RECONNAISSANCE FOR AN EDIACARAN FAUNA, KINGDOM OF SAUDI ARABIA

By

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Index map of the Arabian Peninsula

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استطلاع حول حوانيات العصر الإديكاري في المملكة العربية السعودية

خاصة

هذا التقرير يقدم نتائج رحلات مستحاثين استطلاعين نظمتها هيئة المساحة الجيولوجية السعودية في عامي 200 و 2009، بالتعاون مع خصائصين من أستراليا وروسيا بفضل الإحوات الديفية من قبلي الرواسب الإديكاريانية متعددة الحالت في المملكة العربية السعودية. إن إصدار الرواسب الإديكاريانية المعروفة في المملكة العربية السعودية، هي تلك الموجودة في مجموعة جبلية، وقد تم اختيار عشر مناطق للبحث فيها عن تلك الرواسب.

وتزعم غلبت الأصل الحقلي على البحب في التألف غير المحولية والمشكلة بشكل ممتلك بما في ذلك (JIFN) وجوف (DHAQIQA) وناغير (NAGHR) ودايكا، حيث أن التركيب الإديكاريانية الحالة لم يتم العثور على مواد إديكارية. وكأنها ضعيفة عن سطوح مفتوحة ومنشآت تحتوي في السطح المائي، مع إشارة مادرة ماء (إثباتات) ذات الطلب المفتوحة.

كما نشأ بعض الترتيب الذي يمكن أن تكون ذات طبعة متعددة الحالت، وتمت الأجزاء التي تشبه البرونديوم، وأخرى تمثل مرحلة من أشياء الحولات متعددة الحالت، ثلاثيات الجدار من الإيديكارياوات والكريات.

وهناك عينة واحدة من طبعة طف بلايك تأتي الشيء من الجزء الأوسط من معسكر دايكا، أظهرت تدفقاً عرضاً ياظم لتماثل زراعة جيدة أخذ عمر 670 ± 4 مليون سنة، مما يشير إلى أقصى عمر من التربة.  

INTRODUCTION AND BACKGROUND

The rocks of the Arabian Shield are part of the greater Arabian Plate, which is currently drifting away from Africa and colliding with Eurasia (fig. 1). At the end of the Neoproterozoic era, roaks of the Arabian-Nubian Shield formed a unified structure that was part of the East African Orogen, a great collision zone originated between the West and East Gondwana paleocontinents (Stern, 1994; Meert, 2002). This Pan-African orogen stretched from Antarctica to Jordan along the present-day eastern margin of Africa, and through Madagascar, parts of India and the Arabian Peninsula (fig. 2).

The latest tectonic models recognize that many crustal blocks in the Arabian-Nubian Shield have particular stratigraphic, structural, and geochemical / isotopic characteristics which distinguish them from adjacent blocks, and therefore should be interpreted in terms of neotectonic orogenic terranes (Cenna and others, 2002; Johnson and Woldehaimanot, 2003; Steurer and Frost, 2006, with references therein). The terrains seem to have converged and amalgamated over a period of about 100 million years, between about 780-680 Ma, forming a neotectonic crust that was later overtopped by younger, post-amalgamation basins (Johnson, 2003). The basins accumulated both sedimentary and volcanic content and were intruded by enormous volumes of magma producing significant granite bodies, so completing a cycle of continental growth and culminating in the formation of continental lithosphere 45 km thick near the end of the Neoproterozoic. During this dynamic interval (ca. 780-542 Ma), oceanic basins formed and were destroyed, global and local glaciations affected the Earth surface, and unprecedented biological, biochemical and climatic changes took place. It was also a time when animal and plant life proliferated and some of the first animals - the Ediacarans - appeared followed by an explosion of biodiversity in the first 20-30 million years of the Cambrian, beginning around 542 Ma ago.

Ediacarans, the world’s oldest known diverse metazoans, have a fossil record with near global distribution, but are sporadic in their occurrence. For the most part they are restricted to late Neoproterozoic sequences. As outlined in Pedonkin and others (2007) and in the chart created by Vickers-Rich, Gelt and Trinder (in Vickers-Rich and Komarow, 2007) shown in plate 1, the biodiverse assemblages are best known, from oldest to youngest: in China, Newfoundland, the White Sea of northern Russia, the Flinders Ranges of South Australia, and the southern deserts of Namibia in Africa. Smaller and less diverse assemblages occur in Siberia, the Ukraine, the UK, India and a few other sites in Asia, North and South America. Most Ediacarans are preserved in shallow marine-derived sands and clays, although the Newfoundland forms appear to have lived in light deep waters in volcanic marine terranes.
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Ediacaran sedimentary sequences are widespread in the Arabian Shield, and selected exposures were the target of our project. Suggestions have been made that Ediacaran fossils are found in some of the youngest Neoproterozoic sedimentary sequences, especially those that seem to be quite undisturbed (Johnson, 2016; Miller and others, 2008). Thus, extensive sampling of many of these sequences was planned and carried out from 2008-2009 A.D. (1429-1430 A.H.), a joint effort of the Saudi Geological Survey, Monash University and the Paleontological Institute of the Russian Academy of Sciences, part of the UNESCO International Coordination Project IGCP493 (www.geosci.monash.edu.au/prespect).

PRECAMBRIAN SEQUENCES ON THE ARABIAN SHIELD

The history of the Arabian Shield begins with rocks of Archean and Paleoproterozoic continental crust, which nowadays form small occurrences in Yemen and west-central Saudi Arabia (Wisley and others, 1996; Whitehouse and others, 2001). These rocks are small parts of a vast supercontinent Rodinia, which assembled between 1000-1100 Ma and broke apart at the beginning of the Neoproterozoic (ca 870 Ma). This fragmentation resulted in formation of the Monazahique Ocean, a large seaway between rifted and drifted continents plates that later amalgamated as West and East Gondwana (Stenz, 1994; Meert, 2002). Passive margin sediments were deposited along the flanks of some of these plates, for example epiclastic-carbonate sequences at the eastern edge of the East Saharan craton in Africa (Abdelhamid and others, 2002) and in Oman (Allon, 2007). The succession in Oman developed as nearly continuous sedimentation between 725 Ma and 540 Ma of the Hauf Supergroup (Rieu and others, 2007; Hossellin, 1989, 2008), unconformable on metasedimentary basement (Mercelli and others, 2006) that possibly represent the termination of orogeny in the western part of East Gondwana.

In the Arabian Shield remnants of the Mozambique Ocean are represented by ophiolites, which range in age from ca 790 Ma to ca 675 Ma and document a nearly 200 million year period of oceanic magmatism (Johnson and others, 2004). Shortly after ocean crust generation, intra-oceanic arcs systems formed which accumulated thick volcanic-sedimentary sequences and later were intruded by plume-related rocks (Roudbol and others, 1983). As early as 800-750 Ma, the rifted fragments of older cratons (i.e. West and East Gondwana), began to rearrange, and over the following 200 million years the Mozambique Ocean was progressively consumed through terrane convergence involving such processes as sea-floor subduction, arc-arc collision, arc magmatism, ophiolite emplacement, intracrustal processes, and polyphase deformation and metamorphism. This convergence swept together deformed oceanic terranes of the Mozambique Ocean and reworked the margins of older cratonic blocks, such as the eastern part of the Saharan Massif (Abdelhamid and others, 2002), ultimately generating the vast East African orogen (Stenz, 1994; Meert, 2002; Collins and Piarrevez, 2005, fig. 2). Oceanic crusts in the Arabian Shield disappeared by ca 695 Ma and tectonic amalgamation was complete by ca 620-600 Ma (Genna and others, 2002). The resulting Arabian Shield tectogen is represented mostly by juvenile crust, formed by successive amalgamation of at least seven terranes (Johnson and Woldelakin, 2003; Stoner and Frost, 2006). The East African orogeny, ca 620-600 Ma, was followed by extension, associated with intra-plate magmatism and strong shearing along prevailing NW-SE trending zones known as the Najd fault system (Aar, 1986; Blachband and others, 2000; Genna and others, 2002). Synchronous with the Pan-African orogenetic events were general topographic uplift, onset of erosion, and development of sedimentary basins, tectonically classified as "post-amalgamation basins" (Johnson, 2003, 2006). The map presented in fig. 3 shows their distribution in the Arabian Shield and roughly supposed ages. This compilation indicates that some post-amalgamation basins are entirely Cyprogenian, some span the Cyprogenian-Ediacaran boundary, and others are entirely Ediacaran.

EDIACARAN BASINS

The Ediacaran period extends from 630 Ma (the top of the Cyprogenian) to 542 Ma (the base of the Cambrian; Knoll and others, 2006) and in Saudi Arabia is represented by volcano-sedimentary basin deposition and by vast amounts of pluictic, mainly granitic rocks. In general, the Ediacaran basins are clearly unconformable above the volcanic-sedimentary assemblages that constitute some of these deposits, for example epiclastic-carbonate sequences at the eastern edge of the East Saharan craton in Africa (Abdelhamid and others, 2002) and in Oman (Allon, 2007). The succession in Oman developed as nearly continuous sedimentation between 725 Ma and 540 Ma of the Hauf Supergroup (Rieu and others, 2007; Hossellin, 1989, 2008), unconformable on metasedimentary basement (Mercelli and others, 2006) that possibly represent the termination of orogeny in the western part of East Gondwana.

A number of different types of basins are present in the Arabian Shield, but their precise structural controls are not fully understood. Some basins, especially those of the Ediacaran Jibalah group, are conventionally interpreted as classic pull-aparts developed in the Arabian Shield toward the end of the Neoproterozoic along strike-slip shear zones of the NW-trending Najd fault system (Mashal and Kusky, 1999; Johnson, 2003; Miller and others, 2008). Others appear to be half-grabens developed in extensional environments or to be sag basins (Johnson, 2003, 2006). Fundamental unanswered question concern (1) the extent to which the basins were originally interconnected, and whether (2) some, all, or none were marine or connected to the Ediacaran ocean. The Ediacaran volcanic and sedimentary rocks now occupy separate basins, but are these basins original depositional basins that were formerly more extensive sheets of Ediacaran deposits, or did they originate as separate basins? Many of the Ediacaran basins contain red beds (reddish sandstone and siltstone) – does this mean that they are intra-continental deposits? If entirely intracratonic, then one must ask whether it is a likely place to find fossils. Recent investigations report that outcrops of the Jibalah Group display the same three-fold internal stratigraphy regionally across the Arabian Shield, indicating deposition within a single, laterally continuous basin that evolved from proximal fluvial conditions at its base, to a marine shelf setting at the top (Nicholson and others, 2008).

Among Ediacaran basins of special interest – considering their potential for containing metazoans - are the youngest sequences known as the Jibalah group. The group was originally defined by Delfour (1970), and extended by Johnson (2006) to include other formations of volcanic and sedimentary rocks that are separately named in various parts of the Shield, for example the Salawas, Salayyah, Nugh, Miqal, Salih, Matar, Dhaqaa and Murakhay formations in the northwest, and the Zargath and Jif formations in the north. These deposits are lumped into a single group because of their non-metamorphosed characteristic and their inferred Ediacaran age. Typical Jibalah group rocks are usually red, brown, purplish-brown or variegated grey-green and red. Successions, up to a few km thick, are composed of polymictic conglomerates, well-bedded arkosic sandslues, silstones to stromatolithic limestones, shales, cherts and sandstones of desertic limestones, breccia, and riffs (Johnson, op. cit.). Locally extensive carbonate deposits originated in lagoonites, estuarine or shallow marine environments (Miller and others, 2008). Suspect macrofossils were previously reported from some successions, and those were recommended to be...
searched for representatives of an Ediacaran fauna and (as) isotopic and sedimentologic evidence of Marianne-Vendian glaciation (e.g., Le Guerrouët and others, 2005; Miller and others, 2008).

Relationships to intrusive rocks in the Sheld imply that the Jihalab group is generally younger than about 620 Ma. SHRIMP analyses of zircons from two beds within the Muraykhah formation of the Jihalab group (in the Midyan Terrane, NW Saudi Arabia) yielded robust U-Pb ages ranging from 588 to 600 Ma (Nicholson and others, 2008). The same authors identified also the "Kurayshah group", which comprises a sequence of terminal Neoproterozoic andesitic lavas (containing pebbles of Muraykhah formation) and basalts unconfornably on the underlying Jihalab group (see also Hueensch, 2008). A sample of green volcanoclastic sandstone collected from the upper part of the Dhaqaa formation (from the Midyan Terrane) produced concordant (within 10%) detrital zircon ages. The youngest concordant age was 570 ± 4.6 Ma from the rim of the same zircon core generating the 599 ± 4.8 Ma date. The data indicate that the Dhaqaa formation is obviously younger than 599 Ma or even younger than 570 Ma (Kennedy and others in prep.; Miller and others, 2008). Kasaby and Masahi (2005) report a U-Pb zircon date of 624 ± 4.2 Ma from rhyolitic basement of the Jifina formation (Jihab group) that gives a lower limit for the formation of the basin while a 576 ± 5.3 Ma U-Pb zircon date from an undeformed felsite dyke that intrudes the sediments gives an upper time limit for their deposition.

An Ediacaran basin of tectonic character is represented by the Abu formation in the eastern part of the shield. SHRIMP dating of detrital zircons in the Abu formation indicates that it has a maximum depositional age of about 600 Ma, similar to that of the Dhaqaa formation (Kennedy and others in prep.). The basin for this conclusion is shown in the histogram below (fig. 4), which is a frequency plot of concordant ages of detrital zircons from the formation. Concordant, in this case, means ages that are within ±10 percent concordant on a U-Pb concordia diagram, a measure that helps to eliminate data affected by Pb loss or other isotopic disturbances, and so yield the most robust ages on which to base conclusions about deposition. Deposition presumably ceased about the time of emplacement of the main granites in the region at about 575 Ma. Based on the SHRIMP dating of detrital zircons, the Abu formation is now thought to be an Ediacaran rather than Cryogenian deposit (Kennedy and others, in prep.).

The Abu comprises a large basin in the eastern part of the shield and may well be a fore-arc basin with respect to the Aray volcano-tectonic terrane. In the literature, it is considered to be marine in origin, although specific studies of affiliated sedimentary environments have not been conducted. The formation consists of monotonous, fine-grained sandstone, some siltstone and limonite. The Abu formation differs from other post-amalgamation basins in that its base is nowhere exposed. Accordingly, it may be more appropriate to classify the Abu as a terrane-forming rock unit rather than as a post-amalgamation basin.

EDICARAN METAZOANS

The Ediacaran fauna is named after discovery by R. Sprigg, in March 1946, of organic impressions in the Ediacaran Hills, South Australia. It is now known that the oldest Ediacaran metazoans are represented by simple, disc-like forms discovered in the 610 to 600 Ma Twisted Formation (Mackenzie Mountains, NW Canada) and interpreted as uncalcified-grade body fossils (Hoffmann and others, 1990). An impoverished but characteristic Ediacaran assemblage (595-565 Ma old) was found in the upper part of the Drook Formation (SE Newfoundland, Canada), representing the oldest of the large, architecturally complex fossils (Narbonne and Gehling, 2004). About 1.5 km higher in the profile of the Drook Formation are localities of the well-known Mistaken Point fossils, which represent the oldest - dated at ca 575 Ma - diverse Ediacaran assemblage (Benus, 1988; Clapham and others, 2003). The richest and most diverse Ediacaran fossil assemblages are ca 555 Ma old and were recognized in the White Sea coast of Russia (Martin and others, 2000) and from the Flinders Ranges in South Australia (Glaessner and Wade, 1964; Vickers-Rich and Kemparower, 2007). The Ediacara fauna continued in full bloom until the Ediacaran-Cambrian boundary. The youngest forms, ranging in age from ca 548 to 534 Ma, are known from the Nama Group in Namibia (Grotzinger and others 1995, 2000) and Taqquq Gol Formation of southwestern Mongolia (Rasier and others, 1997). Although some taxa may linger into the Cambrian the characteristic Ediacara assemblage as a whole abruptly disappears at the beginning of Cambrian.

The available geochronological data suggests that the Jihalab group was contemporary with the radiation of the Ediacarans worldwide, and under favorable circumstances could contain representatives of the fauna. The most favorable part of the Jihalab group would be rocks younger than 575 Ma. Unfortunately, most of the Jihalab sequences in the Shield are not dated to this level of detail and the initial investigations reported here are therefore preliminary in nature.

INVESTIGATED OUTCROP AREAS OF THE JIHALAB GROUP: STRATIGRAPHY, SEDIMENTOLOGY, GEOCHRONOLOGY AND POSSIBLE EDICARANS

Fieldwork by our group in 2008 targeted areas in the southwestern part of the Arabian Shield island from Dibah and Al Wajh. Our team returned to these areas in 2009 and then moved to the south and east of the shield, concentrating on areas in the Antaq, Jfins and Sija basins.

AREA NO. 1: NAGHR FORMATION

Prospecting began in the Naghr formation inland from Dibah, mapped on the Shaghab Quadrangle (Grainer and Hanif, 1989, Johnson, 2005). The Naghr formation lies atop the Fara'a formation and the Bayda group. It is unconformably overtopped by early Paleozoic sandstone and siltstone (fig. 5). Like with other sequences we targeted in this study, these sediments were almost not affected by metamorphism, gently folded and generally dipping to the north, although the formation is locally vertical. The Naghr formation is composed of sandstones with horizons of conglomerate (fig. 6) and lesser amounts of siltstones, claystone and limestone (containing stromatolitic build-ups fig. 7). Ripple marks in sandstone beds point to shallow water conditions (fig. 8). Some of the conglomerates with large boulders of rhyolitic and granitic composition resemble glacial diamicnites with cuestas forms (fig. 9). Locally observed dropstones (fig. 10) further suggest a glacial environment. Some of the well-bedded sand-siltstone sequences contain structures resembling tee-pots, recently reinterpreted as megagrapheles (Allen and Hoffman, 2005) or fluidals (water/meteates) escape structures (compare Granger and others, 2000) providing reliable indicators of way-up direction (fig. 11). A few horizons of vesiculae, basic to intermediate, lava flows are locally present in the upper part of the Naghr formation (fig. 12) and may be contemporary with rare, concordant, reddish layers of brecciated rhyolitic sills (fig. 13).

Fine-grained siltstone in the lower part of the Naghr formation contains "elephant skin" structures (fig. 14) and "colonies" of unidentified oval structures that resemble Belauullinaeidae and Nemiana, an Ediacaran taxon with a debated aegid or metazoa origin (Podolinks and others, 2007, fig. 15).

Overall, the Naghr formation contains clear indications of microbial mat structures and stromatolites, but no definitive evidence of Ediacaran taxa. Etogenic structures suggestive of Belauullinaeidae or something similar (Nemiana) were observed but further discoveries are needed to confirm their identity.
Figure 6. Outcrops of the Naghr formation, showing well-bedded sandstones (in the upper part) and conglomerates (in the lower part); rocks are slightly dipping to the north.

Figure 7. Stromatolites in the Naghr formation.

Figure 8. Vertical surface of sandstone bedding with ripplemarks in the Naghr formation.

Figure 9. Possible glacial diamictite in the Naghr formation.

Figure 10. Possible dropstones (volcanic; pebbles), closely associated with the diamictite, in sandy-carbonate sequence in the Naghr formation.

Figure 11. Water (methylene?) escape structures or "tepee structures" (mega-ripple?) in alternating sandstone-limestone sequence in the Naghr formation.
Figure 12. Vesicular texture of basic to intermediate lava flows in the Naghr formation.

Figure 13. Fragment of brecciated rhyolitic sill in the Naghr formation.

Figure 14. Elephant-skin structures in the Naghr formation, indicative that the depositional surface was colonised by widespread microbial mats. Scale bar is 1 cm.

Figure 15. Beltanelloides or Neomiana-like structures in the Naghr formation; scale bar is 1 cm.

AREA NO. 2: SALUWAINI AND SALAHIYAH FORMATIONS

Johnson (2005) reports that the Saluwaini and Salahiyah formations, located about 50 km east of Duba, are possibly part of the Jihlab group. Davies & Green (1985) assigned them to the Ihalab group in the geological map of the Al Mowaykh Quadrangle. Nonetheless, both formations are isolated from the main outcrops of these groups, and therefore their exact stratigraphic position is uncertain. The Saluwaini formation is mostly conglomerate, which grades up into pebble conglomerate interbedded with sandstone and gray-green siltstone, and, at the top, contains rhyolite. The overlying Salahiyah formation includes sandstone, red and green siltstone, rhyolite crystal and lithic tuff, and local welded rhyolite tuff and agglomerate. It is intruded by sheets of rhyolite reaching up to 50 m thickness.

A single outcrop was made to the Saluwaini and Salahiyah formations and lithologies with regular bedding were investigated. However, no organic remains were discovered.

AREA NO. 3: DIAHQA FORMATION

Of all the sections examined in 2008-2009, the most promising was in the Diahqa formation to the west of Al Ula, near the confluence of Wadi al Fajr and Wadi Dihyag (fig. 16). The Diahqa formation, together with the underlying Maatar formation, are exposed in a small, isolated sedimentary basin unconformable on both the Bayda group and Marahit-suite granite, which implies that they are younger than 620 Ma (Johnson, 2006, fig. 17).

The Maatar formation consists of an approximately 100-m thick sequence of polymict conglomerate containing pebble-sized clasts of rhyolite, dacite, andesite, monzogranite, and alkali-feldspar granite, and interbedded pebbly lithic arenite and arkose in the upper part.

The Diahqa formation is about 400 m thick (see fig. 17), composed predominantly of regularly laminated limestones, litharenites and arkoses (fig. 18). It locally contains conglomerates (fig. 19), chert nodules and beds
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(fig. 20) and thin layers of volcanic ash-tuffs (fig. 21). Limestones are thin-bedded and laminated, with well preserved stromatolitic bioherms that are locally reworked to limestone breccia. It was from this section that Miller and others (2008) reported possible Ediacarians and trace fossils. For this reason, our team revisited this section again in 2009.

In addition to the investigated transect between ridges 1 and 3 documented by Miller and others (2008, fig. 17), we measured three more sections (marked as A, B and C on figs. 17, 21 and 22). Especially important is section B, bearing a possible Petromius imprint (figs. 26a, b). We must emphasize, however, that more material needs to be discovered before confirming this identification. A number

Figure 16. Section of the Al Wajj Quadrangle (after Davies, 1985) prospected for Ediacarians. This area at the confluence of Wadi ad Dayjah and Wadi al Matar exhibits a variety of lithologies, which although structurally affected are not highly altered. The Dhaiga formation (j) crops out in the lower right hand corner of the map overlying a complex of volcanics and coarse clastics of the Matar formation (jm).

Figure 17. Oblique, looking from SW, topography-draped GoogleEarth™ satellite view of the Dhaiga basin. Numbers 1, 2 and 3 refer respectively to ridge 1, 2 and 3, white line shows the transect route and green points are sample localities, all described by Miller and others (2008). Yellow lines and letters indicate sections A, B and C presented in this report. A total thickness of the Dhaiga formation between points 1 and 4 is about 400 m. Abbreviations: jm – Matar formation, bka – Belaya group, gs – unassigned syenogranite.

Figure 18. Regular, parallel bedding of sandy–carbonate sequence in the Dhaiga formation; view looking west between ridges 2 (left) and 3 (right) with vehicles in centre.

Figure 19. Conglomerates in the Dhaiga formation, ridge 2.

Figure 20. Dark, cherty inliers within limestones; lower part of the Dhaiga formation.
of other possible traces and body fossil imprints were noted and are illustrated below with their stratigraphic occurrence in the Dhaiba Formation, relative to the dated ash sample of 560±4 Ma (this paper). This places them well within the time range of Ediacaran known exclusively in Newfoundland and Russia.

The first measured section "A" illustrates a sedimentary transition between the Maitar and Dhaiba formations. It is noteworthy that coarse-grained facies of the Maitar formation are abruptly followed by limestones of Dhaiba formation, which possibly indicates a rapid sea level rise, a transgression of marine waters onto a continental environment.

Figure 21. Section "A" across contact between the Maitar and Dhaiba formations (ridges 1 of Miller and others, 2008), interval is 25 m thick. Units defined in section "A".
- Member a. Arkose conglomerate, with pebbles, gravel and boulders of predominantly igneous composition. 17 m thick. Member defined in section "A".
- Member b. Concretions, coarse sandstones with rare igneous breccias, blue-grey in colour. 3 m thick.
- Member c. Grey, wavy limestones solid limestone. 0.25 m thick.
- Member d. Arctositic medium-grained sandstone, 0.02 m thick.
- Member e. Grey, wavy laminated, solid limestone with chert concretions. 0.24 m thick.
- Member f. Unconsolidated conglomerate with carbonate cement. 0.13 m thick. Member g. Interbedded thin, laminated limestones and sandstones. 3 m thick.
- Member h. Thin, wavy-laminated, stratified limestone. 0.4 m thick.
- Member i. Thin, laminated sandstone. 0.3 m thick.
- Member j. Wavy laminated, stratified limestone with chert nodules in the upper part. 0.6 m thick.

Figure 22. Stratigraphic section "B" from the middle part of the Dhaiba formation; the top part of ridge 3 (Fig. 17). Units defined in section "B".
- Member a. Interbedded stromatolitic limestones and calcareous shales, 4.4 m thick.
- Member b. Greenish wavy limestone with nodules. 1.4 m thick.
- Member c. Green mudstone with two layers of reddish grey ash at the top. 0.3 m thick. Ash sample with date of 560 ± 4 Ma (Levinson/Hollings, this paper).
- Member d. Interbedded stromatolitic limestones and calcareous shales. 3.4 m thick.
- Member e. Greenish coarse-grained sandstone with pyrite silt clasts, overlain by conglomerate with pebbles and breccia of both sedimentary and intrusive origin. 0.8 m thick.
- Member f. Massive greyish-yellow limestone without clearly defined lamination. 0.8 m thick.
- Member g. Interbedded stromatolitic limestones and calcareous shales. 3.3 m thick.

Figure 23 a-b. Pteridinium-like structure preserved as a "ghost" in a coarse sandstone from the Dhaiba formation. At first thought to be simply ripple structures, the fine detail is suggestive of a multi-layered texture that has some similarities with fossils of this genus from Namibia. Images a and b are the same fossil with different lighting. There appear to be three superposed layers from top to bottom, in the lower third of the specimen besides tubular structures that run vertically in these images. Within the tubes there are further subdivisions. These smaller subdivisions could also be simple structure superimposed by deformation, so this specimen remains enigmatic, but likewise intriguing as a possible Ediacaran (scale in cm). c, d: comparison. Pteridinium simplex from the late Neoproterozoic Nama Group of Namibia.

Figure 24 a-b. Ediacaran-like structures (Cyclomedusa holdfast or concretions?, see Fig. 42a) from the Dhaiba formation derived from ridge 2 (photo a) and from sediments in section "B" (photo b) preserved as a positive feature on top of bed in member b (photo b).
A zircon concentrate was prepared at the Museum für Mineralogie und Geologie (Senckenberg Naturhistorische Sammlungen, Dresden). The fines samples were crushed in a jaw crusher and sieved for the fraction 63-400 μm. Density separation of this fraction was accomplished using LST (solution of lithium hexaneptane) in water, followed by magnetic separation of the heavy minerals in a Frantz isodynamic separator. Final selection of zircon grains for U-Pb dating was achieved by hand-picking under a binocular microscope. Zircon grains of all grain sizes and morphological types were selected, mounted in resin blocks and polished to half their thickness.

Zircons were analyzed for U, Th, and Pb isotopes by LA-ICP-MS techniques at the Museum für Mineralogie und Geologie (Senckenberg Naturhistorische Sammlungen, Dresden), using a Thermo-Scientific Element 2 XR sector FLD ICP-MS coupled to a NewWave UP-193 Excimer Laser System. A triangle-shaped, low volume laser cell developed by Ben Jahnke (Dresden, Germany) was used to enable sequential sampling of heterogeneous grains (e.g., growth zoned) during time resolved data acquisition. Each analysis consisted of approximately 15 s background acquisition followed by 35 s data acquisition, using a laser spot-size of 25 and 35 μm, respectively. A common-Pb correction based on the interference and background-corrected 206Pb/207Pb signal and a model Pb composition (Stacey and Kramers, 1977) was carried out if corrected 208Pb/232Th exceeded the internal errors of the measured ratios.

Discordant analyses were interpreted with care. Raw data were corrected for background signal, common Pb, laser induced elemental fractionation, instrumental mass discrimination, and time-dependent elemental fractionation of Pb/Th and Pb/U using an Excel® spreadsheet program developed by Axel Gerdts (Institute of Geosciences, Johann Wolfgang Goethe-University, Frankfurt, Frankfurt am Main, Germany). Reported uncertainties were propagated by quadratic addition of the external reproducibility obtained from the standard zircon GJ-1 (-0.6‰ and 0.5-1‰ for the 206Pb/207Pb and 206Pb/206Pb, respectively) during individual analytical sessions and the within-run precision of each analysis. Concordia diagrams (2 SD error ellipses) and Concordia ages (95% confidence level) were produced using Isoplot/Ex 2.49 (Ludwig, 2001). Frequency and relative probability plots were generated using AgeDisplay (Snoeckheert, 2004). The 207Pb/206Pb ages were used for zircons >1.0 Ga, and 208Pb/232Th ages for younger grains.
Further details of this analytical protocol are described in Frei & Gerdts (2008). Results of LA-ICP-MS U-Pb zircon dating are summarized in table 1 and shown as Concordia diagrams in figures 30 and 31. The geologic time scale of Gradstein and others (2004) was used.

Thirty-seven zircon grains produced concordia dates (94-104 Ga) ages (figs. 30, 31; table 1). The ages are all Neoproterozoic, ranging between 555±15 Ma and 837±25 Ma (table 1). The spread of ages suggests that the sample is a re-deposited volcanic ash, a tuffite. Zircon ages cluster in the ranges of 555 ± 56 Ma (17 grains), 598 ± 51 Ma (8 grains), and 623 ± 61 Ma (16 grains), with two older zircons at 743 and 837 Ma (table 1). A Concordia age calculated from the youngest zircon population (17 grains) of 560 ± 4 Ma (fig. 31) is interpreted as a maximum age constraint for deposition in the middle part of the Dhaisha formation, possibly recording a contemporary Ediacaran volcanic event.

A possible Pericontinent-like isochron complex is observed during our exploration of this area just below this ash layer is therefore well within the time range of Ediacaran. Other zircon populations from this layer seem to be related to earlier Pan-African orogenic events.

The third section studied (sec. "C" on fig. 17) represents the topmost part of the Dhaisha formation and constitutes a continuation of the 320 m thick profile described by Millard and others, (2008). Rocks of this section form an isolated hill with a flat summit (figs. 32, 33). The section is about 65 m thick and made up of sandstone and limestone beds (partly stromatolites) with interbeds of conglomerate and breccia. Conglomerate in the lower part of the section is particularly coarse grained and contains boulders of plutonic rocks floating in a sandy matrix; such conglomerate may be glacial diamictite (fig. 34). Locally these diamictites are overlain with erosional unconformity by other classic coarse-grained deposits forming channel fillings (fig. 35).

Figure 30. Concordia plot of all U-Pb ages for the ash-fall sample. Ellipses show 2σ uncertainties.

Figure 31. Concordia plot and age of 560 ± 4 Ma for the youngest zircon population of the ash-fall sample. Ellipses show 2σ uncertainties.
Figure 33. Section "C" of the uppermost part of the Dhaïqa formation cropping out on an isolated hill in the SE part of the Dhaïqa basin. Units defined in section "C":

Member a. Inter-bedded limezones and carbonate-rich shales. Rhythmic unit, the thickness of the individual cycles 1.5 to 2 m thick. Rare beds of massive yellow sandstone up to 20 cm thick. 7 m thick

Member b. Rhythmically interbedded unit of horizontally and wavy-laminated limestone. Cycles around 1.5 m thick, 8 m thick

Member c. Greasy, arcticus, medium to coarse-grained sandstones with conglomerate. Medium to thin lamination. 5 m thick

Member d. Non-laminated sandstones. Lower boundary sharp with layers of argillaritic, with clasts of breccia and gravel-size rounded dispersed. Color dirty-red to brown. Middle section with several boulder-sized clasts that are randomly distributed in the sandstone matrix. 8 m thick

Member e. Conglomerate and breccia with clasts of many different lithologies. Lower boundary unconformable. 4 m thick

Member f. Sandstones with dispersed boulders near base. Lower boundary not well exposed. 1 m thick

Member g. Breccia with abundant clasts 3-7 cm in diameter. Lower boundary unconformable. 2 m thick

Member h. Sandstones with dispersed boulders near top. 3 m thick

Member i. Breccia with abundant clasts 3-7 cm in diameter. Lower boundary unconformable. 2 m thick

Member j. Sandstones with several large boulders. Several lenses present and filled with grey gravels in the upper part. 12 m thick

Member k. Conglomerate consisting of well-rounded pebbles and boulders of varied lithology. 0.35 m thick

Member l. Poorly sorted sandstone with gravel-sized clasts. 0.25 m thick

Member m. Grauwacke which grades upwards into a breccia. Lower boundary unconformable 0.2 m thick

Figure 34. Conglomerates, possibly glacial diamictites, containing boulders and pebbles of plutonic and volcanic rocks in sandy matrix; Dhaïqa formation, member "d" in section "C" from figure 33.

Figure 35. Diamictites cut unconformably by chaotic deposits (possibly lahars). Dhaïqa formation, member "c" in section "C" from figure 33.

Figure 33. (Continuation) Section "C" of the uppermost part of the Dhaïqa formation cropping out on an isolated hill in the SE part of the Dhaïqa basin. Units defined in section "C":

Member n. Poorly sorted sandstone containing some gravel-sized clasts. 1 m thick

Member o. Breccia. 0.35 m thick

Member p. Conglomerate with carbonate cement. 0.15 m thick

Member q. Massive grey-yellow carbonate. 0.25 m thick

Member r. Wavy-laminated stromatolitic limestone. 0.2 m thick

Member s. Massive, grey-yellow limestone. 0.15 m thick

Member t. Laminated carbonate-rich shale. 0.3 m thick

Member u. Massive limestone lacking any lamination. 2.2 m thick

Member v. Stromatolitic limestone. 0.8 m thick

Member w. Muddy laminated limestone. 1.8 m thick

Member x. Inter-bedded limestone and conglomerates. 1.2 m thick

Member y. Laminated limestone. 2 m thick
which may represent high-energy debris-flow deposits similar to lahars.

The upper part of section “C” is composed of thinly laminated limestones and carbonaceous siltstones locally showing syn-sedimentary brecciation (layers of flat pebble conglomerates, fig. 36) and slump-folding (fig. 37). Sometimes limestones contain “exotic” boulders and pebbles of red granites and volcanics, possibly consistent with glacial “dropstones” released from icebergs while carbonate sedimentation was taking place in much warmer sea waters (fig. 38).

Apart from the enigmatic fossil forms described above, several other structures of possible biogenic origin were recovered. These include microbial bound-ripple marks (fig. 39), trace fossils (fig. 40) and oval metazans (?), which could be concretions or spongostromatoidal structures (figs. 41, 42a,b).

Summing up, a number of intriguing specimens were collected from the Dhaiga formation, some of which may be of organic origin. Throughout the formation, microbial mat structures and low-relief spongostromatoids are common. Certain structures, previously tentatively interpreted as possibly Ediacaran (Miller and others, 2008), appear to be metazoan concretions. Although specimens collected in 2008 and 2009 are quite suggestive of metazoan origin, better preserved specimens are required to confirm a metazoan identity. Also challenging is a determination of the sedimentary environment of the Dhaiga deposits. Our initial impression is that the Dhaiga formation resembles sediments that best extend Ediacaran faunas in such places as Namibia and South Australia. It is puzzling therefore why Ediacaran structures are not present in some abundance in the Kingdom. Perhaps the lithologies are similar but the environments of deposition were not favorable for colonization by Ediacaran.

Figure 36. Thinth-laminated limestones locally topped with syn-sedimentary breccias; Dhaiga formation, member “y” in section “C” from figure 33.

Figure 37. Thinly-laminated limestones folded by syn-sedimentary slumping, Dhaiga formation, member “y” in section “C” from figure 33.

Figure 38. Thinv-laminated limestones with possible “dropstones” (redish volcanic boulders and pebbles), Dhaiga formation, lower part of member “x” in section “C” from figure 33.

Figure 39. Microbial bound ripple marks in the Dhaiga formation are common.

Figure 40. Possible trace fossils of metazans from the Dhaiga formation noted previously in Miller and others (2008).
In addition to the Dhaisha Formation, outcrops of the Mijil Formation at 37°15′E/36°15′E were prospected along Wadi al Ward to the WSW of the Dhaisha section (fig. 16). Rocks in this area were fairly deformed, but some bedding planes were discerned. We found no indications of fossils and little evidence of microbial bound surfaces.

**Area No. 4: Jibalah group undivided and Muraykah Formation (southeast of Al ‘Ula)**

Jibalah group rocks were prospected southeast of Al ‘Ula in the Al Bada region and to the east of the main highway along much of the drainage of the Shih’ ad Dahshan wadi as well sections along the eastern side of the Wadi al ‘Ula (fig. 43).

Of special interest were occurrences of the Muraykah formation, which is considered to be the youngest unit in the Jibalah group (Hodges, 1987) and has been recently dated by Nicholson and others (2008). In these exposures the rocks are carbonate dominated and chert-rich, with significant indications of microbial bound sediments. In the locality west of the Muraykah village (close to the asphalt road from Al ‘Ula to Yanbu, fig. 44), down section from carbonate and chert intervals, are fine sandstones and siltstones that contain concretionary bodies of possible organic origin (fig. 45). Microbial bound sediments, indicated on both upper and lower bedding planes, are abundant and resemble sediments preserving Ediacaran elsewhere in the world. However, the only possible organic forms discovered are structures resembling *Bhathratheterax* or *Nemiana* (fig. 46), similar to *Eoanomia conchochirita* (figs. 47, 48), and possible tracc fossils (figs. 49, 50) very similar to those found in the Dhaisha formation (cf. fig. 40).

Other well exposed sections of (undivided) Jibalah group rocks are found along Wadi Shi’s, Wadi Dahshan, and the eastern side of the Wadi Al ‘Ula. Although the lithologies were very promising, showing well-exposed and well-preserved bedding planes of alternating sandstones, siltstones and limestones (figs. 51, 52) organic forms were not noticed.

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**Figure 43.** Portion of the Saih Al Matran Quadrangle (Hodges, 1987) prospected for Ediacaran. Blue area (u) is the Jibalah group undivided, bright blue (j) is the Muraykah formation.

**Figure 44.** Outcrops of the Muraykah formation to the south of Al ‘Ula, west of Muraykah village.
Figure 45. Concretions (?) on the bedding plane of sandstones; Muraykhah formation, west of Muraykhah village.

Figure 46. Beltanellaides - or Nemuana - like structures or could they be simply mudcreaks?; Muraykhah formation.

Figure 47. Possible metazoan fossils and burrows/ traces in the Muraykhah formation, west of Muraykhah village; reminiscent of Ioaspondylos octobrachiata from the Joushanduo black shale of south China and sandstones of the Fildem Ranges of Australia, both of Neoproterozoic age. I. octobrachiata appears to be a diplioelastic-gradiola animal that shares some features with conodonts and ctenophores, but whose phylogenetic relationships are unclear (Zhi and others, 2008).

Figure 48. Outline of structure on upper right-hand specimen in figure 45, indicative of detailed structure. Although superficially similar to Ioaspondylos from the Neoproterozoic of China and Australia, when other structures on the same slab are examined in more detail there is high variability in construction. These structures are more likely trace fossils, as are other linear structures on the slab, suggestive of yet another type of trace. Further collection and detailed examination are needed to resolve the origin of these structures and whether or not they are biotic and metazoan.

Figure 49. Possible metazoan fossils and burrows/traces in the Muraykhah formation.
Area no. 5: Jifn formation (Antaq Basin)

Much of the 2009 field season was spent searching the area on the eastern part of the Arabian Shield in the region of Ad Dawadimi as far south as Halaban and following the fault-bounded basins as far north as the Jifn Basin near Nukrah. Of these locations most of the time was spent in the Antaq Basin, a region of Jiblah group rocks divided into a lower unit of the Umm Al Aisha formation and an upper unit of the Jifn formation (Delfour, 1979: fig. 53). The Umm Al Aisha formation unconformably overlies magmatic rocks of the Suwaj terrane composed chiefly of gabbros, diorites, granodiorites and tonalites dated at 695-685 Ma (Sweeney and others, 1984). The Umm Al Aisha formation consists of conglomerates (at the base), cherty limestones, shales and sandstones. The exposures occur as numerous low relief outcrops of limited aerial extent; they are commonly sand covered and consequently difficult to examine. The Jifn formation, in contrast, is very well exposed, particularly in the area of the Jabal Antqa (fig. 54), and could be explored across an approximately 1.5 km-thick continuous succession of sandstones, arizons, shales, conglomerates, and subordinate limestones, andesites and basalts. Nettles (2009) presented U-Pb detrital zircon datings from three inter of ash beds, with maximum depositional ages on each ash bed being 573 ± 12 Ma, 568 ± 11 Ma and 584.8 ± 9.8 Ma, which constrain the maximal depositional age of the Jifn formation at approximately 570 Ma.

Sandstones commonly preserve ripple-marks (fig. 55), cross-bedding (fig. 56), mudcrack casts (fig. 57), post-depositional convolute folding (fig. 58), “ball and pillow” structures (fig. 59), enigmatic bag-like structures (figs. 60, 61), and very rare groove marks indicating dragging of clasts by water currents (fig. 62).

Organic forms found in the Jifn formation in Jabal Antqa are represented by microbially bound ripple marks and algal mats (figs. 63, 64, 65, 66), trace fossils (fig. 67), and two enigmatic structures of possible organic origin, one of tube-like body (fig. 68) and the second one, found by Nettles (2009), who interpreted it as Chasmosaurs (fig. 69) and which could alternatively represent a fragment of Presentia. Nettles (op.cit) also reports Apipodinia from the Antqa Basin.
Figure 54. Jibalah group (Jlfm formation) cropping out at the Jabal Antaq. This long, step-like sequence is formed by differential weathering of alternating lithologies. Cliffs are composed of greenish-gray sandstones with conglomerates, whereas flat structural benches correspond to less resistant reddish limestones and ripple-marked sandstones (Delfour, 1979).

Figure 55. Wavy ripple marks on the bedding surface of sandstones; Jlfm formation; Antaq Basin.

Figure 56. Cross-beding in sandstones, Jlfm formation; Antaq Basin.

Figure 57. Mud-crack casts in sandstones, Jlfm formation; Antaq Basin.

Figure 58. Convolute folding in sandstones, Jlfm formation; Antaq Basin.

Figure 59. Post-depositional “ball and pillow” structures formed at the boundary between sandstone and mudstone layers; Jlfm formation; Antaq Basin.
Figure 60. Bag-like structures in sandstones, Jilf formation; Antaq Basin. Whether these are simply sedimentary structures, as in Figure 61, or bag-like structures associated with metazoans common found in the Namibian and Australia Ediacaran sediments remains to be determined.

Figure 61. Sedimentary structures in recent dune sands are possible analogs for some of the "bag-like" structures noted in several of the Neoproterozoic sections prospected for Ediacaran metazoans. The only certain way in which inorganic can be distinguished from organically induced bag formation is if, as in the case of fossils discovered in the Neoproterozoic of Namibia and Australia, internal structures are located proving their organic nature.

Figure 62. Groove marks; Jilf formation; Antaq Basin.

Figure 63. Microbially bound ripple marks with possible mat breakup in progress or even possible desiccation cracks; Jilf formation; Antaq Basin.

Figure 64. Microbially bound ripple marks; Jilf formation; Antaq Basin.
Figure 56. Microbial mat (7); Jfn formation; Antaql Basin.

Figure 57. Trace fossils or sedimentary structures; Jfn formation; Antaql Basin.

Figure 66. Microbial mat bound (7); Jfn formation; Antaql Basin.

Figure 69. Enigmatic structure (fragment of Pteridinium? or Chondrodiscus?; see Nettle, 2000) found in sandstones; diameter of coin is 1 cm; Jfn formation; Antaql Basin.

AREA NO. 6: JFN FORMATION (Jabal Jalaylah)
A half-day field trip was carried out to a small outcrop of the Jfn formation at Jabal Jalaylah near Abu Asirahsh village, 15 km north of Bijdjah (about 100 km NW from the Jabal Antaq, close to the Halabat-Zanglat fault zone). According to exploratory notes for the geological map of the Ad Dawadimi Quadrangle (Dalfour and others, 1982) the Jfn formation is chiefly composed here of well bedded, reddish to brownish lithic to feldspathic arenites with intercalations of alunite, shale, and conglomerates. Locally the formation contains vitrified tuffs or amygdaloidal and autobrecciated andesitic lavas. One sample of the volcanic ash was collected at Jabal Jalaylah (24°33'34.9"N / 45°33'37.66"E) for geochemistry, as were greenish/grey shale samples for stratigraphic studies, which will be carried out in the future. In this region, as at Jabal Antaq, bag-like structures are present. So too are ironstones, which were thoroughly searched because ironstones in Namibia have produced highly detailed, three dimensional specimens of zain germanospora, some of the most primitive Ediacaran. Unfortunately, no discoveries were made.

AREA NO. 7 AND 8: JIBALAH GROUP UNDIVIDED (BE B SJA BASIN) AND JFN FORMATION (JEFN BASIN)
Additional prospecting was carried out in the B's Sja Basin southwest of Alif (area no. 7) and further north, in the Jfn basin along the Halabat-Zanglat fault zone (area no. 8). Sediments in these areas, chiefly sandstones, mudstones with interbedded ironstones, are virtually unmetamorphosed and appear suitable for the preservation of soft-bodied Ediacarans. Observed structures included abundant microbial bound sediments, bag-like structures, and a variety of enigmatic structures of uncertain organic origin. In the Jfn Basin, some rocks mapped at Jibalah appear to belong to the Cambrian Sja Sandstone due to both the lithology and trace fossil content, and should be further prospected.

AREA NO. 9: HABID FORMATION
The Habid formation, located about 250 km NE of Jeddah, crops out as a discontinuous rim surrounding a circular Cretaceous monometer intrusion (Khosandi, 1982). The
formation consists of thickly bedded, massive graywackes, sandstones and conglomerates as well as minor interbedded layers of fine-grained marls to intermediate psammolastics. Southernmost exposures at Jabal Ushwa'aa were examined in a one-day fieldtrip. No organic forms were found except for enigmatic oval-shaped structures resembling *Bellanelloides* (fig. 70) preserved in a bedding plane from a loose sandstone block.

**Area No. 10: Fatima Formation**

The Fatima Formation (Bahsed and others, 1984; Dube, Dube and others, 1985; Duggerman, 1991) crops out east of Jiddah, half-way between Jiddah and Mecca, and has produced material worthy of further investigation, including: (1) possible Ediacaran found during our prospecting of this area in 2008 (fig. 71) along with stromatolites (*Canophyton*), (2) deep burrow structures (*Skolithus*) and (3) structures assigned to archaeocyathiids (Basahl and others, 1984). This sequence needs further investigation to refine its age and thereby resolve conflicting reports of Cambrian (Basahl and others, 1984) and Neoproterozoic (Darbyshire and others, 1983) ages. The material assigned to archaeocyathiids (Basahl and others, 1984) are of minute size - much smaller than known archaeocyathids - and should be restudied and compared to such forms as *Gondwania*, a form well established in the Neoproterozoic, because of similar size and perhaps similar morphology. *Gondwania* was a significant reef-builder in late Neoproterozoic sequences globally.

**Cambrian Fossils**

Our work centered on the Neoproterozoic of the Arabian Shield, and no significant time was spent prospecting the base of the Cambrian, so well represented by the *Saq Sandstone* (fig. 72) and other related units. The Neoproterozoic / Cambrian boundary is highly unconformable, and the metazoan faunas that succeed the soft-bodied Ediacaras exploded in diversity during the first 20 million years of the Phanerozoic (Bedonie and others, 2007 and references therein). The Early Cambrian faunas of the Arabian Shield are almost unknown, but *Craniote* traces (fig. 73), abundant in even the oldest Phanerozoic sediments of the northern Shield, denote the presence of trilobites - the most dominant metazoans of the time.

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**Figure 70.** *Bellanelloides*-like structures on what appear to be the upper surface of a bed in the Habit formation.

**Figure 71.** Frond-like possible Ediacaran from the Fatima formation near Jiddah, Saudi Arabia.

**Figure 72.** Contact between the overlying *Saq Sandstone* and the underlying Neoproterozoic units near Al 'Ula in the northwestern part of the Arabian Shield.

**Figure 73.** *Craniote* trails in the Scoyenia ichnofacies, Sajir member of the *Saq Sandstone*, the basal Cambrian unit on the Arabian Shield. From a locality in the Duba region.
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Chart created by Patricia Vickers-Rich, Peter Trusler, and Draga Gell