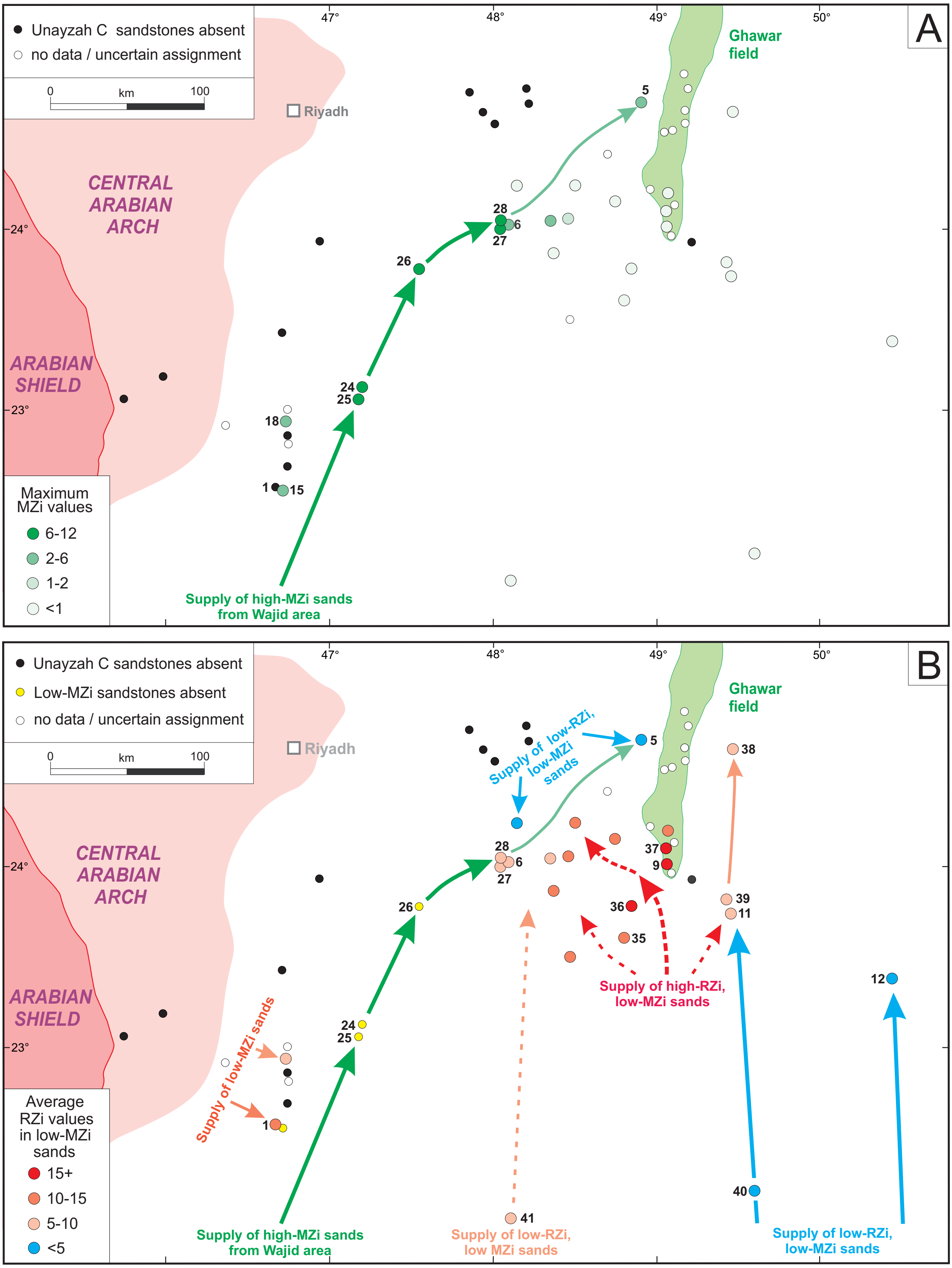

West
East
Well 7
Well 9
Well 12
GR
ATi RZi
MZi eZi
M&S (2006)
Unayzah A Member
UMU member
Unayzah B Member
Unayzah C Member
PUU
Cm
Cm*
?
P2U
KFS
P2L
ATi marker
UMU mbr
P4U
KHUFF D CARBONATE
BASAL KHUFF MUDSTONE
UNZ0 MARINE FACIES
UNZ0 RED-BED FACIES
UNZ1A
UNZ1B / ATi MARKER
UNZ2
UNZ2 CHLORITOID-BEARING DIAMICTITE
UNZ3
metres
feet
100
300
200
50
100
0
0

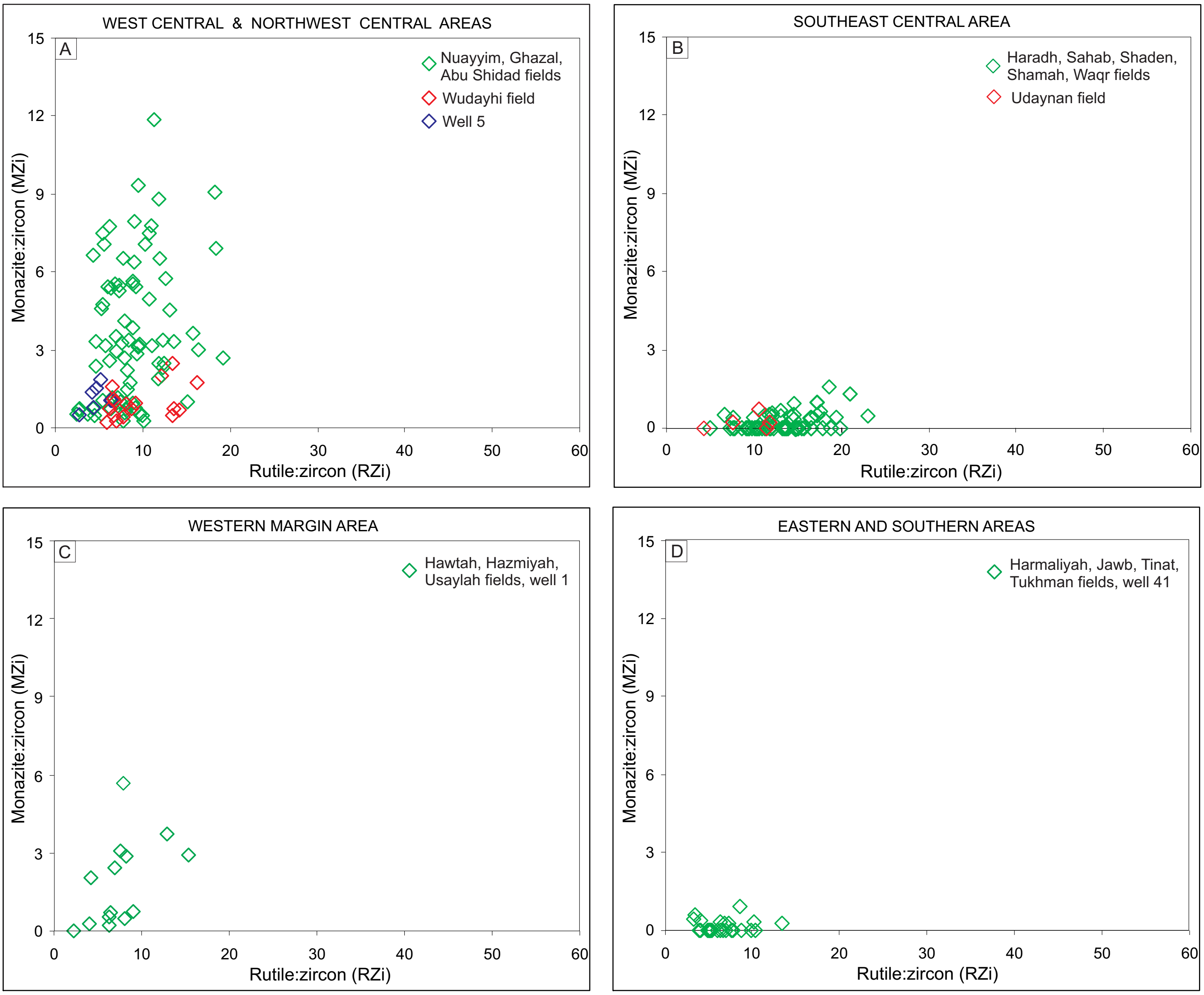

Well 12
GR
pZi RZi
MZi
ATi (▸Ct)
eZi (▸fish)
M&S 2006
S&D 2001
0 50 100 150
0 10 20 30 40
0 3 6 9 12 15
0 25 50 75 100
14000 feet
14100
14200
14300
14400
14500
14600
14700
14800
14900
15000
15100
15200
Khuff Fm.
PKU
Unayzah Formation
Unayzah A Member
PUU
UMU mbr
Unayz. B Mbr
Jawb Fm
Unayzah C Member
Haradh Formation
PUU
PHU
KHUFF CARBONATE AND MUDSTONE
UNZ0
UNZ1A
UNZ1B
UNZ1B?
UNZ2
UNZ3
SILURIAN
P1/ P2U
P2U
P2L
P4U
CHLORITOID-BEARING DIAMICTITE

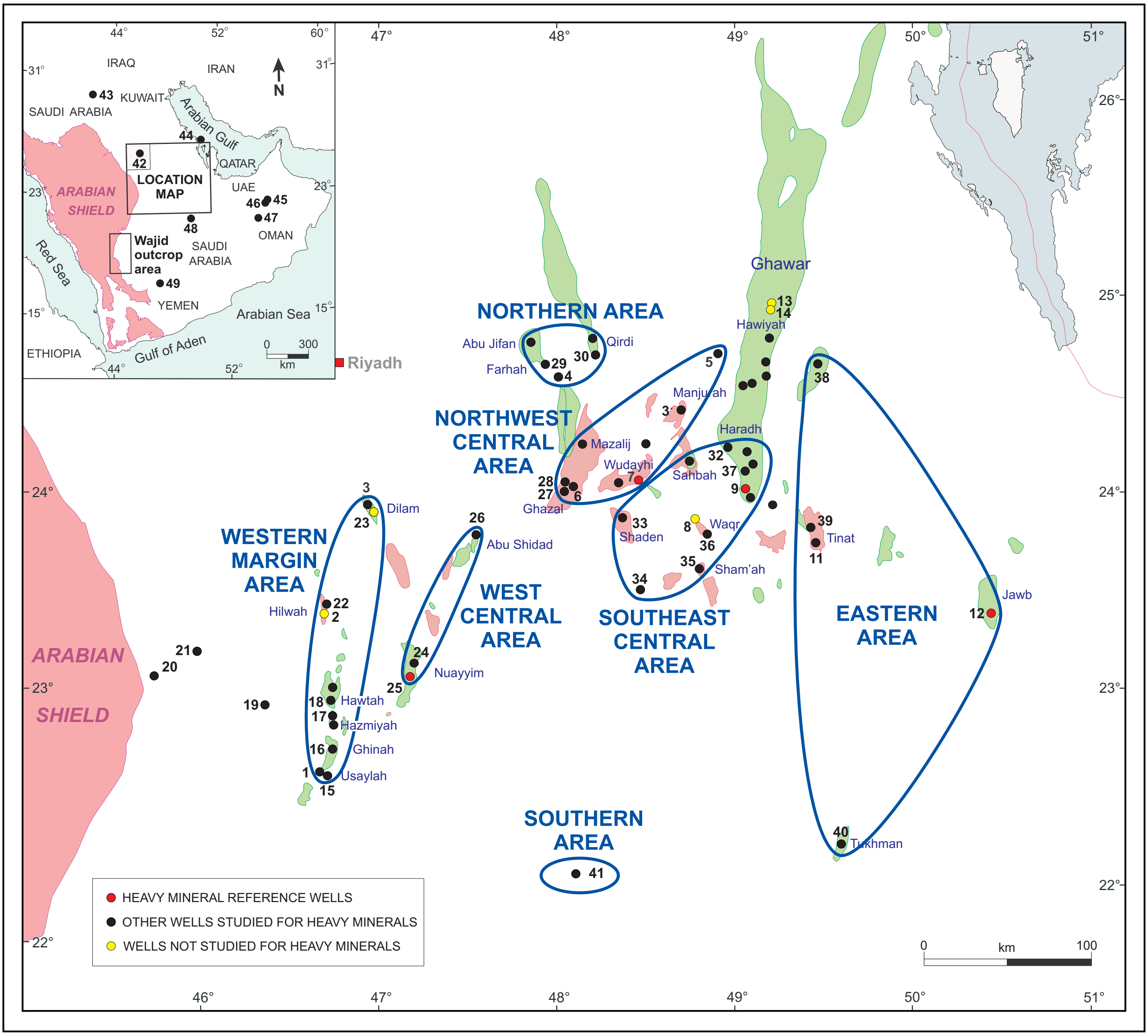

Well 9
M&S 2006
Al-H 2004
S&D 2001
GR
pZi RZi
MZi
ATi
eZi
0 100 200
0 10 20 30 40
0 3 6 9 12 15
0 25 50 75 100
0 5 10 15 20 25
13700 feet
13800
13900
14000
14100
14200
14300
14400
14500
14600
14700
14800
14900
15000
15100
15200
15300
Khuff Formation
Khuff Fm.
Ash-Shiqqah Formation Upper Member
PKU
PAU
Unayzah A Member?
'Unayzah Formation
Un-named Middle Unayzah Member
PUU
Unayzah B Mbr
Unayzah B Member
Haradh Formation
Unayzah C Member
Unayzah C Member
PUU
PUU
PHU
KHUFF CARBONATE AND MUDSTONE
P1/ P2U
P2U
UNZ1A
UNZ1A
UNZ1B
UNZ3
Cm
UNZ3
SILURIAN

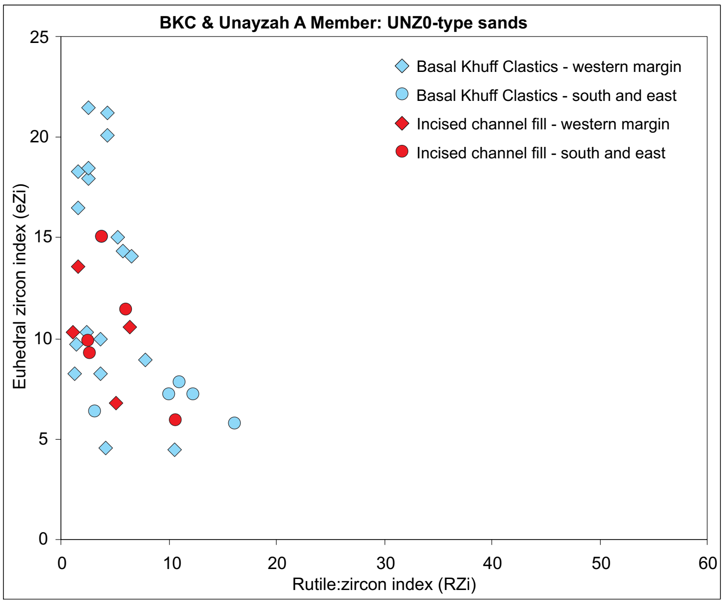

Well 7
M&S 2006
Unayzah A Member
UMU member
Unayzah B Mbr
Unayzah C Member
PUU
GR
0
125
250
13600 feet
13700
13800
13900
14000
14100
14200
14300
14400
pZi RZi
0 10 20 30 40
MZi
0 3 6 9 12 15
ATi
0 25 50 75 100
eZi
0 5 10 15 20 25
KHUFF CARBONATE AND MUDSTONE
P2U
UNZ1A
UNZ1B
UNZ1A
UNZ1B
UNZ2
Cm
Cm*
UNZ3
NO DATA
LOCAL HIGH-ATI UNIT
SILURIAN

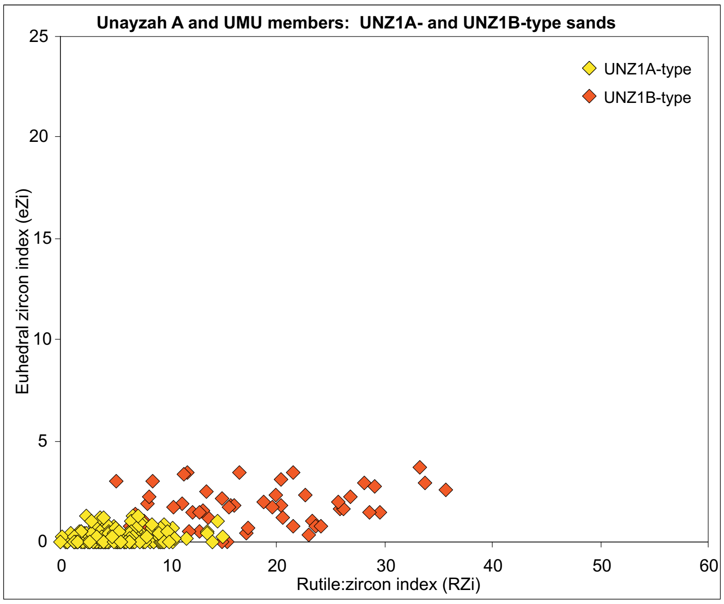

South
East
Well 1
Well 16
Well 17
Well 18
Well 25
Well 7
GR
ATi
RZi
MZi
eZi
KFS
PUU
P2U
P1/
P2U
P4U
P4*
P4
Cm
Cm*
?
ATi marker
See Figure 14 for lithostratigraphic assignments
M&S (2006)
Unayzah A Member
UMU member
Unayzah B Mbr
Unayzah C Member
metres
feet
100
300
200
50
100
0
0
KHUFF D CARBONATE
BASAL KHUFF MUDSTONE
UNZ0 MARINE FACIES
UNZ0 RED-BED FACIES
UNZ1A
UNZ1A HIGH-MZi SANDSTONES
UNZ1B / UNZ1 UNDIFFERENTIATED
UNZ1B / ATi MARKER
UNZ2
UNZ2 CHLORITOID-BEARING DIAMICTITE
UNZ3

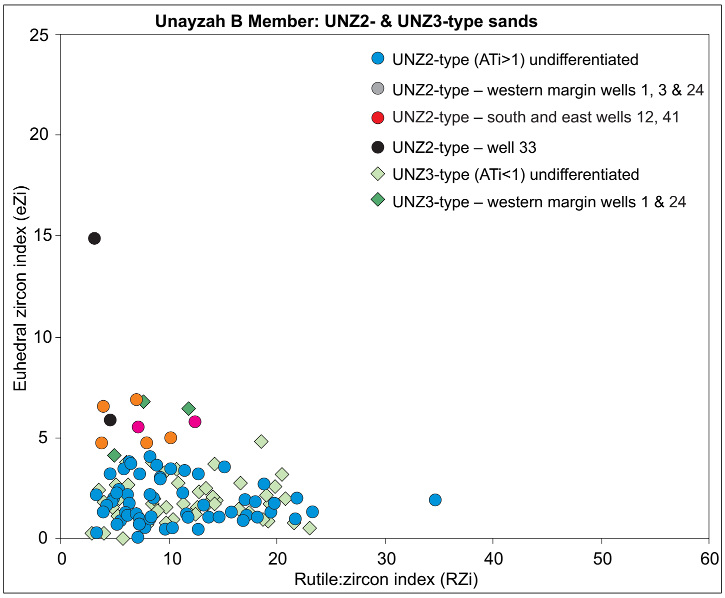

A
● Unayzah C sandstones absent
○ no data / uncertain assignment
0
km
100
47°
48°
49°
50°
24°
23°
Riyadh
Ghawar field
CENTRAL ARABIAN ARCH
ARABIAN SHIELD
5
28
6
27
26
24
25
18
1
15
Maximum MZi values
6-12
2-6
1-2
<1
Supply of high-MZi sands from Wajid area
B
● Unayzah C sandstones absent
● Low-MZi sandstones absent
○ no data / uncertain assignment
Supply of low-RZi, low-MZi sands
38
37
9
36
35
39
11
12
40
41
Supply of high-RZi, low-MZi sands
Supply of low-MZi sands
Average RZi values in low-MZi sands
15+
10-15
5-10
<5
Supply of low-RZi, low MZi sands
Supply of low-RZi, low-MZi sands

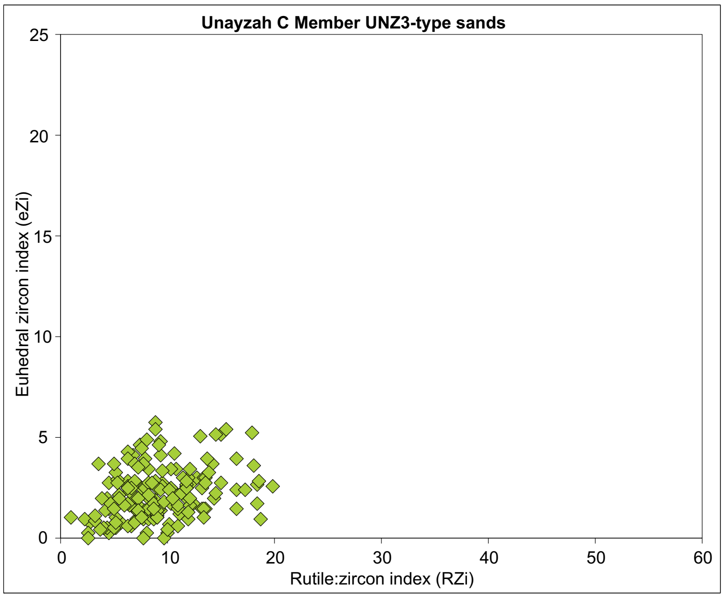

WEST CENTRAL & NORTHWEST CENTRAL AREAS
A
Nuayyim, Ghazal, Abu Shidad fields
Wudayhi field
Well 5
SOUTHEAST CENTRAL AREA
B
Haradh, Sahab, Shaden, Shamah, Waqr fields
Udaynan field
WESTERN MARGIN AREA
C
Hawtah, Hazmiyah, Usaylah fields, well 1
EASTERN AND SOUTHERN AREAS
D
Harmaliyah, Jawb, Tinat, Tukhman fields, well 41
Monazite:zircon (MZi)
Rutile:zircon (RZi)
0
3
6
9
12
15
0
10
20
30
40
50
60

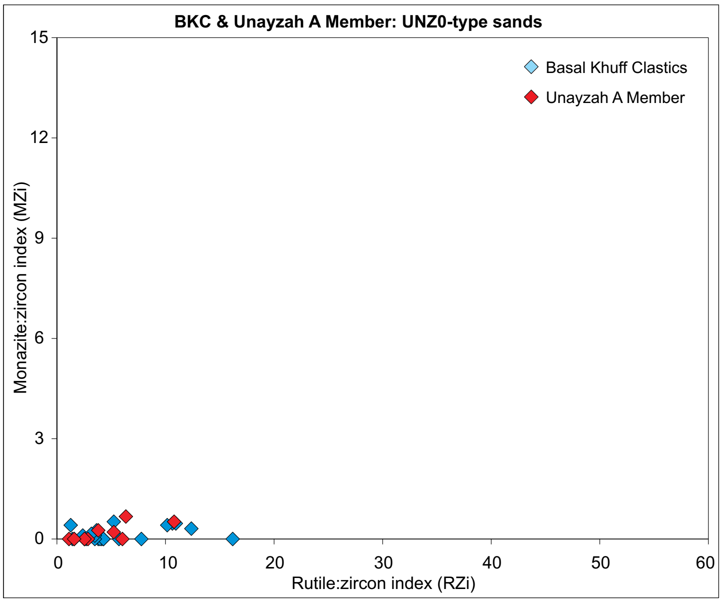

IRAQ
IRAN
KUWAIT
SAUDI ARABIA
Arabian Gulf
QATAR
UAE
OMAN
YEMEN
ETHIOPIA
Red Sea
Gulf of Aden
Arabian Sea
ARABIAN SHIELD
LOCATION MAP
Wajid outcrop area
N
0 300 km
Riyadh
Ghawar
Hawiyah
Haradh
NORTHERN AREA
Abu Jifan
Farhah
Qirdi
NORTHWEST CENTRAL AREA
Manjurah
Mazalij
Wudayhi
Ghazal
Sahbah
WESTERN MARGIN AREA
Dilam
Hilwah
Hawtah
Hazmiyah
Ghinah
Usaylah
WEST CENTRAL AREA
Abu Shidad
Nuayyim
SOUTHEAST CENTRAL AREA
Shaden
Waqr
Sham'ah
EASTERN AREA
Tinat
Jawb
Tukhman
SOUTHERN AREA
ARABIAN SHIELD
● HEAVY MINERAL REFERENCE WELLS
● OTHER WELLS STUDIED FOR HEAVY MINERALS
● WELLS NOT STUDIED FOR HEAVY MINERALS
0 km 100
46° 47° 48° 49° 50° 51°
22° 23° 24° 25° 26°

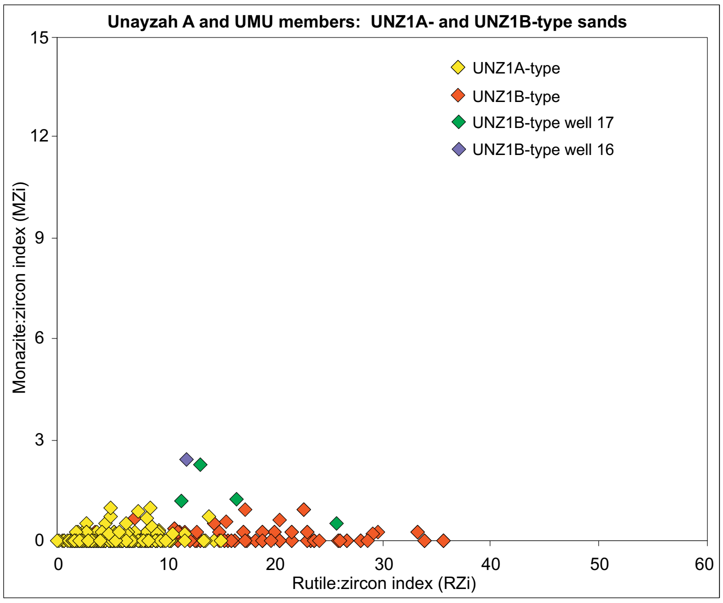

BKC & Unayzah A Member: UNZ0-type sands
Basal Khuff Clastics - western margin
Basal Khuff Clastics - south and east
Incised channel fill - western margin
Incised channel fill - south and east
Euhedral zircon index (eZi)
Rutile:zircon index (RZi)
0
5
10
15
20
25
0
10
20
30
40
50
60

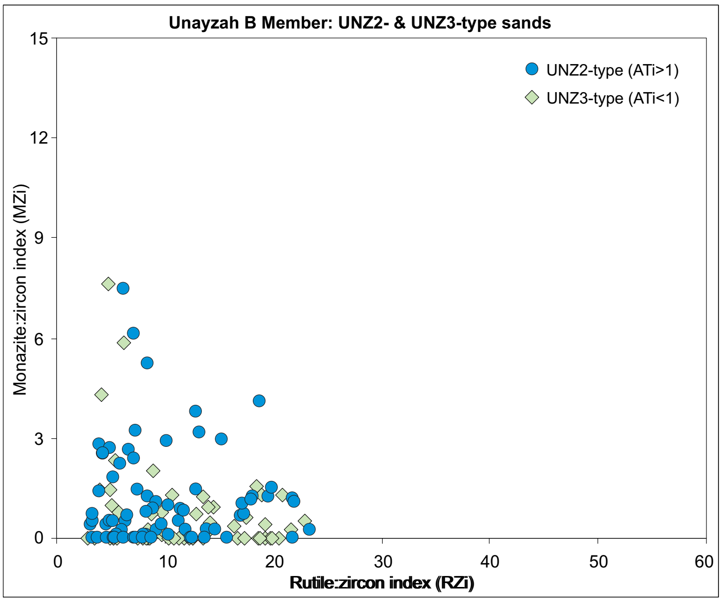

Unayzah A and UMU members: UNZ1A- and UNZ1B-type sands
UNZ1A-type
UNZ1B-type
Euhedral zircon index (eZi)
Rutile:zircon index (RZi)
0
5
10
15
20
25
0
10
20
30
40
50
60

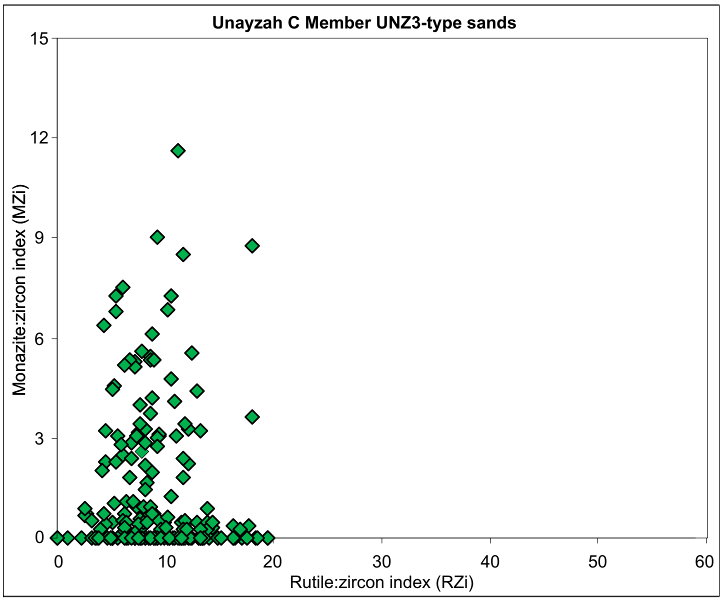

Unayzah B Member: UNZ2- & UNZ3-type sands
UNZ2-type (ATi>1) undifferentiated
UNZ2-type – western margin wells 1, 3 & 24
UNZ2-type – south and east wells 12, 41
UNZ2-type – well 33
UNZ3-type (ATi<1) undifferentiated
UNZ3-type – western margin wells 1 & 24
Euhedral zircon index (eZi)
Rutile:zircon index (RZi)
0
5
10
15
20
25
0
10
20
30
40
50
60

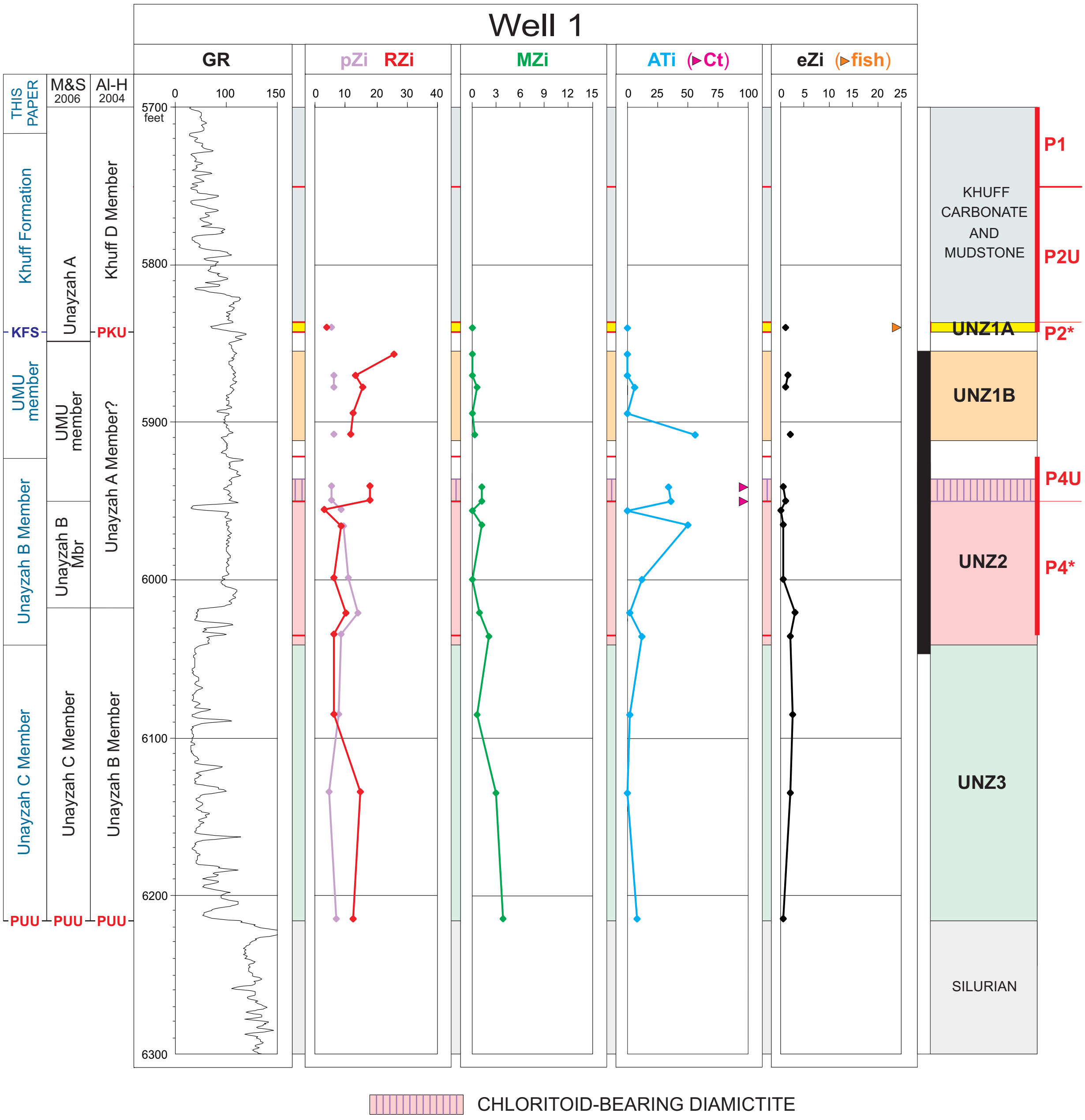

Unayzah C Member UNZ3-type sands
Euhedral zircon index (eZi)
Rutile:zircon index (RZi)
0
5
10
15
20
25
0
10
20
30
40
50
60

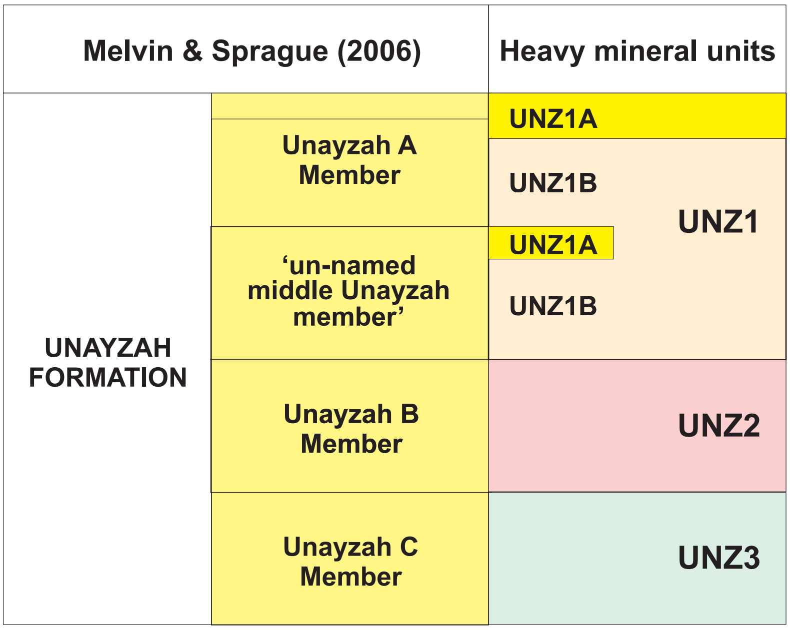

BKC & Unayzah A Member: UNZ0-type sands
Basal Khuff Clastics
Unayzah A Member
Monazite:zircon index (MZi)
Rutile:zircon index (RZi)
0
3
6
9
12
15
0
10
20
30
40
50
60


Unayzah A and UMU members: UNZ1A- and UNZ1B-type sands
UNZ1A-type
UNZ1B-type
UNZ1B-type well 17
UNZ1B-type well 16
Monazite:zircon index (MZi)
Rutile:zircon index (RZi)
0
3
6
9
12
15
0
10
20
30
40
50
60

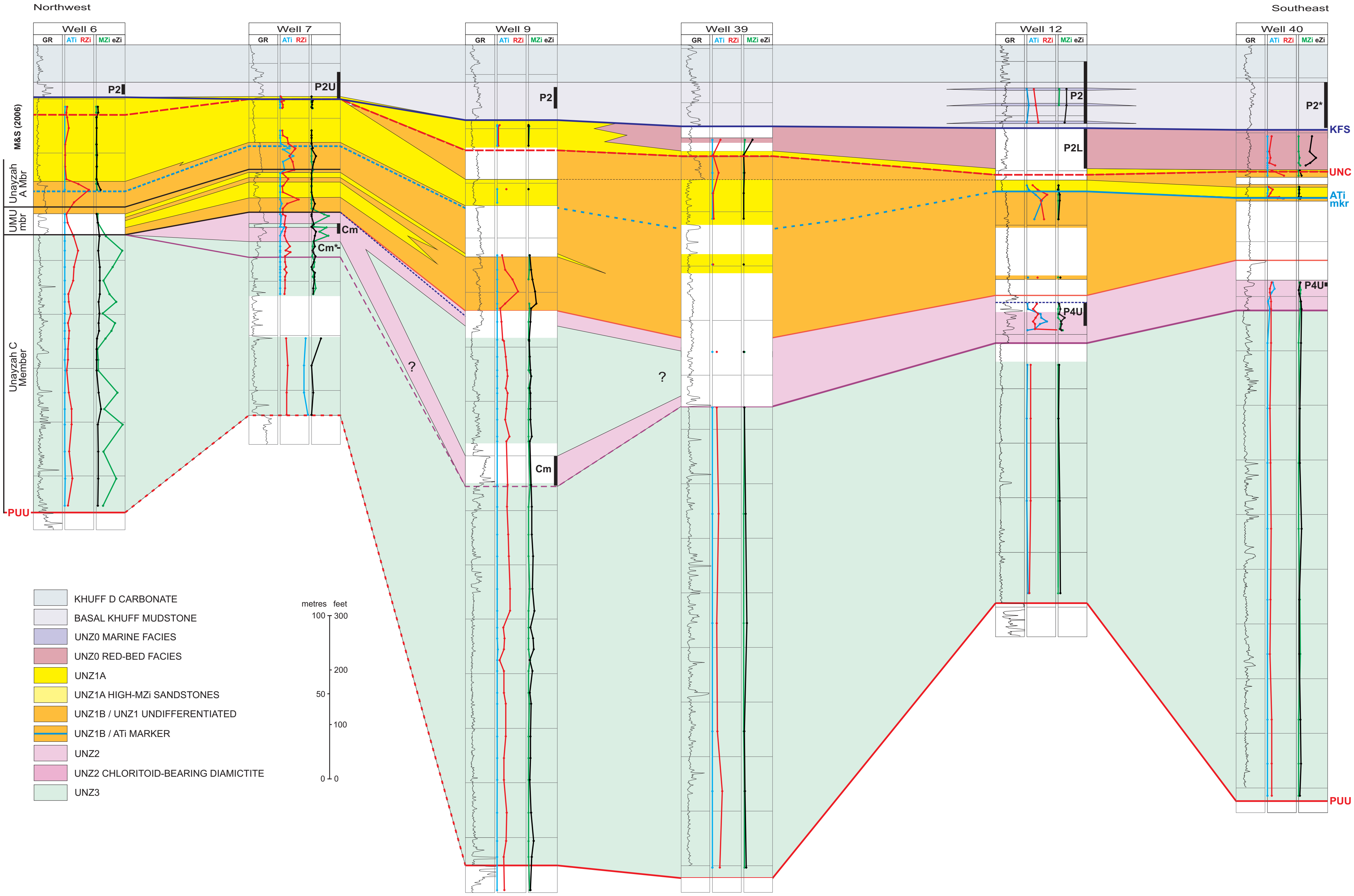

Unayzah B Member: UNZ2- & UNZ3-type sands
UNZ2-type (ATi>1)
UNZ3-type (ATi<1)
Monazite:zircon index (MZi)
Rutile:zircon index (RZi)
0
3
6
9
12
15
0
10
20
30
40
50
60

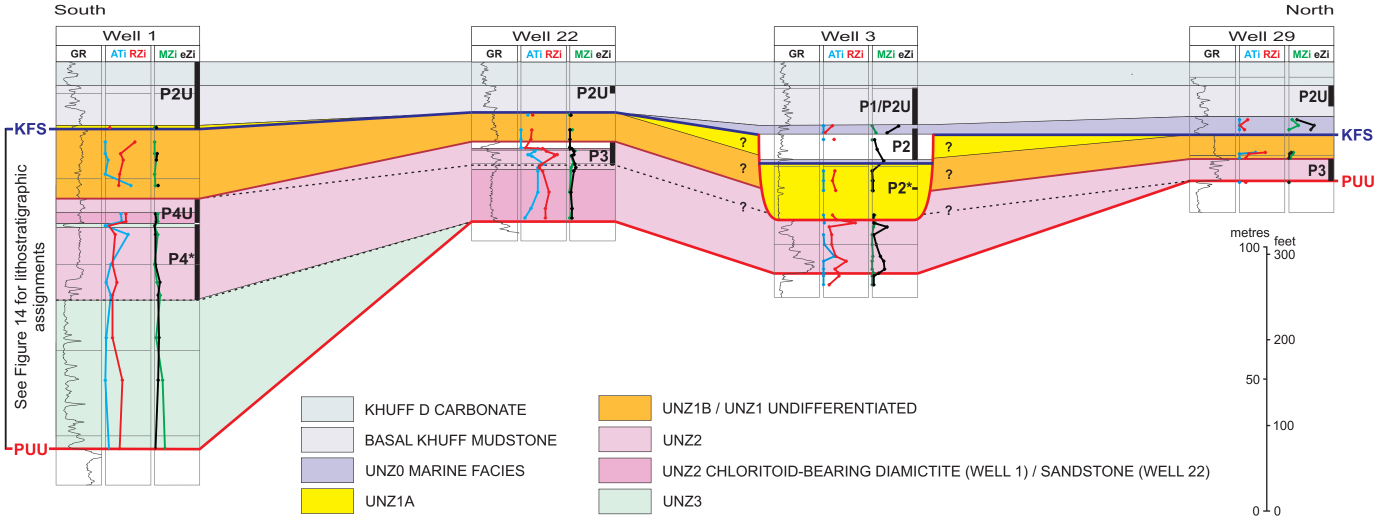

Unayzah C Member UNZ3-type sands
Monazite:zircon index (MZi)
Rutile:zircon index (RZi)
0
3
6
9
12
15
0
10
20
30
40
50
60

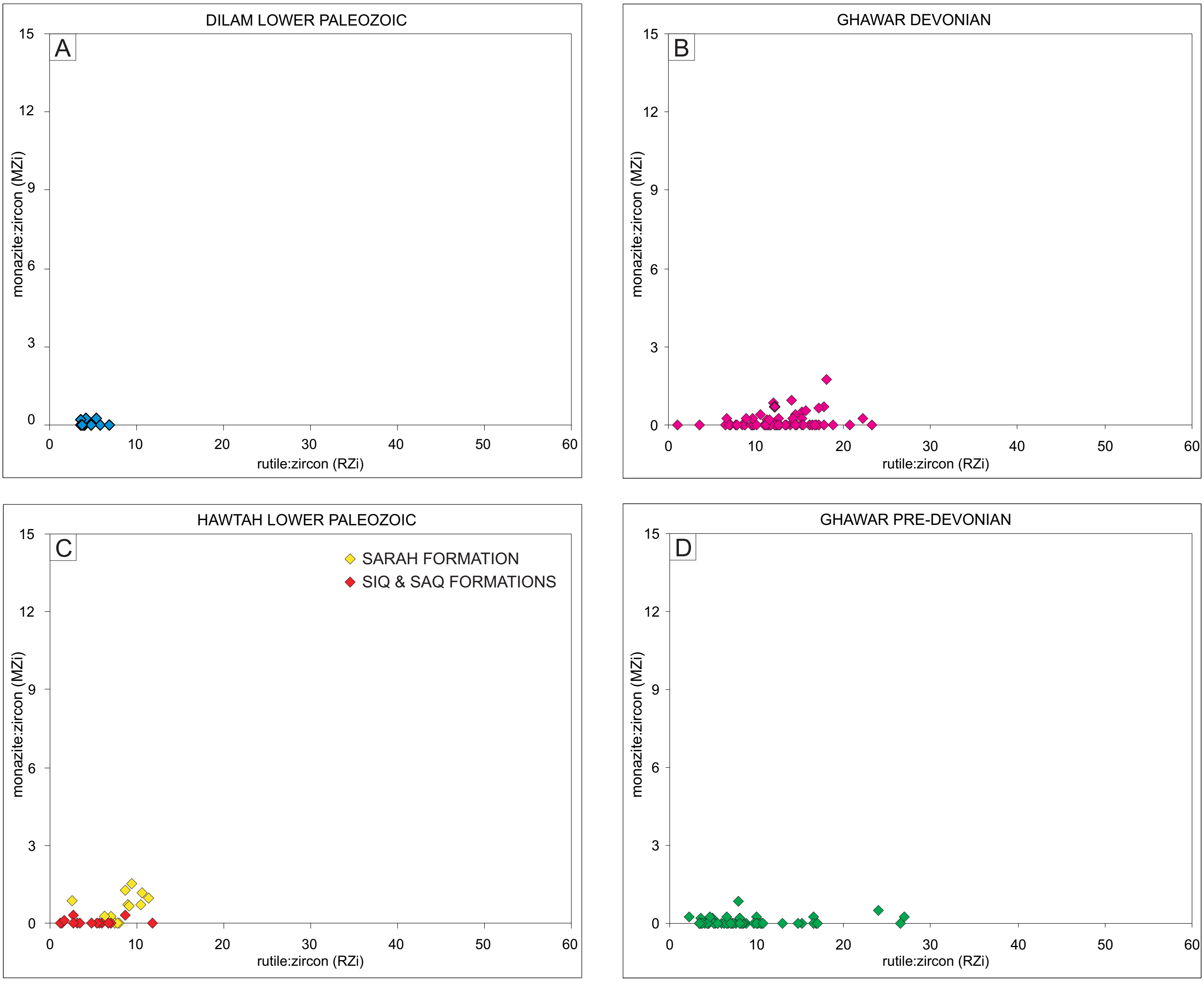

Well 1
GR
pZi RZi
MZi
ATi (▶Ct)
eZi (▶fish)
THIS PAPER
M&S 2006
Al-H 2004
Khuff Formation
KFS
UMU member
Unayzah B Member
Unayzah C Member
PUU
Unayzah A
UMU member
Unayzah B Mbr
Unayzah C Member
Khuff D Member
PKU
Unayzah A Member?
Unayzah B Member
5700 feet
5800
5900
6000
6100
6200
6300
0 100 150
0 10 20 30 40
0 3 6 9 12 15
0 25 50 75 100
0 5 10 15 20 25
KHUFF CARBONATE AND MUDSTONE
UNZ1A
UNZ1B
UNZ2
UNZ3
SILURIAN
P1
P2U
P2*
P4U
P4*
CHLORITOID-BEARING DIAMICTITE

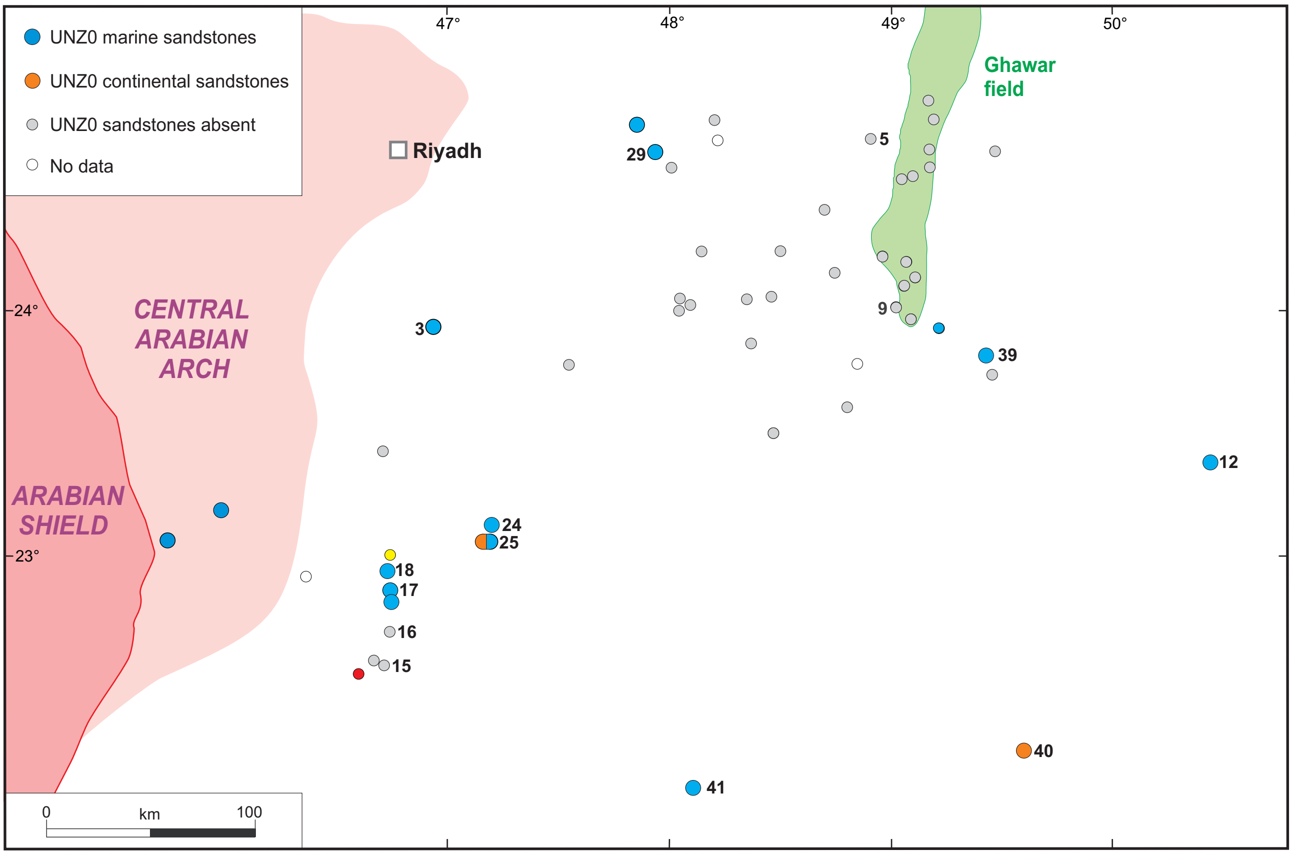


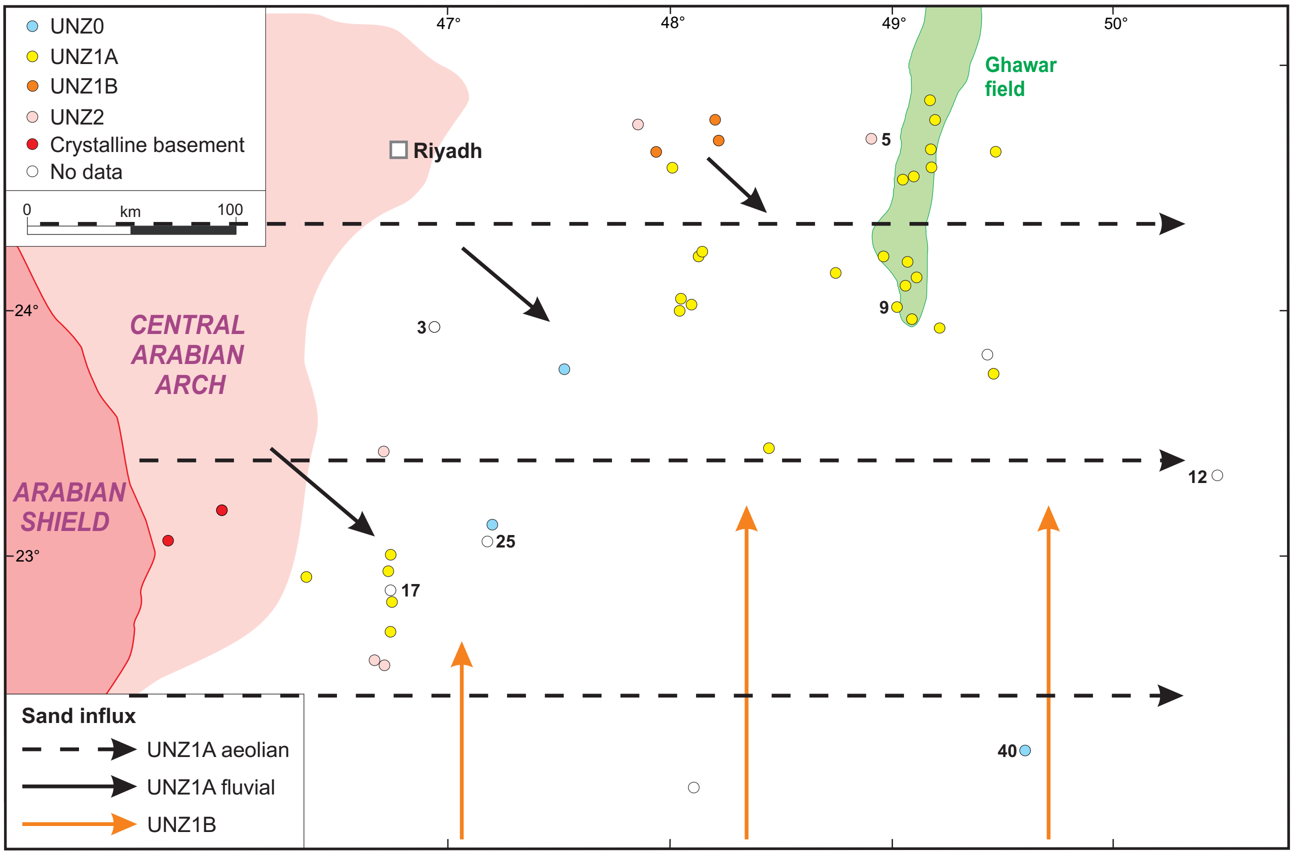
Melvin & Sprague (2006)		Heavy mineral units	
UNAYZAH FORMATION		UNZ1A	UNZ1
	Unayzah A Member	UNZ1B	
	‘un-named middle Unayzah member’	UNZ1A	
		UNZ1B	
	Unayzah B Member		UNZ2
	Unayzah C Member		UNZ3

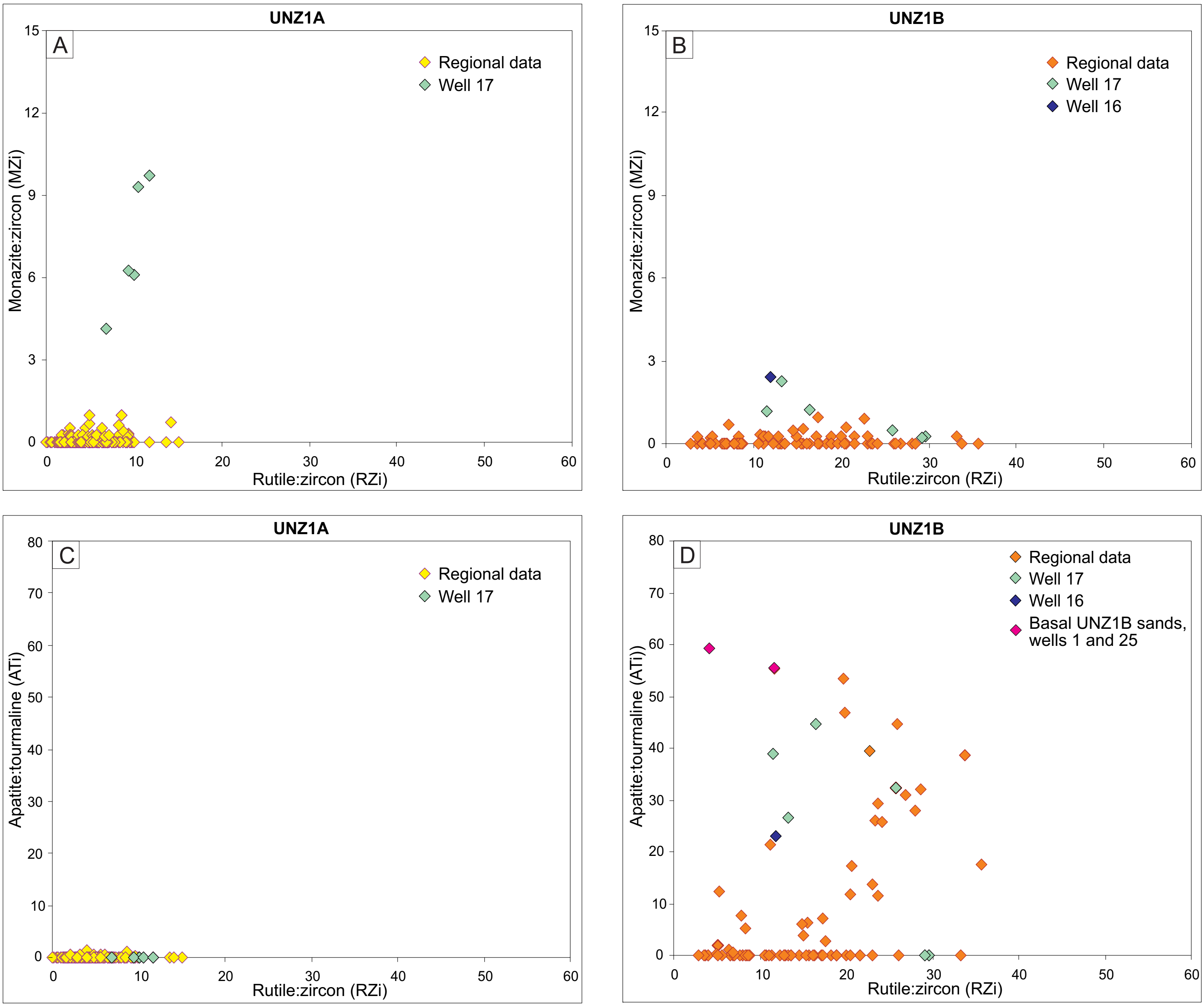

Northwest
Southeast
Well 6
Well 7
Well 9
Well 39
Well 12
Well 40
GR
ATi RZi
MZi eZi
P2
P2U
P2L
P2*
Cm
Cm*
P4U
KFS
UNC
ATi mkr
PUU
?
M&S (2006)
Unayzah A Mbr
UMU mbr
Unayzah C Member
KHUFF D CARBONATE
BASAL KHUFF MUDSTONE
UNZ0 MARINE FACIES
UNZ0 RED-BED FACIES
UNZ1A
UNZ1A HIGH-MZi SANDSTONES
UNZ1B / UNZ1 UNDIFFERENTIATED
UNZ1B / ATi MARKER
UNZ2
UNZ2 CHLORITOID-BEARING DIAMICTITE
UNZ3
metres feet
100 300
200
50
100
0 0

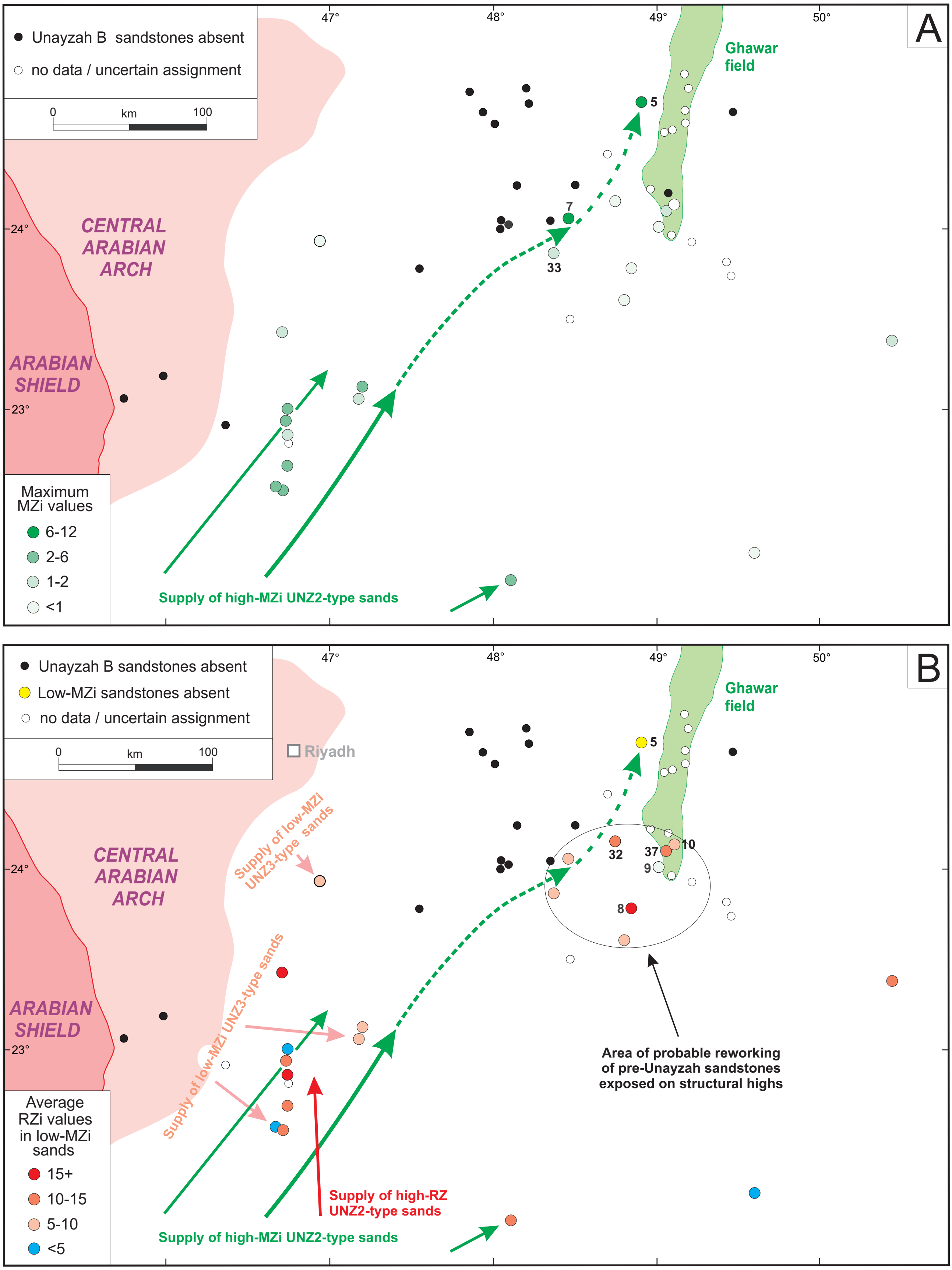

South
North
Well 1
Well 22
Well 3
Well 29
GR
ATi RZi
MZi eZi
P2U
P1/P2U
P2
P2*-
P3
P4U
P4*
KFS
PUU
?
See Figure 14 for lithostratigraphic assignments
metres
feet
100
300
200
50
100
0
0
KHUFF D CARBONATE
BASAL KHUFF MUDSTONE
UNZ0 MARINE FACIES
UNZ1A
UNZ1B / UNZ1 UNDIFFERENTIATED
UNZ2
UNZ2 CHLORITOID-BEARING DIAMICTITE (WELL 1) / SANDSTONE (WELL 22)
UNZ3

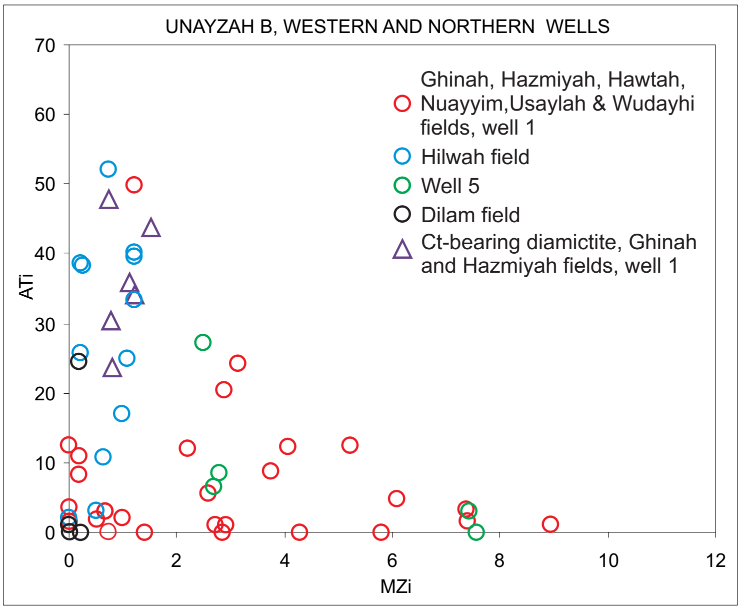

DILAM LOWER PALEOZOIC
A
GHAWAR DEVONIAN
B
HAWTAH LOWER PALEOZOIC
C
◆ SARAH FORMATION
◆ SIQ & SAQ FORMATIONS
GHAWAR PRE-DEVONIAN
D
monazite:zircon (MZi)
rutile:zircon (RZi)
0
3
6
9
12
15
0
10
20
30
40
50
60

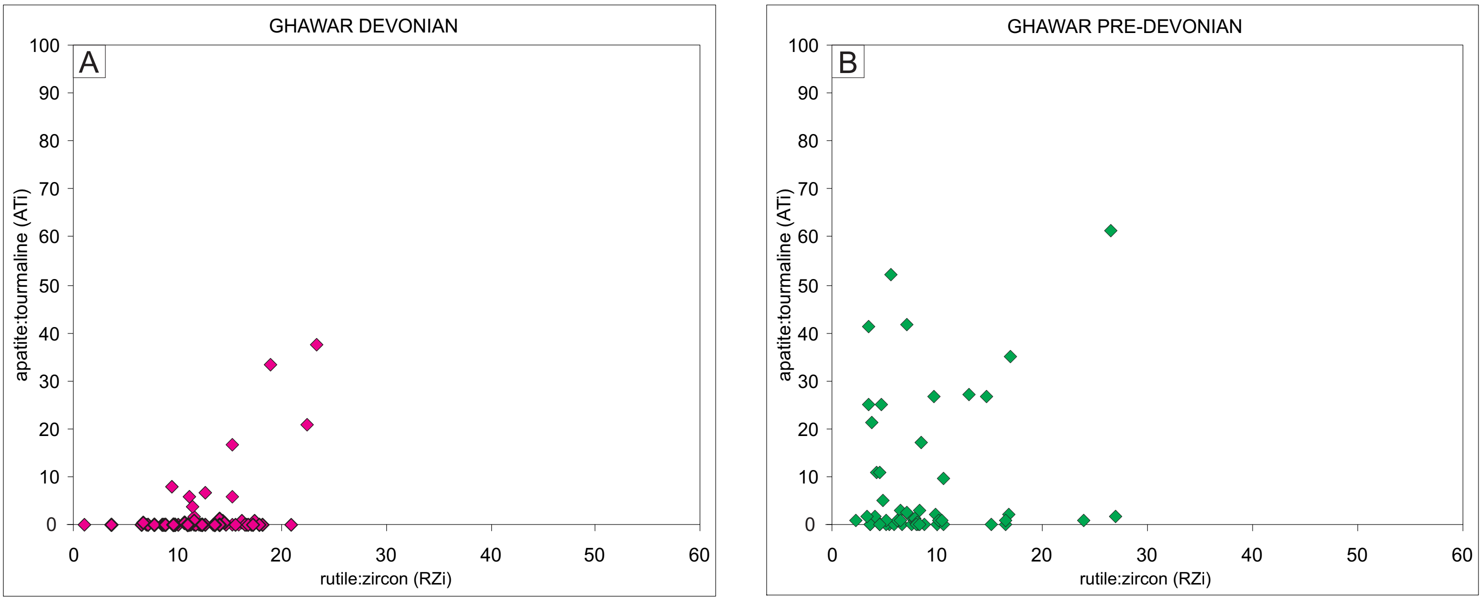

UNZ0 marine sandstones
UNZ0 continental sandstones
UNZ0 sandstones absent
No data
47°
48°
49°
50°
24°
23°
Riyadh
Ghawar field
CENTRAL ARABIAN ARCH
ARABIAN SHIELD
29
5
3
9
39
12
24
25
18
17
16
15
40
41
0
km
100

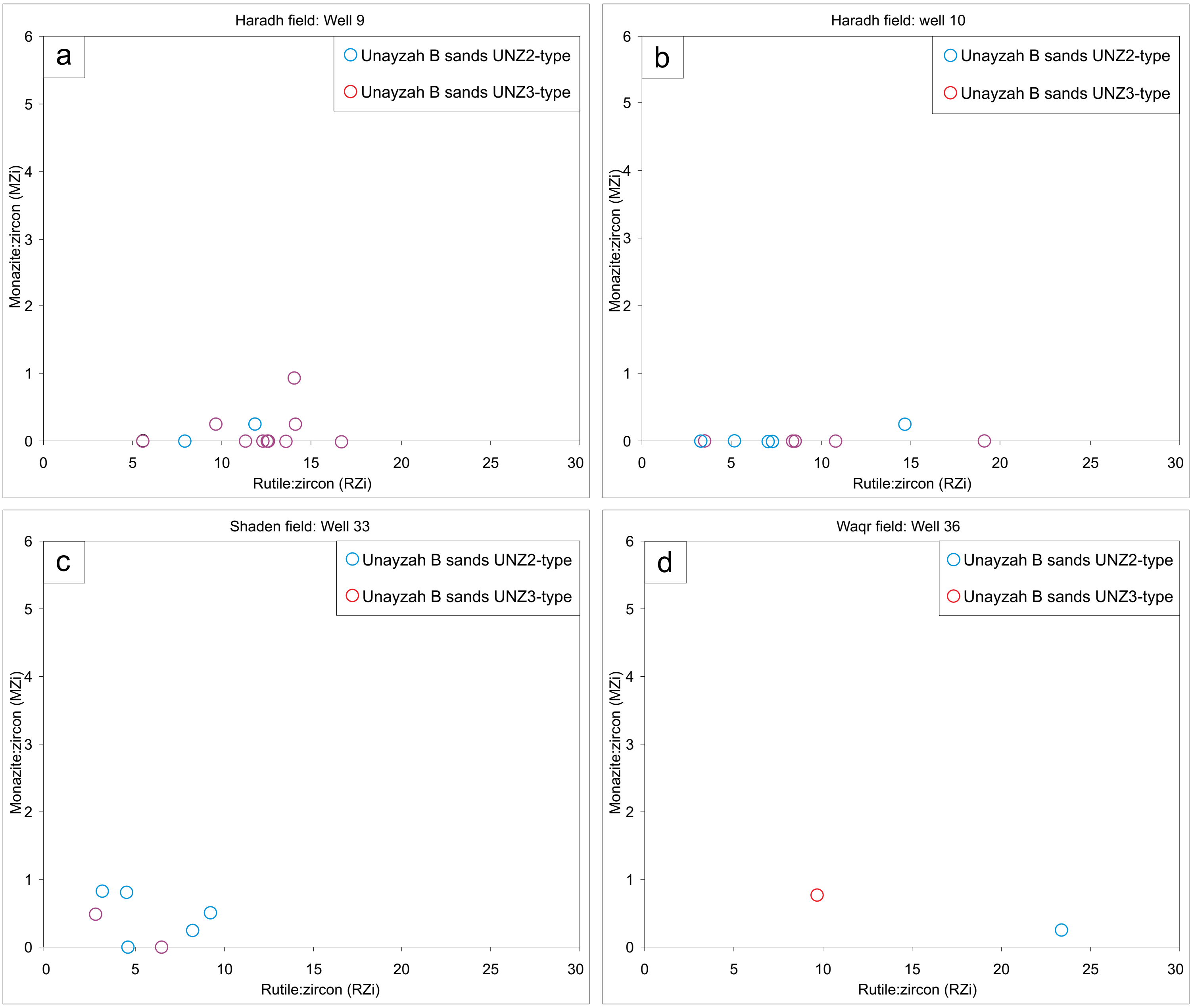

UNZ0
UNZ1A
UNZ1B
UNZ2
Crystalline basement
No data
0
km
100
47°
48°
49°
50°
24°
23°
Ghawar field
Riyadh
CENTRAL ARABIAN ARCH
ARABIAN SHIELD
3
5
9
12
17
25
40
Sand influx
UNZ1A aeolian
UNZ1A fluvial
UNZ1B

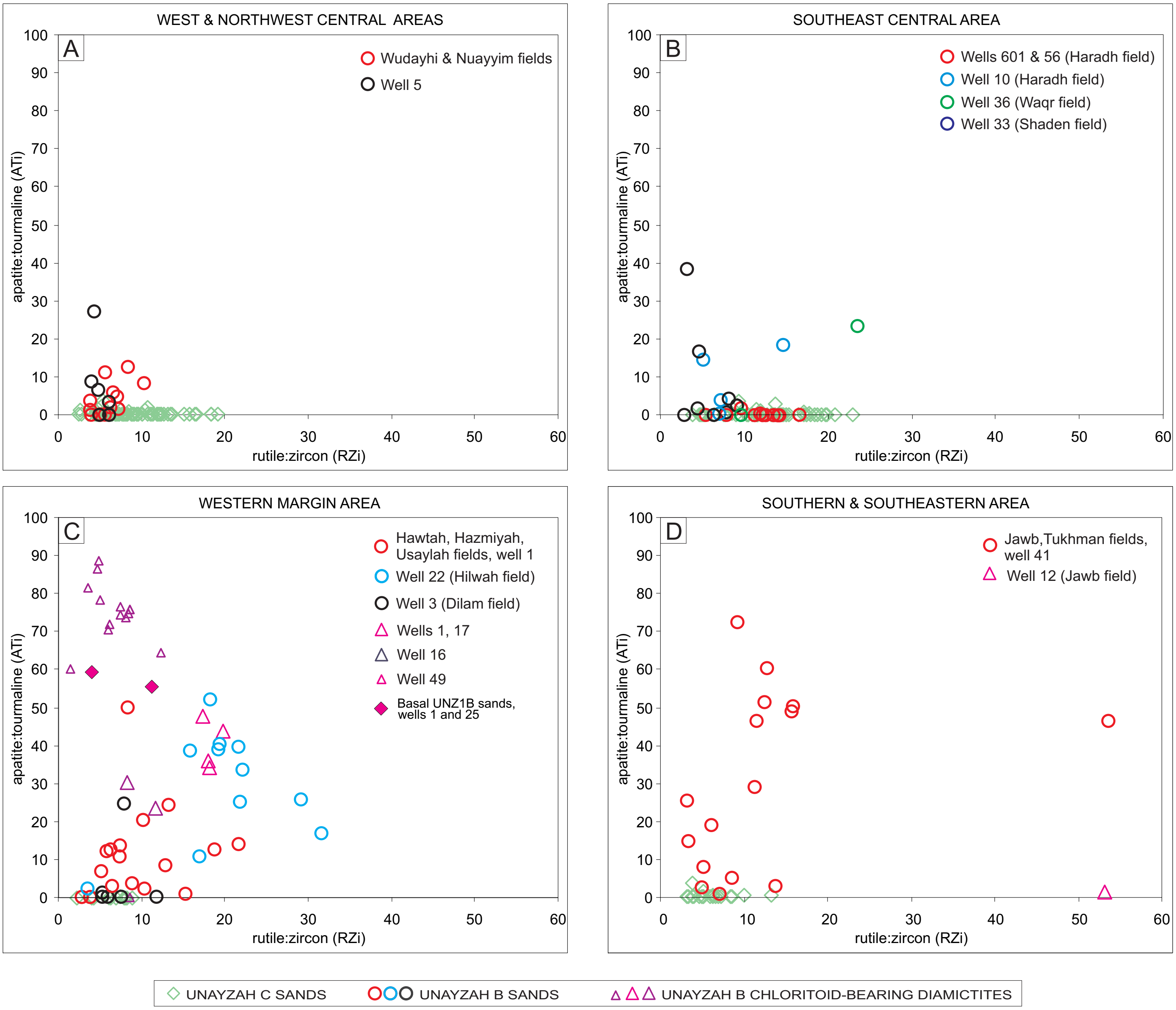

UNZ1A
A
Regional data
Well 17
Monazite:zircon (MZi)
0
3
6
9
12
15
0
10
20
30
40
50
60
Rutile:zircon (RZi)
UNZ1B
B
Regional data
Well 17
Well 16
Monazite:zircon (MZi)
Rutile:zircon (RZi)
UNZ1A
C
Regional data
Well 17
Apatite:tourmaline (ATi)
0
10
20
30
40
50
60
70
80
Rutile:zircon (RZi)
UNZ1B
D
Regional data
Well 17
Well 16
Basal UNZ1B sands, wells 1 and 25
Apatite:tourmaline (ATi)
Rutile:zircon (RZi)

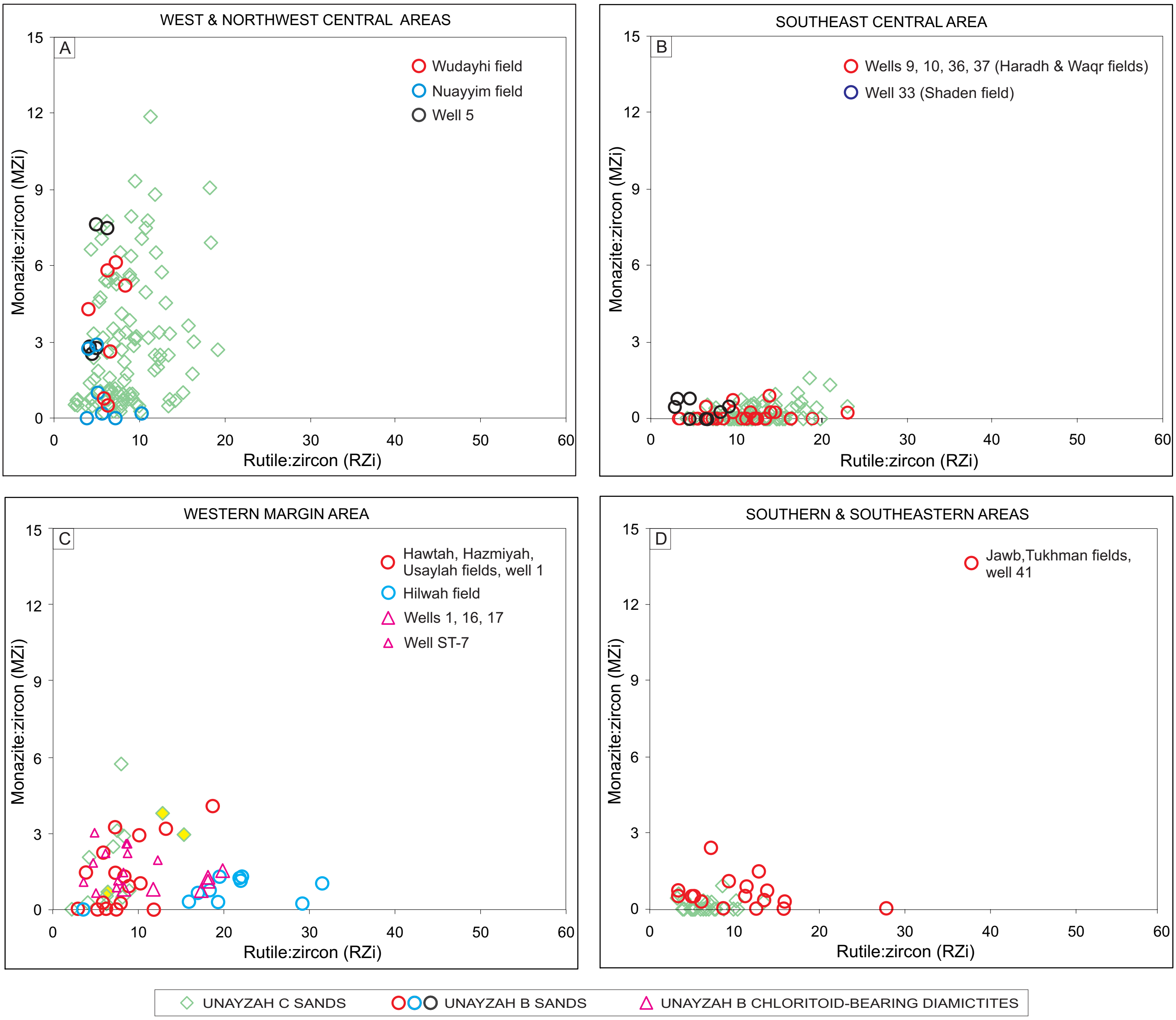

A
● Unayzah B sandstones absent
○ no data / uncertain assignment
0 km 100
47°
48°
49°
50°
Ghawar field
CENTRAL ARABIAN ARCH
ARABIAN SHIELD
24°
23°
5
7
33
Maximum MZi values
6-12
2-6
1-2
<1
Supply of high-MZi UNZ2-type sands
B
● Unayzah B sandstones absent
● Low-MZi sandstones absent
○ no data / uncertain assignment
0 km 100
Riyadh
Supply of low-MZi UNZ3-type sands
Supply of low-MZi UNZ3-type sands
32
37
10
9
8
Area of probable reworking of pre-Unayzah sandstones exposed on structural highs
Supply of high-RZ UNZ2-type sands
Supply of high-MZi UNZ2-type sands
Average RZi values in low-MZi sands
15+
10-15
5-10
<5

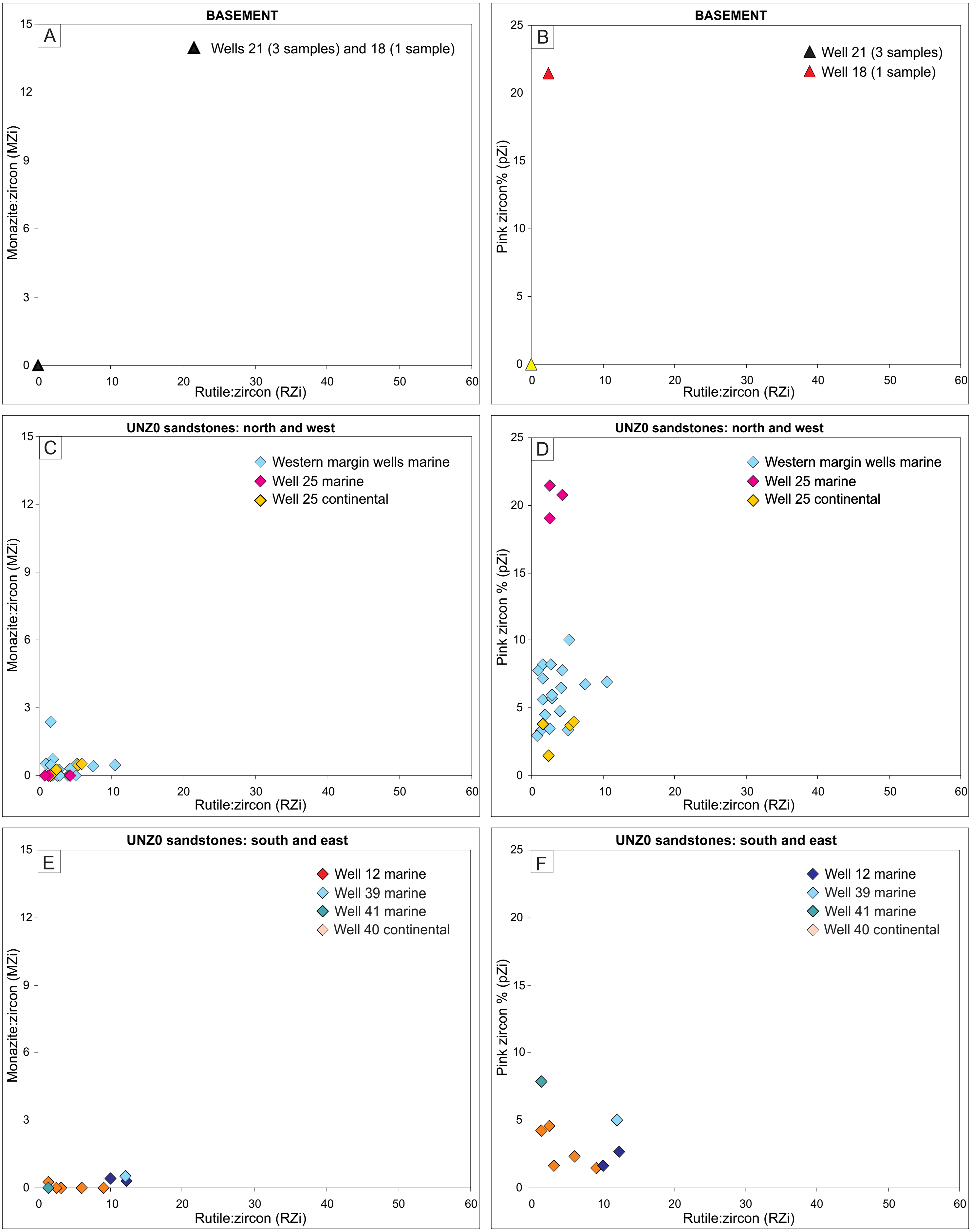

UNAYZAH B, WESTERN AND NORTHERN WELLS
ATi
70
60
50
40
30
20
10
0
MZi
0
2
4
6
8
10
12
Ghinah, Hazmiyah, Hawtah, Nuayyim,Usaylah & Wudayhi fields, well 1
Hilwah field
Well 5
Dilam field
Ct-bearing diamictite, Ghinah and Hazmiyah fields, well 1

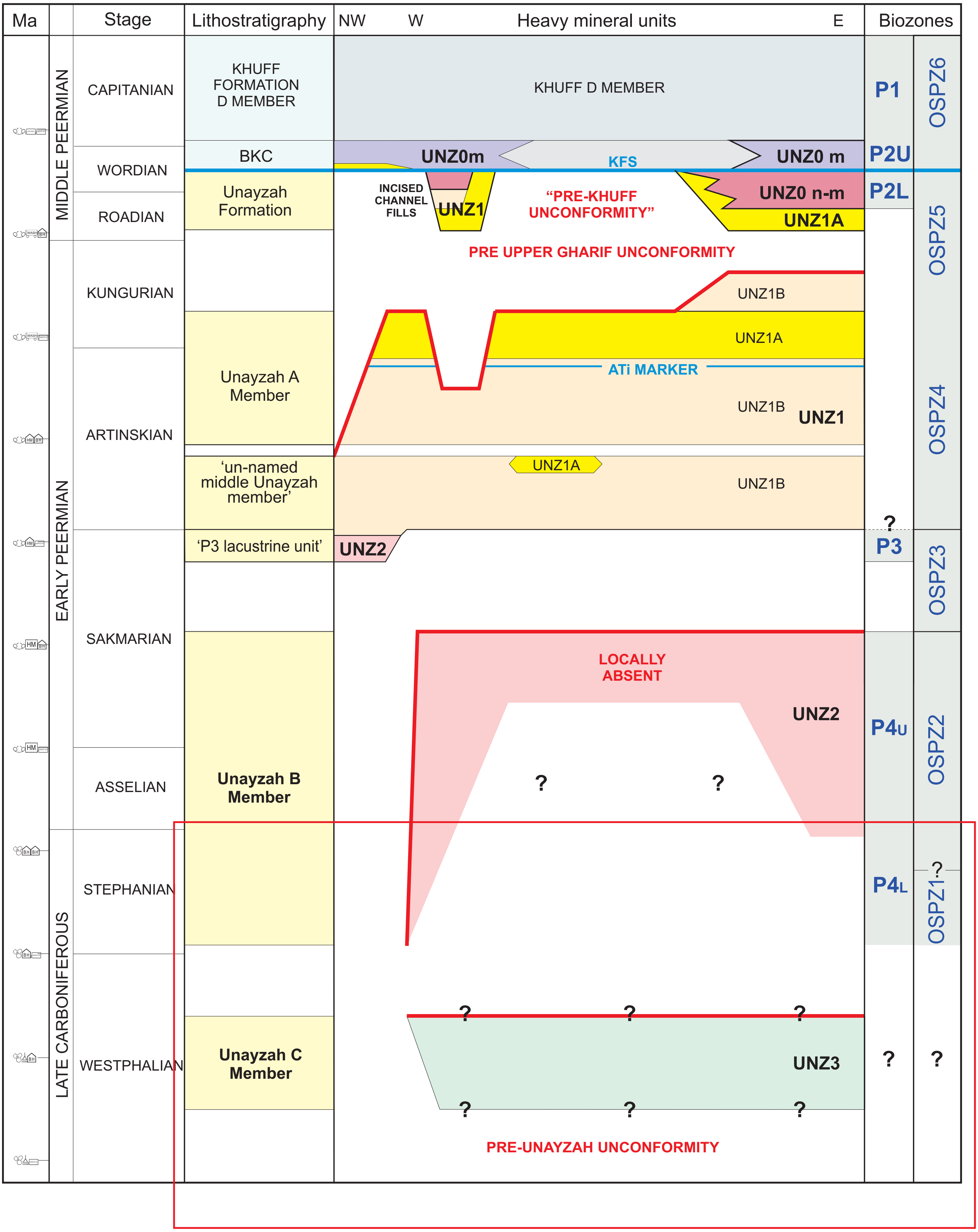

GHAWAR DEVONIAN
A
apatite:tourmaline (ATi)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
rutile:zircon (RZi)
GHAWAR PRE-DEVONIAN
B
apatite:tourmaline (ATi)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
rutile:zircon (RZi)

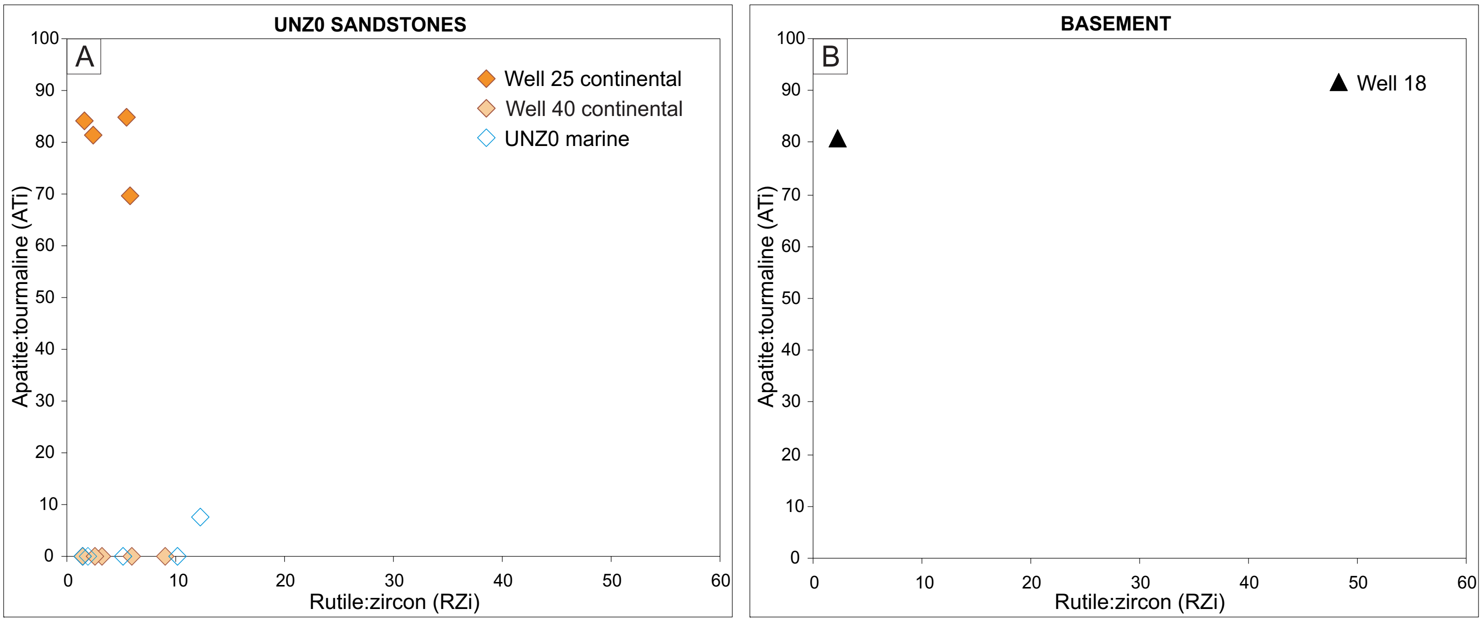

Haradh field: Well 9
a
Unayzah B sands UNZ2-type
Unayzah B sands UNZ3-type
Monazite:zircon (MZi)
Rutile:zircon (RZi)
0
1
2
3
4
5
6
0
5
10
15
20
25
30
Haradh field: well 10
b
Unayzah B sands UNZ2-type
Unayzah B sands UNZ3-type
Monazite:zircon (MZi)
Rutile:zircon (RZi)
0
1
2
3
4
5
6
0
5
10
15
20
25
30
Shaden field: Well 33
c
Unayzah B sands UNZ2-type
Unayzah B sands UNZ3-type
Monazite:zircon (MZi)
Rutile:zircon (RZi)
0
1
2
3
4
5
6
0
5
10
15
20
25
30
Waqr field: Well 36
d
Unayzah B sands UNZ2-type
Unayzah B sands UNZ3-type
Monazite:zircon (MZi)
Rutile:zircon (RZi)
0
1
2
3
4
5
6
0
5
10
15
20
25
30

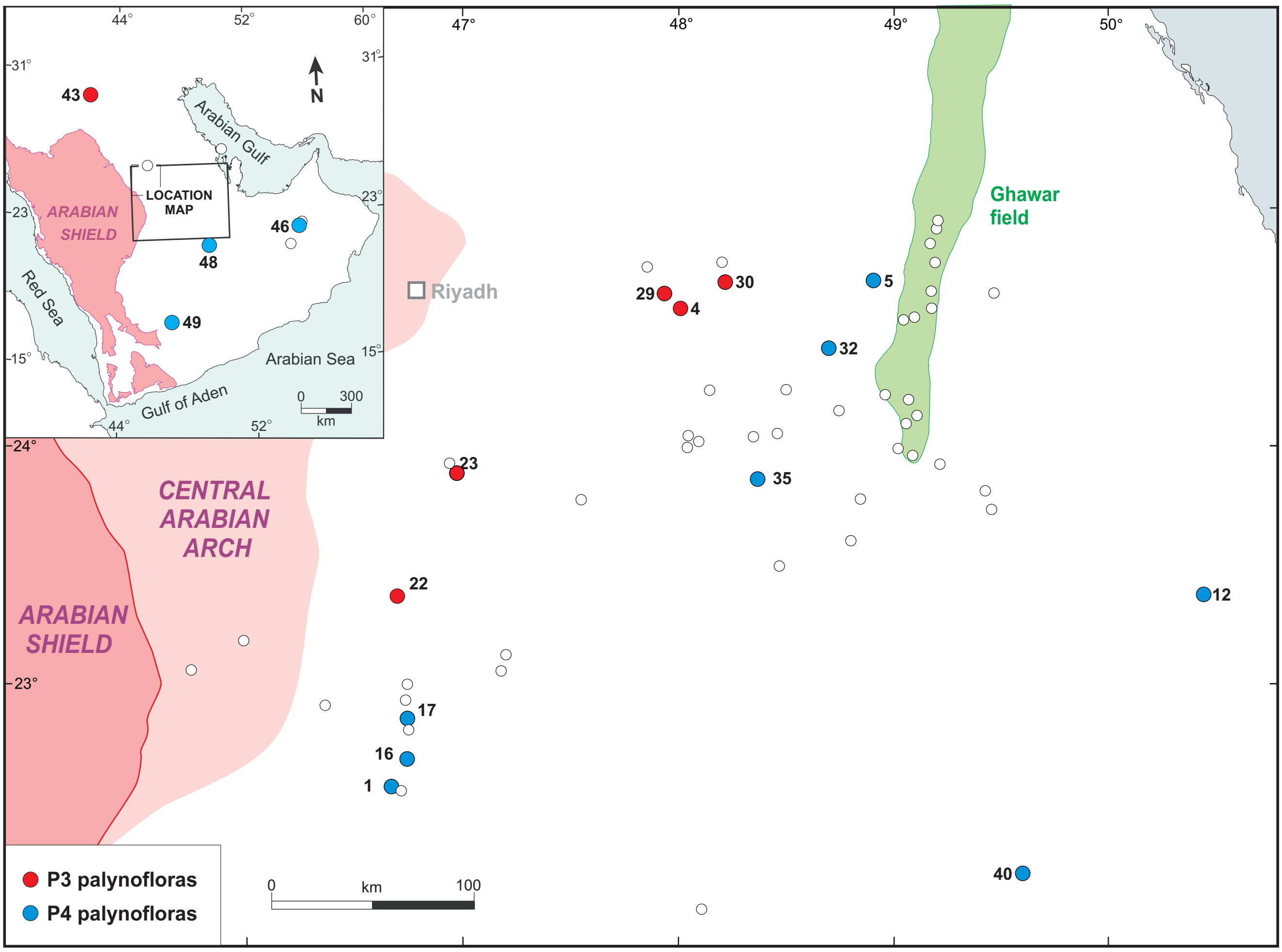

WEST & NORTHWEST CENTRAL AREAS
A
Wudayhi & Nuayyim fields
Well 5
SOUTHEAST CENTRAL AREA
B
Wells 601 & 56 (Haradh field)
Well 10 (Haradh field)
Well 36 (Waqr field)
Well 33 (Shaden field)
WESTERN MARGIN AREA
C
Hawtah, Hazmiyah, Usaylah fields, well 1
Well 22 (Hilwah field)
Well 3 (Dilam field)
Wells 1, 17
Well 16
Well 49
Basal UNZ1B sands, wells 1 and 25
SOUTHERN & SOUTHEASTERN AREA
D
Jawb,Tukhman fields, well 41
Well 12 (Jawb field)
apatite:tourmaline (ATi)
rutile:zircon (RZi)
0
10
20
30
40
50
60
70
80
90
100
UNAYZAH C SANDS
UNAYZAH B SANDS
UNAYZAH B CHLORITOID-BEARING DIAMICTITES

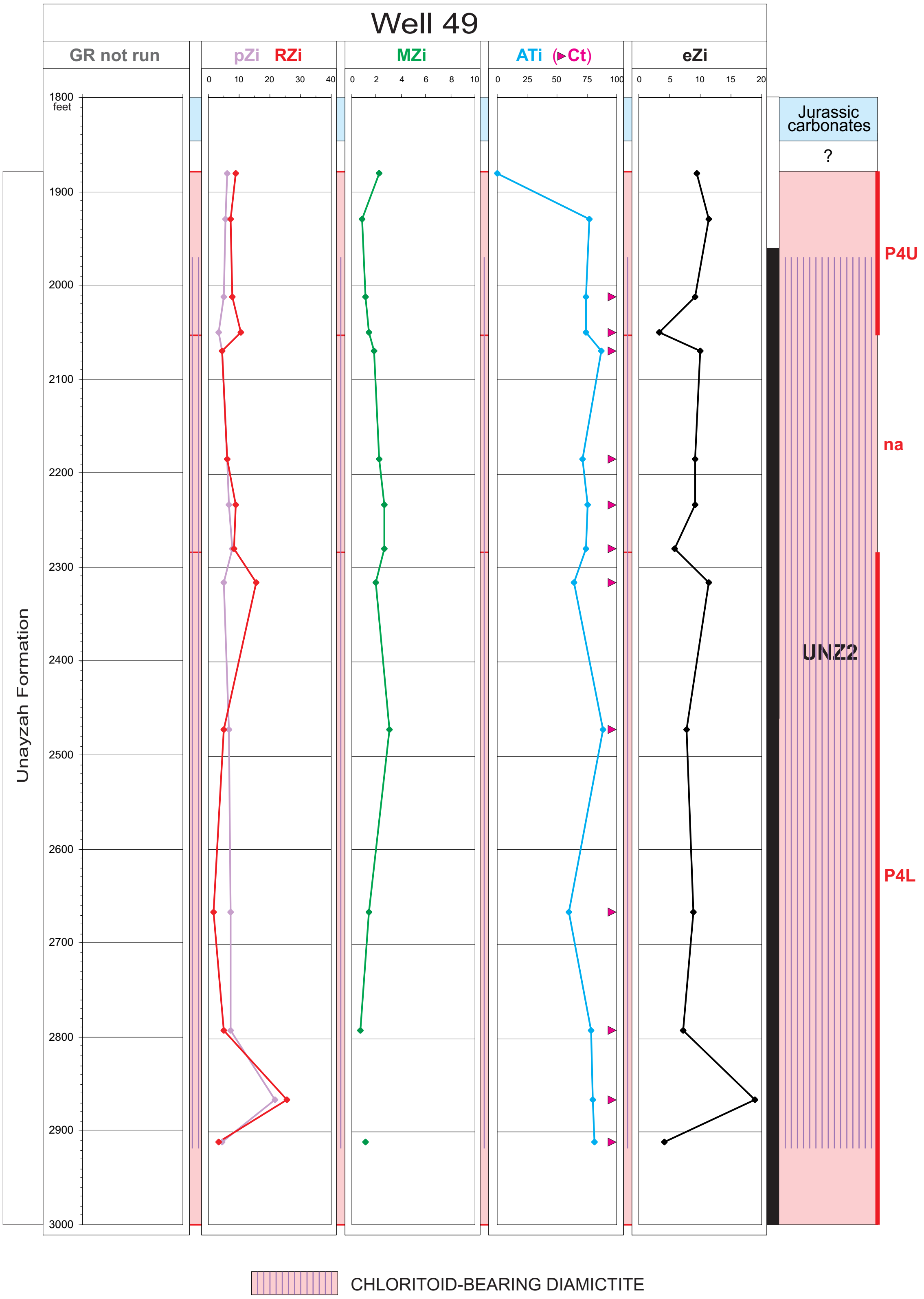

WEST & NORTHWEST CENTRAL AREAS
A
Wudayhi field
Nuayyim field
Well 5
SOUTHEAST CENTRAL AREA
B
Wells 9, 10, 36, 37 (Haradh & Waqr fields)
Well 33 (Shaden field)
WESTERN MARGIN AREA
C
Hawtah, Hazmiyah, Usaylah fields, well 1
Hilwah field
Wells 1, 16, 17
Well ST-7
SOUTHERN & SOUTHEASTERN AREAS
D
Jawb,Tukhman fields, well 41
Monazite:zircon (MZi)
Rutile:zircon (RZi)
0
3
6
9
12
15
0
10
20
30
40
50
60
UNAYZAH C SANDS
UNAYZAH B SANDS
UNAYZAH B CHLORITOID-BEARING DIAMICTITES

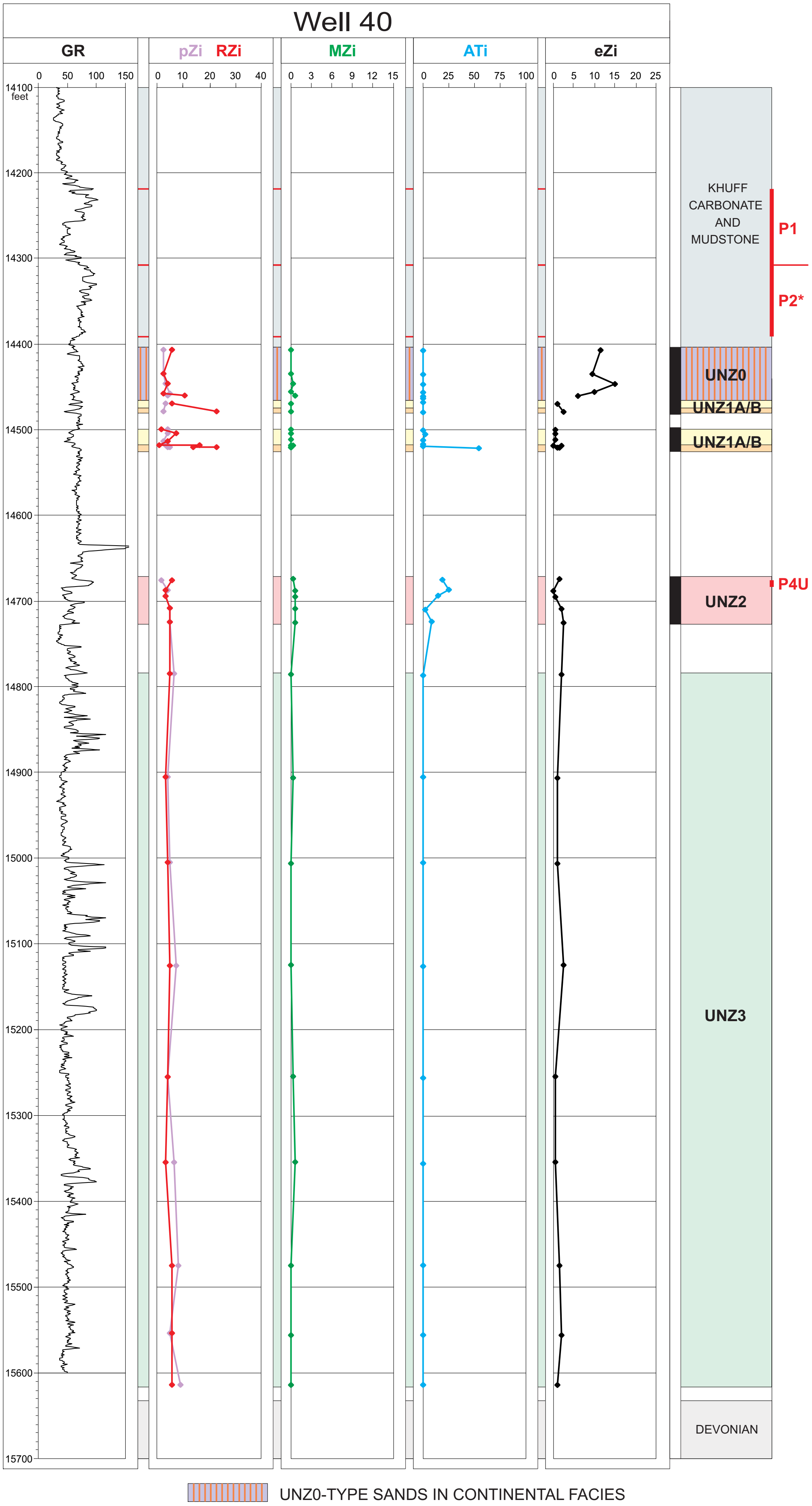

BASEMENT
A
Wells 21 (3 samples) and 18 (1 sample)
Monazite:zircon (MZi)
Rutile:zircon (RZi)
0
3
6
9
12
15
0
10
20
30
40
50
60
BASEMENT
B
Well 21 (3 samples)
Well 18 (1 sample)
Pink zircon% (pZi)
Rutile:zircon (RZi)
0
5
10
15
20
25
UNZ0 sandstones: north and west
C
Western margin wells marine
Well 25 marine
Well 25 continental
Monazite:zircon (MZi)
Rutile:zircon (RZi)
UNZ0 sandstones: north and west
D
Western margin wells marine
Well 25 marine
Well 25 continental
Pink zircon % (pZi)
Rutile:zircon (RZi)
UNZ0 sandstones: south and east
E
Well 12 marine
Well 39 marine
Well 41 marine
Well 40 continental
Monazite:zircon (MZi)
Rutile:zircon (RZi)
UNZ0 sandstones: south and east
F
Well 12 marine
Well 39 marine
Well 41 marine
Well 40 continental
Pink zircon % (pZi)
Rutile:zircon (RZi)

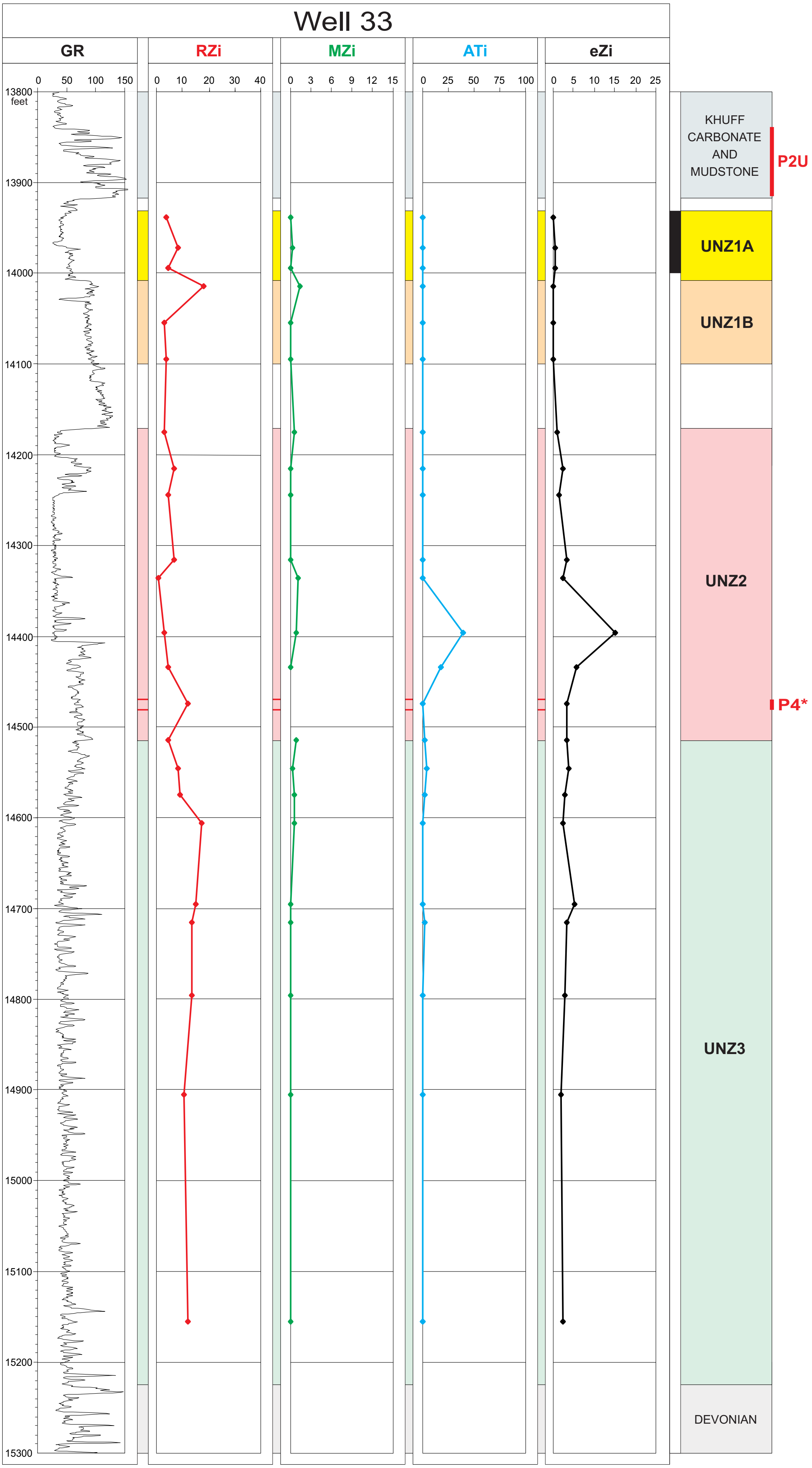

Ma
Stage
Lithostratigraphy
NW
W
Heavy mineral units
E
Biozones
MIDDLE PEERMIAN
EARLY PEERMIAN
LATE CARBONIFEROUS
CAPITANIAN
WORDIAN
ROADIAN
KUNGURIAN
ARTINSKIAN
SAKMARIAN
ASSELIAN
STEPHANIAN
WESTPHALIAN
KHUFF FORMATION D MEMBER
BKC
Unayzah Formation
Unayzah A Member
'un-named middle Unayzah member'
'P3 lacustrine unit'
Unayzah B Member
Unayzah C Member
KHUFF D MEMBER
UNZ0m
KFS
UNZ0 m
INCISED CHANNEL FILLS
UNZ1
"PRE-KHUFF UNCONFORMITY"
UNZ0 n-m
UNZ1A
PRE UPPER GHARIF UNCONFORMITY
UNZ1B
UNZ1A
ATi MARKER
UNZ1B
UNZ1
UNZ1A
UNZ1B
UNZ2
LOCALLY ABSENT
UNZ2
?
?
?
?
?
UNZ3
?
?
?
PRE-UNAYZAH UNCONFORMITY
P1
P2U
P2L
?
P3
P4U
P4L
?
OSPZ6
OSPZ5
OSPZ4
OSPZ3
OSPZ2
OSPZ1-?
?

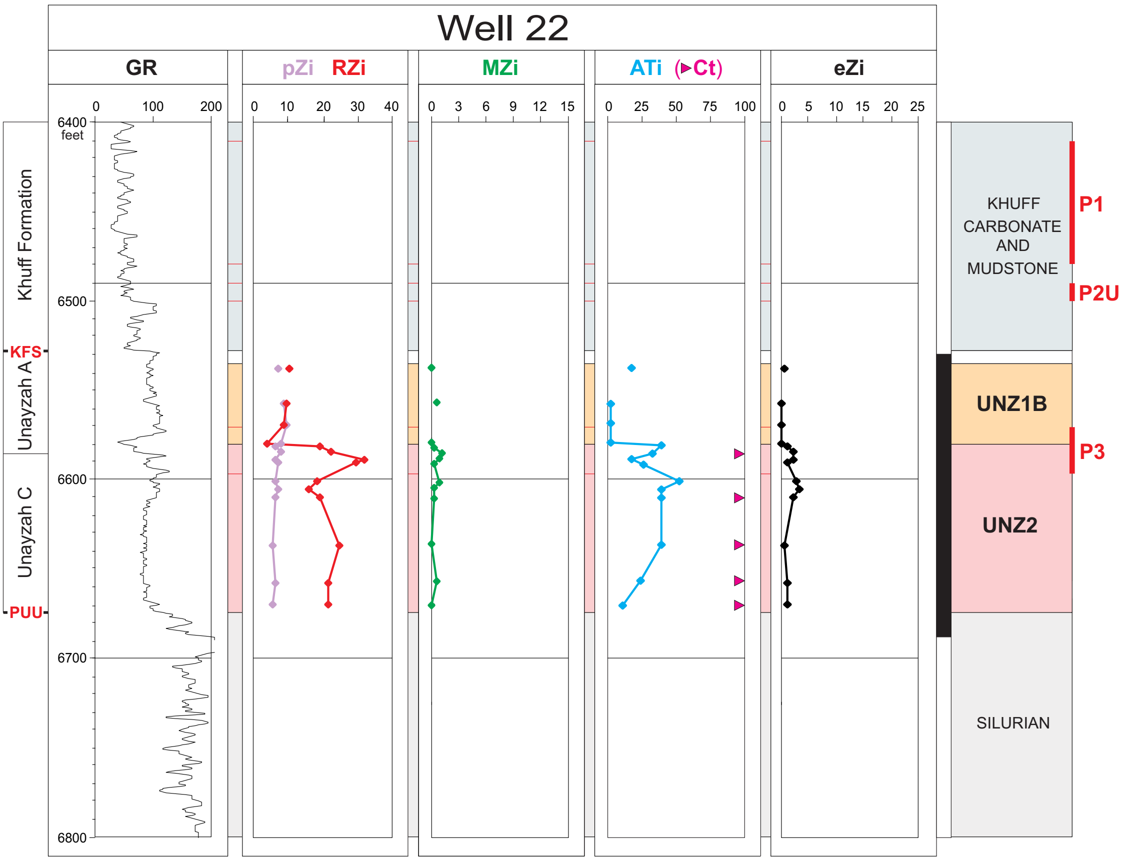

UNZ0 SANDSTONES
A
Well 25 continental
Well 40 continental
UNZ0 marine
Apatite:tourmaline (ATi)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
Rutile:zircon (RZi)
BASEMENT
B
Well 18
Apatite:tourmaline (ATi)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
Rutile:zircon (RZi)

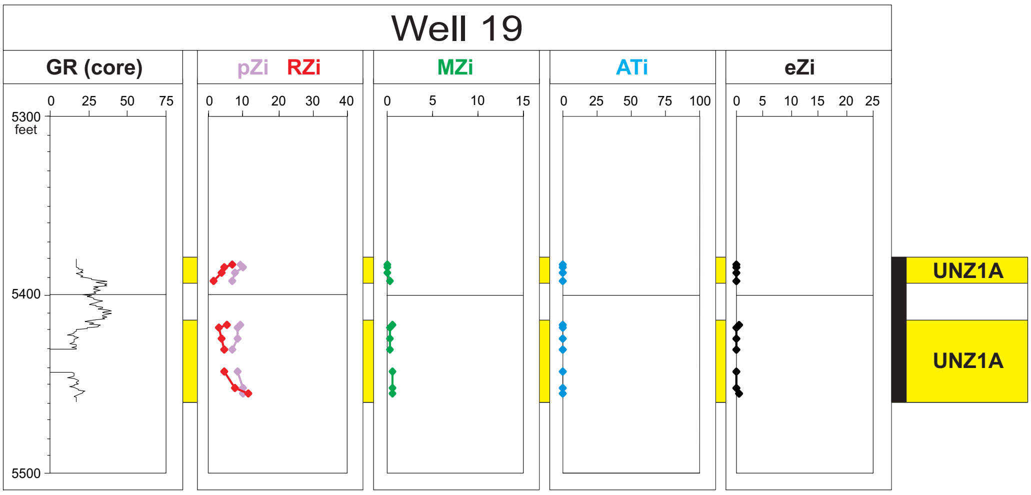

44°
52°
60°
31°
43
N
Arabian Gulf
LOCATION MAP
23°
ARABIAN SHIELD
46
48
Red Sea
49
Arabian Sea
15°
Gulf of Aden
0
300
km
44°
52°
47°
48°
49°
50°
Ghawar field
Riyadh
29
4
30
5
32
35
24°
23
CENTRAL ARABIAN ARCH
ARABIAN SHIELD
22
12
23°
17
16
1
40
● P3 palynofloras
● P4 palynofloras
0
km
100

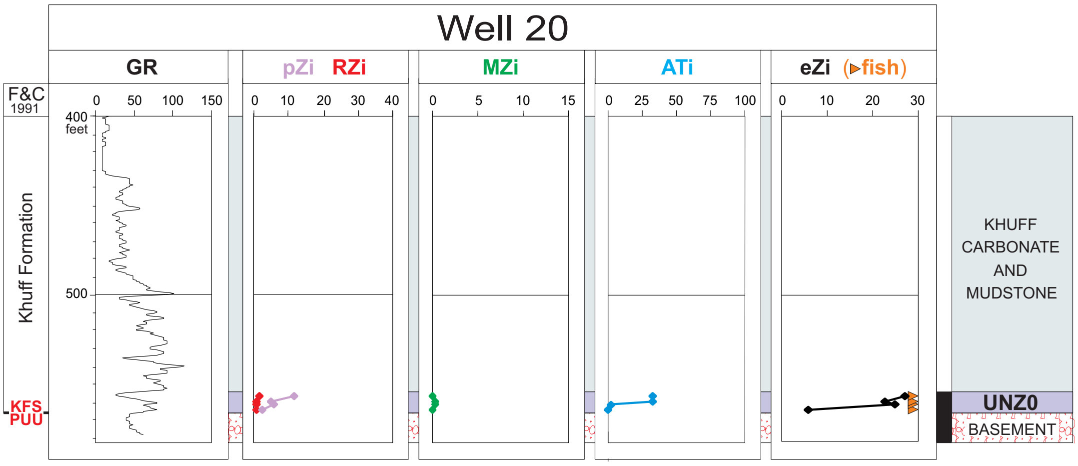

Well 49
GR not run
pZi RZi
0 10 20 30 40
MZi
0 2 4 6 8 10
ATi (▸Ct)
0 25 50 75 100
eZi
0 5 10 15 20
1800 feet
1900
2000
2100
2200
2300
2400
2500
2600
2700
2800
2900
3000
Unayzah Formation
Jurassic carbonates
?
P4U
na
UNZ2
P4L
CHLORITOID-BEARING DIAMICTITE

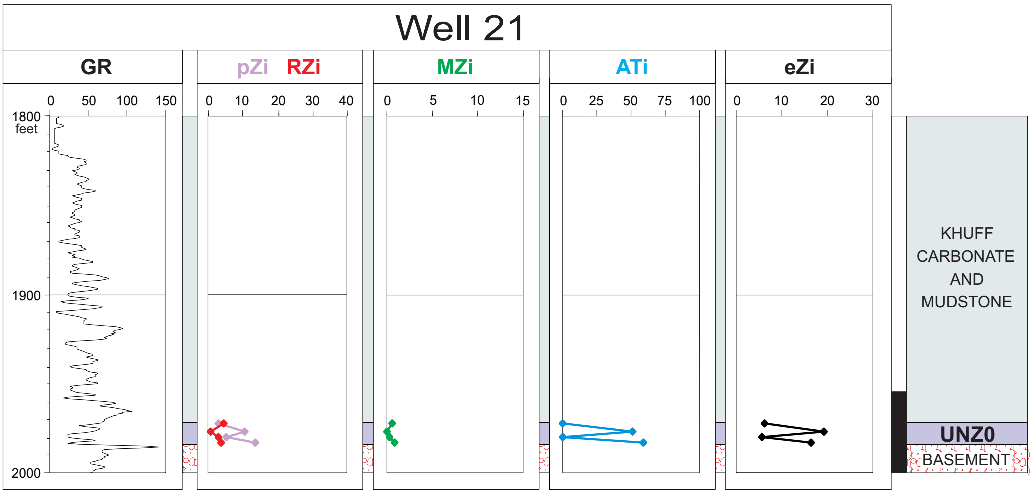

Well 40
GR
0 50 100 150
pZi RZi
0 10 20 30 40
MZi
0 3 6 9 12 15
ATi
0 25 50 75 100
eZi
0 5 10 15 20 25
14100 feet
14200
14300
14400
14500
14600
14700
14800
14900
15000
15100
15200
15300
15400
15500
15600
15700
KHUFF CARBONATE AND MUDSTONE
P1
P2*
UNZ0
UNZ1A/B
UNZ1A/B
UNZ2
P4U
UNZ3
DEVONIAN
UNZ0-TYPE SANDS IN CONTINENTAL FACIES

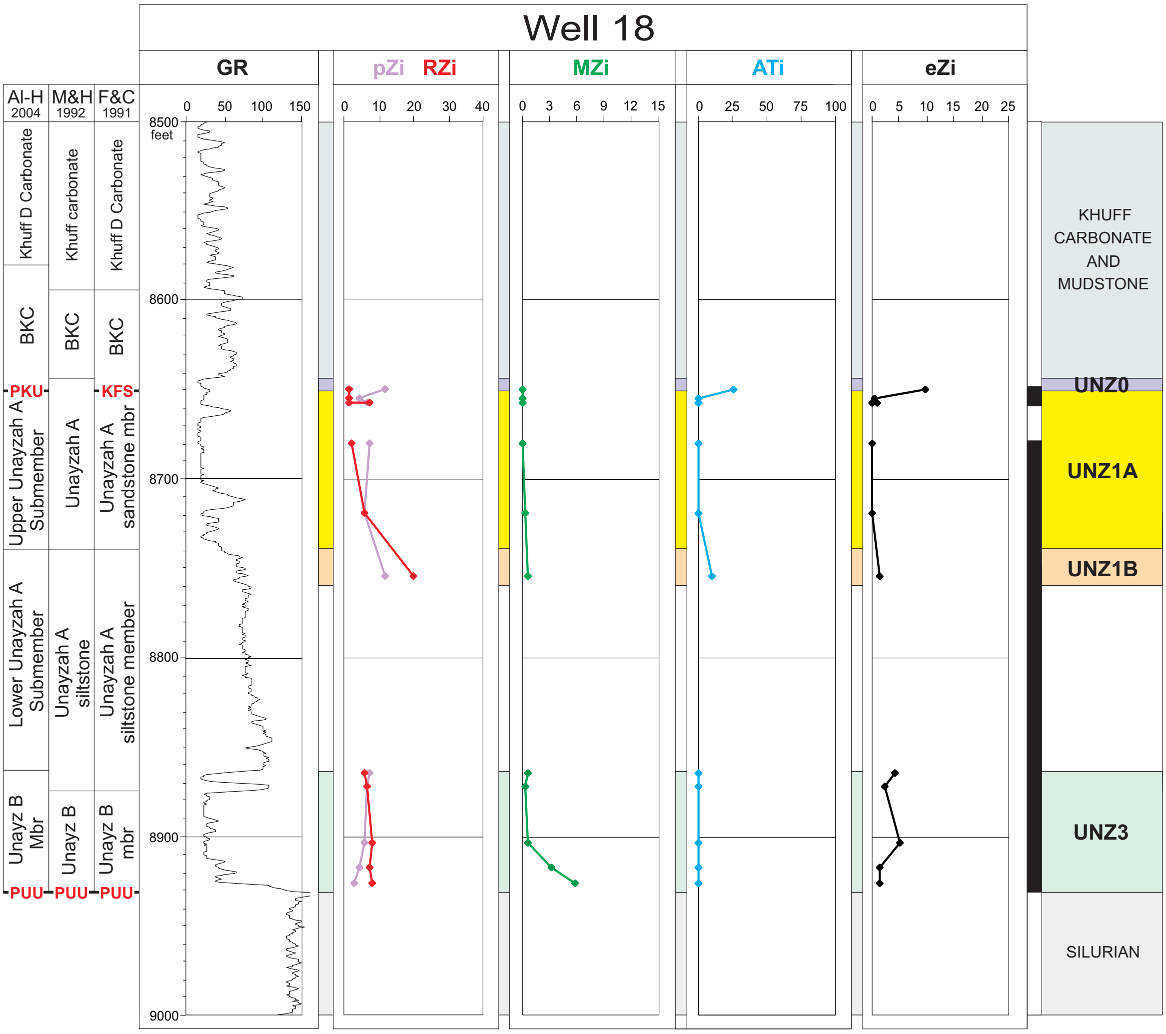

Well 33
GR
RZi
MZi
ATi
eZi
0 50 100 150
0 10 20 30 40
0 3 6 9 12 15
0 25 50 75 100
0 5 10 15 20 25
13800
feet
13900
14000
14100
14200
14300
14400
14500
14600
14700
14800
14900
15000
15100
15200
15300
KHUFF CARBONATE AND MUDSTONE
P2U
UNZ1A
UNZ1B
UNZ2
P4*
UNZ3
DEVONIAN

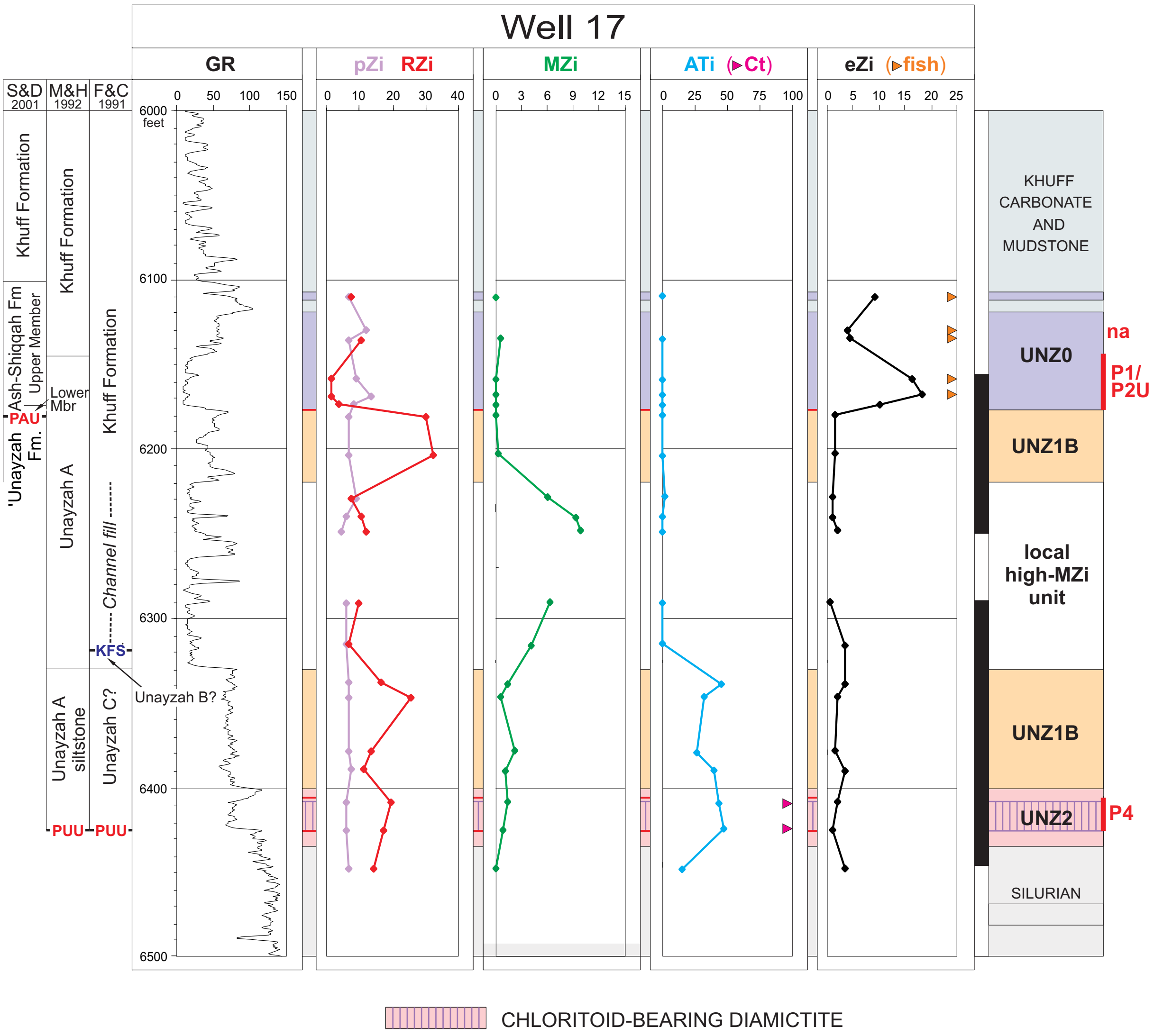

Well 22
GR
pZi RZi
MZi
ATi (▶Ct)
eZi
0
100
200
0
10
20
30
40
0
3
6
9
12
15
0
25
50
75
100
0
5
10
15
20
25
6400
feet
6500
6600
6700
6800
Khuff Formation
KFS
Unayzah A
Unayzah C
PUU
KHUFF CARBONATE AND MUDSTONE
P1
P2U
UNZ1B
P3
UNZ2
SILURIAN

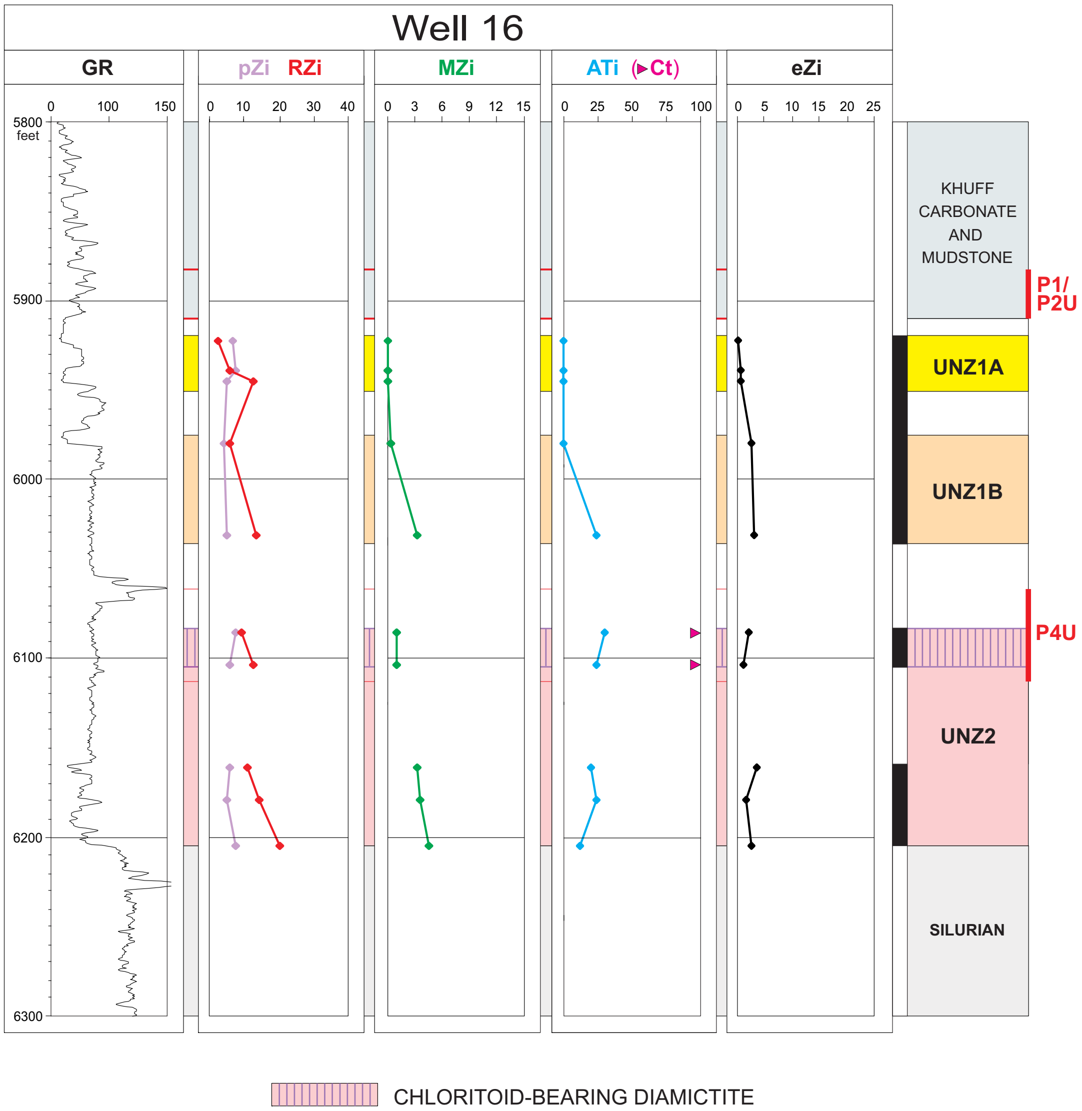

Well 19
GR (core)
pZi RZi
MZi
ATi
eZi
0 25 50 75
0 10 20 30 40
0 5 10 15
0 25 50 75 100
0 5 10 15 20 25
5300 feet
5400
5500
UNZ1A
UNZ1A

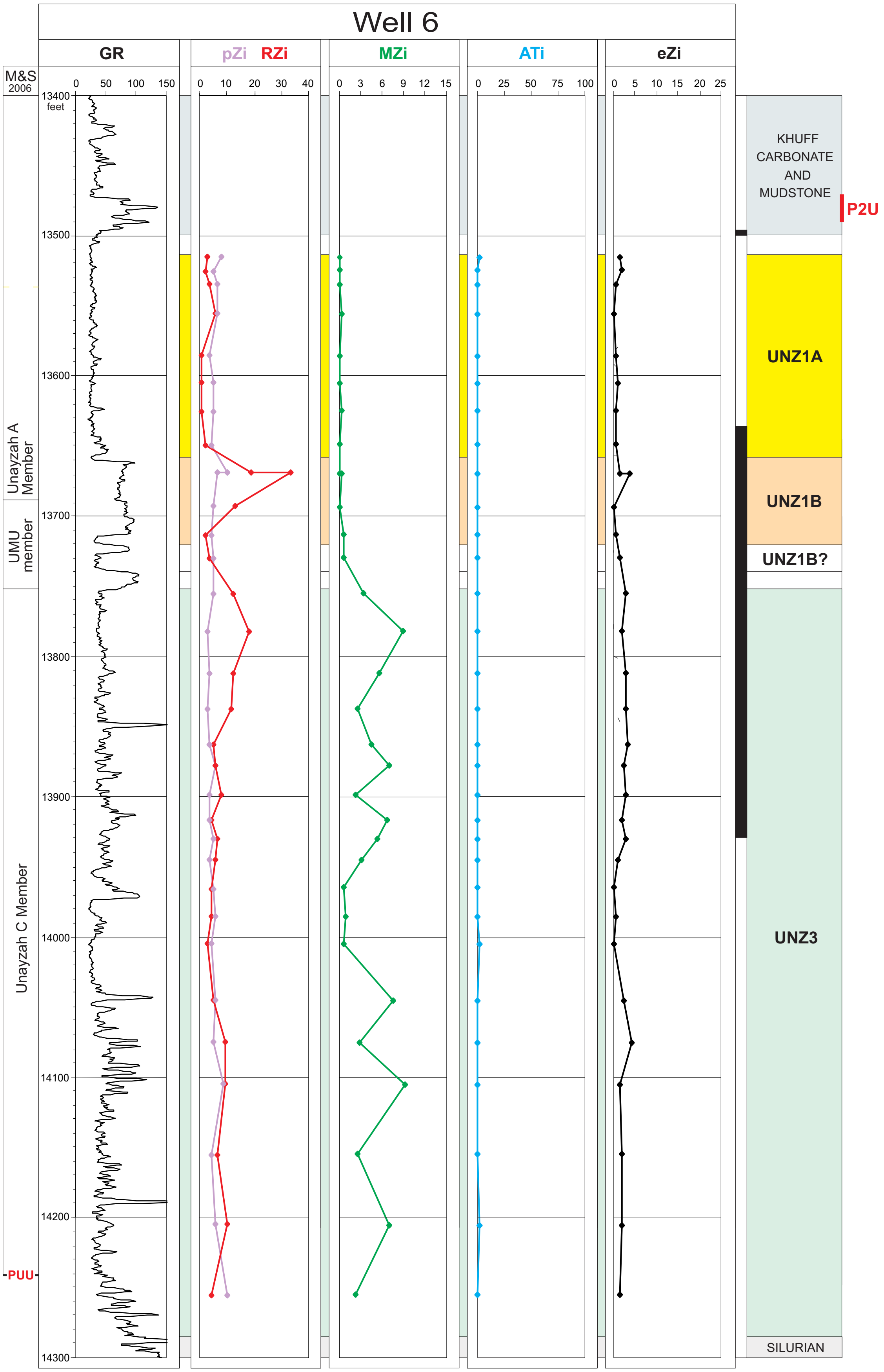

Well 20
GR
pZi RZi
MZi
ATi
eZi (▸fish)
F&C 1991
Khuff Formation
KFS
PUU
0 50 100 150
0 10 20 30 40
0 5 10 15
0 25 50 75 100
0 10 20 30
400 feet
500
KHUFF CARBONATE AND MUDSTONE
UNZ0
BASEMENT

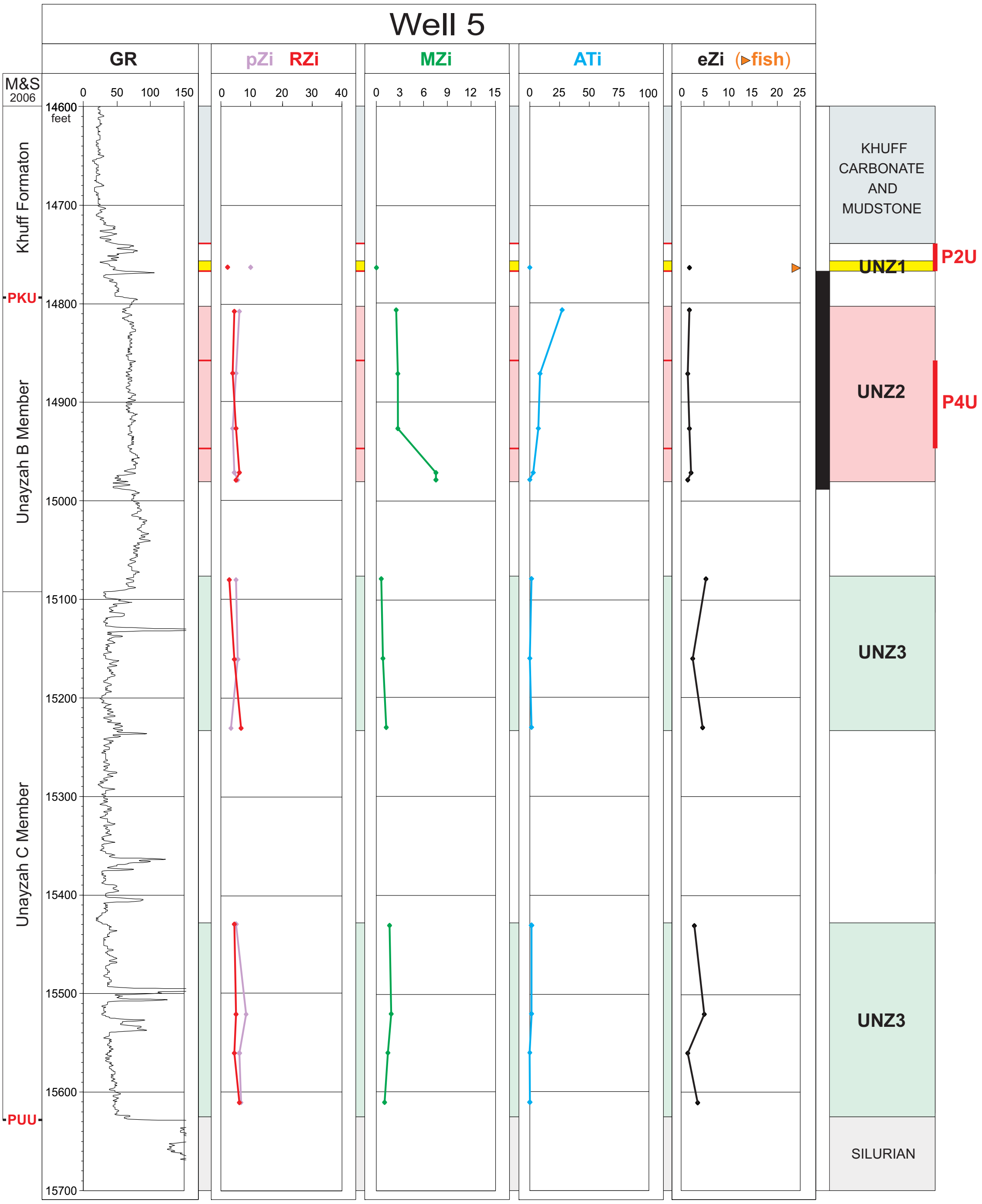

Well 21
GR
pZi RZi
MZi
ATi
eZi
0 50 100 150
0 10 20 30 40
0 5 10 15
0 25 50 75 100
0 10 20 30
1800 feet
1900
2000
KHUFF CARBONATE AND MUDSTONE
UNZ0
BASEMENT

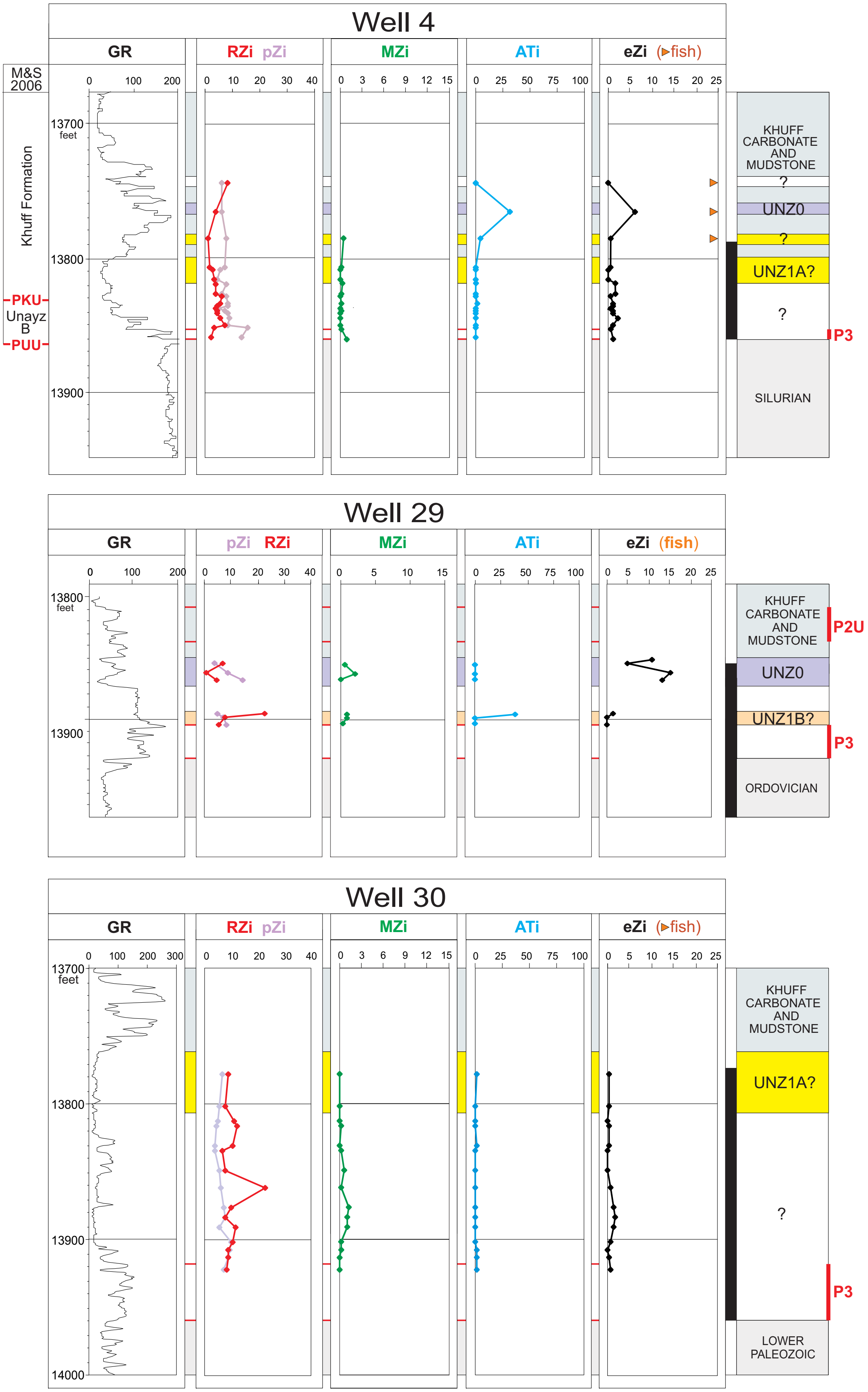

Well 18
GR
pZi RZi
MZi
ATi
eZi
Al-H 2004
M&H 1992
F&C 1991
0 50 100 150
0 10 20 30 40
0 3 6 9 12 15
0 25 50 75 100
0 5 10 15 20 25
8500 feet
8600
8700
8800
8900
9000
Khuff D Carbonate
Khuff carbonate
Khuff D Carbonate
BKC
BKC
BKC
PKU
KFS
Upper Unayzah A Submember
Unayzah A
Unayzah A sandstone mbr
Lower Unayzah A Submember
Unayzah A siltstone
Unayzah A siltstone member
Unayz B Mbr
Unayz B
Unayz B mbr
PUU
PUU
PUU
KHUFF CARBONATE AND MUDSTONE
UNZ0
UNZ1A
UNZ1B
UNZ3
SILURIAN

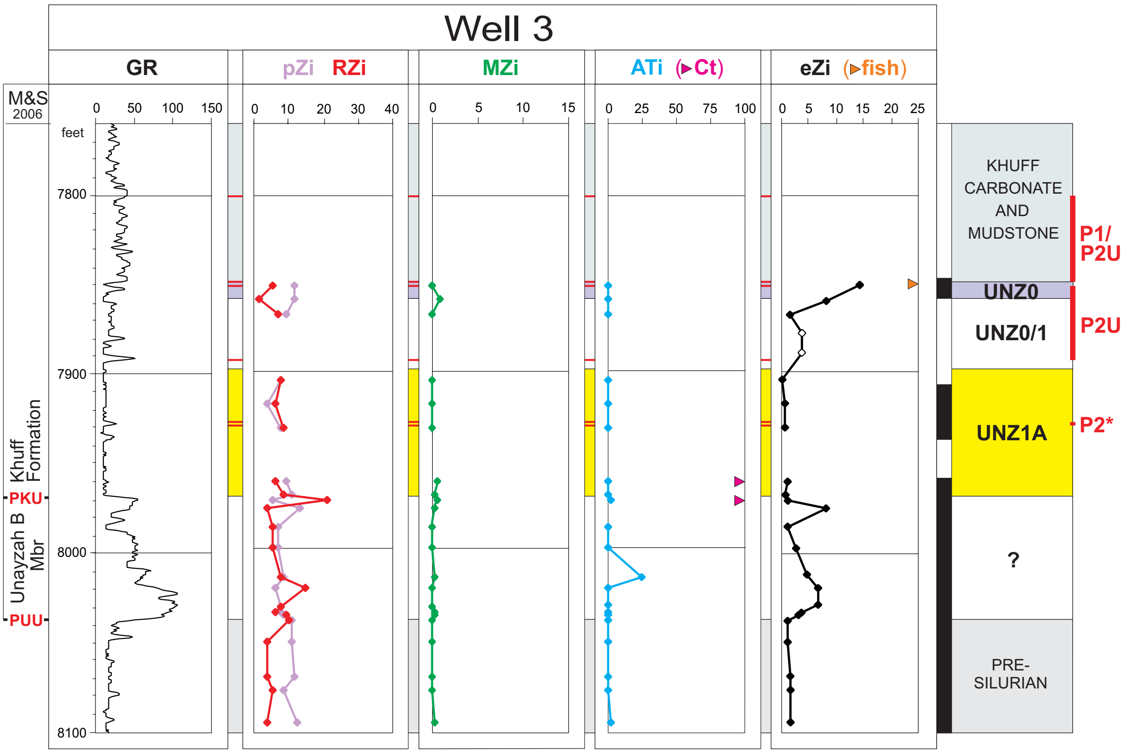

Well 17
GR
pZi RZi
MZi
ATi (▸Ct)
eZi (▸fish)
S&D 2001
M&H 1992
F&C 1991
Khuff Formation
Ash-Shiqqah Fm Upper Member
Lower Mbr
PAU
'Unayzah Fm.
Unayzah A
Channel fill
KFS
Unayzah B?
Unayzah A siltstone
Unayzah C?
PUU
PUU
0 50 100 150
0 10 20 30 40
0 3 6 9 12 15
0 25 50 75 100
0 5 10 15 20 25
6000 feet
6100
6200
6300
6400
6500
KHUFF CARBONATE AND MUDSTONE
UNZ0
na
P1/ P2U
UNZ1B
local high-MZi unit
UNZ1B
UNZ2
P4
SILURIAN
CHLORITOID-BEARING DIAMICTITE

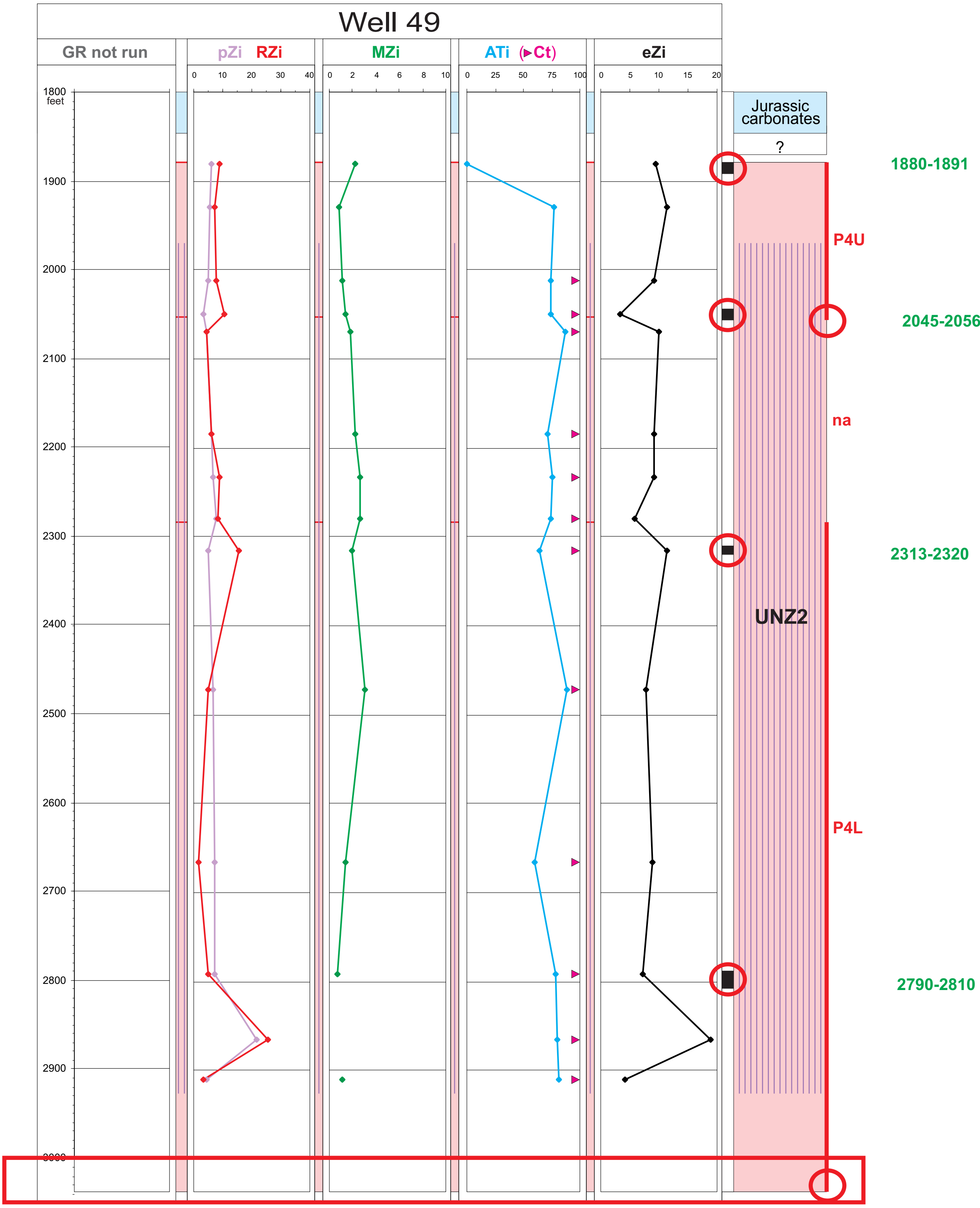

Well 16
GR
pZi RZi
MZi
ATi (▸Ct)
eZi
0
100
150
0
10
20
30
40
0
3
6
9
12
15
0
25
50
75
100
0
5
10
15
20
25
5800
feet
5900
6000
6100
6200
6300
KHUFF CARBONATE AND MUDSTONE
P1/ P2U
UNZ1A
UNZ1B
P4U
UNZ2
SILURIAN
▥ CHLORITOID-BEARING DIAMICTITE


Well 6
GR
pZi RZi
MZi
ATi
eZi
M&S 2006
0 50 100 150
0 10 20 30 40
0 3 6 9 12 15
0 25 50 75 100
0 5 10 15 20 25
13400 feet
13500
13600
13700
13800
13900
14000
14100
14200
14300
Unayzah A Member
UMU member
Unayzah C Member
PUU
KHUFF CARBONATE AND MUDSTONE
P2U
UNZ1A
UNZ1B
UNZ1B?
UNZ3
SILURIAN


Well 5
M&S
2006
GR
pZi RZi
MZi
ATi
eZi (▸fish)
0
50
100
150
0
10
20
30
40
0
3
6
9
12
15
0
25
50
75
100
0
5
10
15
20
25
14600
feet
14700
14800
14900
15000
15100
15200
15300
15400
15500
15600
15700
Khuff Formaton
PKU
Unayzah B Member
Unayzah C Member
PUU
KHUFF CARBONATE AND MUDSTONE
UNZ1
P2U
UNZ2
P4U
UNZ3
UNZ3
SILURIAN


Well 4
GR
RZi pZi
MZi
ATi
eZi (▸fish)
M&S 2006
Khuff Formation
PKU
Unayz B
PUU
13700 feet
13800
13900
0 100 200
0 10 20 30 40
0 3 6 9 12 15
0 25 50 75 100
0 5 10 15 20 25
KHUFF CARBONATE AND MUDSTONE
?
UNZ0
?
UNZ1A?
?
P3
SILURIAN
Well 29
GR
pZi RZi
MZi
ATi
eZi (fish)
13800 feet
13900
0 100 200
0 10 20 30 40
0 5 10 15
0 25 50 75 100
0 5 10 15 20 25
KHUFF CARBONATE AND MUDSTONE
P2U
UNZ0
UNZ1B?
P3
ORDOVICIAN
Well 30
GR
RZi pZi
MZi
ATi
eZi (▸fish)
13700 feet
13800
13900
14000
0 100 200 300
0 10 20 30 40
0 3 6 9 12 15
0 25 50 75 100
0 5 10 15 20 25
KHUFF CARBONATE AND MUDSTONE
UNZ1A?
?
P3
LOWER PALEOZOIC


Well 3
GR
pZi RZi
MZi
ATi (▶Ct)
eZi (▶fish)
M&S
2006
0 50 100 150
0 10 20 30 40
0 5 10 15
0 25 50 75 100
0 5 10 15 20 25
feet
7800
7900
8000
8100
Khuff Formation
Unayzah B Mbr
PKU
PUU
KHUFF CARBONATE AND MUDSTONE
UNZ0
UNZ0/1
UNZ1A
?
PRE-SILURIAN
P1/ P2U
P2U
P2*



DOWNWARD EXTENSION OF PLOT BOXES, COLOUR FILL AND P4L BAR TO 3050 FT

▥ CHLORITOID-BEARING DIAMICTITE