The Ordovician–Silurian boundary in Saudi Arabia

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Synopsis

An account is given of the environments of deposition across the Ordovician–Silurian boundary which occurs within the Tabuk Formation, Saudi Arabia. The results of much recent work are appraised and earlier conclusions are reassessed with respect to it. The late Ordovician glaciation is considered to have been a prime factor influencing sedimentation, for example by restricting land derived clastic input. There appears to be no regionally significant depositional hiatus, and the beds about the boundary are best regarded as conformable. The general environment of deposition was of prograding sandstones, tidal flats, delta cycles and intermittent marine incursions on a tectonically stable structural platform. A basically normal graptolite sequence is deduced across the boundary region, and a précis is given of the relative dating achieved by these and other fossil groups.

Introduction

Early Palaeozoic rocks of the Arabian Peninsula are almost exclusively siliciclastics whose primary source was erosion from the western part of the Precambrian Arabian Shield. These rocks were successively deposited to the east along a regressive shoreline in fluvio-deltaic and shallow water marine environments. The Ordovician–Silurian boundary in Saudi Arabia occurs within the Tabuk Formation of this suite of rocks.

The Tabuk Formation was originally designated by R. A. Bramkamp in 1954 in an unpublished report of the Arabian American Oil Company. His definition in amended form was presented on U. S. Geological Survey Miscellaneous Geologic Investigations Map I-270A (1963). The formation was formally defined by Powers *et al.* (1966). A summary of details of the formation is given by Powers (1968).

The type section, in the Tabuk area of northwest Saudi Arabia (Fig. 1), consists of 1071 m of shale, siltstone and sandstone, deposited in shallow water in a complex of fluviatile, littoral beach, deltaic, and tidal flat sediments. Holomarine shale members, recording marine transgressive phases, occur at the base, near the middle and near the top. These are designated, respectively, the Hanadir, the Ra'an, and the Qusaiba shales. However, in the vicinity of the type section, only the basal member, the Hanadir, shows easily mappable lateral continuity.

Powers (1966) designated a reference section of 677·2 m thickness in the Qasim (Qusaiba) area (Fig. 1) which is a composite section from several excellent exposures in the vicinities of Jebal Hanadir, Khashm Ra'an, and in the Qusaiba depression. For the local definition of the Ordovician–Silurian boundary this section is best, with the advantages that (1) all three holomarine shale members are well developed and well exposed, (2) all three shale members are graptolite-bearing, (3) additional fossil collections, including graptolites and trilobites, have been made in more recent years and serve to refine previous age assignments and stratigraphical relationships within the formation on outcrop as well as in subsurface areas several hundred kilometres to the east, and (4) glacial beds recording an 'end-of-the-Ordovician' glaciation event and stratigraphical and sedimentary details have been recently studied in the area. Fig. 2 shows a generalized stratigraphical section in the Qasim area.

Stratigraphy and sedimentation

Rocks of the Tabuk Formation were deposited in shallow water on a very broad and extensive, gently sloping epicontinental shelf, reflecting the underlying basement structure of a nearly flat, gently dipping, stable homoclinal platform (Powers *et al.* 1966). Present dips on outcrop average less than 2° eastward and have been little disturbed since deposition. Graptolitic shales

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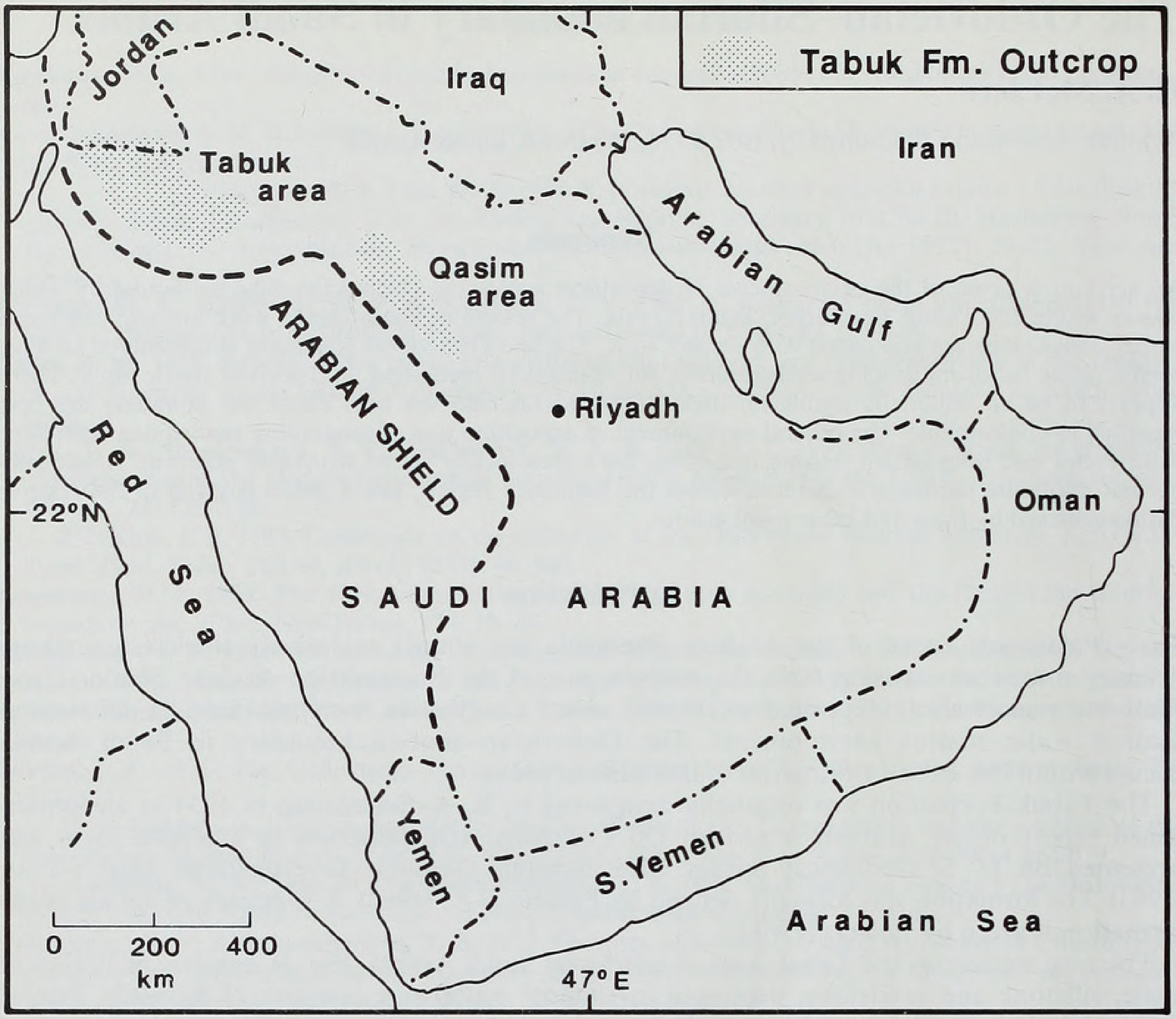

Fig. 1 Outcrop map of the Tabuk Formation in Saudi Arabia. Equivalent rocks on the surface and in the subsurface have been found as far east as Oman.

and sands with other macrofossils and trace fossils as well as a palynomorph suite of chitinozoans, acritarchs and plant spores occur on surface outcrop as well as in the deeper subsurface section of the eastern part of Saudi Arabia and Oman. The Tabuk Formation gradually thickens basinward to the east, where it is extensive in the subsurface, but, except that the three marine shales tend to be less distinct as discrete units, no gross changes in facies or depositional environment are apparent. Carbonate beds are known only as rare thin lenses at outcrop.

Lithologies of the Tabuk Formation comprise three basic types: (1) medium-grained, partly cross-bedded, partly massive-bedded, channelled sandstone, (2) fine-grained, laminated and ripple-marked, micaceous sandstones and siltstones, and (3) laminated and micaceous, fossiliferous shales, the Hanadir, the Ra'an and the Qusaiba. The shales grade upwards through siltstone interbeds at the top into type 2 lithology. Tabuk lithologies are thus arranged in three generally coarsening-upward cycles that, together with the regional sedimentological and structural framework, suggest deposition in a prograding deltaic environment dominated by fluvial sediment input. Lithology type 1 probably represents material derived from a fluvially-fed delta plain and deposited in the distributary system of a delta front; type 2, fine sandstone and siltstone, may have been deposited in intermediate mouth bars; and type 3 is considered to represent a mud-dominated platform in the pro-delta, off-shore area, where holomarine conditions prevailed. Each of the three cycles from bottom to top probably represents sand and silt facies of a delta plain and delta front prograding during periods of eustatic stand-stills over pro-delta muds, which were the product of intermittent, possibly eustatically controlled, marine incursions.

Intertidal deposition as part of the delta plain appears to have been widespread, *Skolithos* beds and tidalite sands being prominent towards the top of the Ordovician part of the Tabuk Formation on outcrop as well as in the subsurface. A non-barred, tidally dominated, sandy coastline was probably present, where extensive fluvially-dumped sediments were contemporaneously reworked and redistributed during periods of active progradation.

Graptolite zonations, documentation of the glacial event, and sedimentary observations are the principal aids available in the area to define the nature of the Ordovician–Silurian boundary. Analysis of the Ra'an and Qusaiba shales and the intervening sandstone is particularly informative, since these units bracket the boundary. (The Hanadir, the basal shale member of the Tabuk, of Llanvirn age, is not discussed here, except briefly in the section on biostratigraphy below.)

The Ra'an is the least distinctive and persistent of the three shale members. At the type locality at Khashm Ra'an (latitude 26° 52′ N, longitude 43° 23′ E), the lithology consists of 67 m of green-grey, silty, micaceous shale and fine-grained, red-brown, ripple marked, micaceous sandstone and siltstone with trace fossils towards the top. Glacial beds are erratically associated with the top of the Ra'an in many places at outcrop. Very rare graptolites, trilobites, brachiopods and molluscs are concentrated in several thin zones at the bottom and top.

The range of the graptolite *Orthograptus amplexicaulis*, which occurs in the lower part of the Ra'an, is from the *clingani* Zone to the *anceps* Zone. *Glyptograptus persculptus* occurs at the top of the Ra'an and, although formerly considered to represent the lowest Silurian, is now taken as uppermost Ordovician. The trilobites indicate a less precise age ranging from about the middle Caradoc to about the late Ashgill. Overall considerations indicate the Ra'an member at outcrop is probably late Caradoc to the latest Ashgill, *persculptus* Zone, in age.

The sandstone overlying the Ra'an, which is similar to the sandstone underlying it, is partly cross-bedded, partly massive-bedded, medium-grained and occasionally channelled. This unit, about 240 m thick in the Qasim area, is probably lower Rhuddanian in age because of its conformable position below the well-dated Aeronian Qusaiba shale and above the *persculptus* Zone. It is generally barren of body fossils, but poorly preserved moulds of molluscs and brachiopods (mostly lingulids) are sometimes present. Trace fossils such as *Cruziana* are frequent.

The Qusaiba shale, like the Ra'an, is erratically distributed along the length of the outcrop. At its best exposure and type locality in the Qusaiba Depression (26° 53′ N, 43° 34′ E), it consists of 57 m of varicoloured, red and grey-green laminated shale with thin interbeds of yellow shale, and red, hematitic, ripple-marked, micaceous and fine-grained sandstone with trace fossils towards the top. A medium-grained, cross-bedded sandstone overlies the shaly-silty interbedded unit. The Qusaiba is especially rich in graptolites, but also contains rare trilobites, brachiopods and molluscs. Graptolites serve to date the Qusaiba as Aeronian, *convolutus* Zone.

Nature of the Ordovician–Silurian boundary

In the Arabian section, both on outcrop and in the subsurface to the east, the *persculptus* Zone is present near the top of the Ra'an shale. On the surface, *persculptus* occurs just below the glacial beds. While this zone has not been documented above the glacial horizon on outcrop, in the subsurface it occurs just above a diamictite suspected of being of glacial origin (Fig. 2).

The contact between the Ordovician and the Silurian, both at outcrop and in the subsurface further to the east, is apparently conformable. Nothing appears to have happened across the boundary that drastically altered the depositional mode characteristic throughout the Tabuk Formation of prograding sands, delta cycles, and intermittent marine incursions on a tectonically stable structural platform. Within the Ra'an, however, extreme cold water conditions were apparently manifested in an impoverished fauna, and local glacial activity took place within the top part of the Ra'an. Fluvioglacial channels, tillite deposits, striated and faceted megaclasts, exotic igneous boulders, pro-glacial sandstone, and other evidence of glaciation occur in this part of the section (McClure 1978; Young 1981). This event is assumed to be approximately coeval with glaciation at this time in north Africa (Beuf *et al.* 1969; Hambrey & Harland 1981).

The glaciation in Saudi Arabia is confined within the top part of the Ra'an, apparently within the *persculptus* Zone, but is ice-marginal and ice-contact and not glacio-marine. Sub-aerial exposure due to sea level drop at the maximum of glaciation during the later phase of the Ashgill probably occurred. Thus, super-imposed upon the Ra'an is a subsidiary sequence of events composed of (1) glacio-eustatic sea level regression, during which glaciation took place, (2) deglaciation during which glaciofluvial and fluvial sands were deposited, finally followed by (3) glacio-eustatic sea level rise, during which the upper part of the *persculptus* Zone shale was deposited. Sea level dropped again toward the beginning of the Silurian and regressive sands were deposited in Rhuddanian time. In later Llandovery (Aeronian) time, a marine transgression apparently unrelated to glacial events deposited the Qusaiba shale. The glacio-eustatically controlled regressive–transgressive sequence at the top of the Ra'an may be synchrononous with similar world-wide events such as those documented by Brenchley & Newall (1980) at the end of the Ordovician in the Oslo region, Norway, and those proposed by Berry & Boucot (1973). The Ordovician–Silurian boundary in Saudi Arabia may thus be taken at the base of the sandstone unit between the Ra'an and Qusaiba shales, or above the *persculptus* Zone.

Lithofacies to the east in the deep subsurface vary little from the outcrop sequence, except that the Ra'an as a discrete shale unit with easily determined top and base is not always present and the sandstone of presumed Rhuddanian age between the Ra'an and the Qusaiba at outcrop is poorly developed. The contact between the Ra'an and the Qusaiba is consequently indistinct, and the Qusaiba sequence is considerably thicker. A distinctive feature of the subsurface is a regionally persistent and prominent, thin, highly organic, pyritic euxinic black shale, often bearing common or abundant *Glyptograptus persculptus* with no benthic fossils and overlying a sandstone with diamictite suspected of being equivalent to the glacial tillite of outcrop. This shale may be equivalent to the post-glaciation upper part of the *persculptus* Zone of outcrop mentioned above and helps place the glaciation event as within the *persculptus* Zone.

The graptolite succession of the deep subsurface requires further study, but appears similar to that of the outcrop. Several differences are that graptolites assignable to the *clingani* to *anceps* Zones as found at the base of the Ra'an on outcrop have not been documented in the subsurface, and a graptolite suite assignable approximately to the boundary between the *magnus* and *leptotheca* Subzones of the *gregarius* Zone has been recovered in one drill hole. The most perplexing anomaly, however, is that, in another representative drill hole with continuous core sequence, a *convolutus* Zone graptolite suite occurs within about 6 m of the euxinic *persculptus* Zone shale. Intervening graptolite zones of the lower Llandovery therefore appear to be largely missing or drastically telescoped. (See Note, p. 163).

The 'missing' graptolite zones are assumed to be represented on outcrop by the non-fossiliferous Rhuddanian sandstone and their apparent absence in the deeper section where this sandstone is not present and shales were continuously deposited is puzzling. However, these zones are also 'compressed' in some standard British successions (R. B. Rickards, personal communication) and lower Llandovery marine fossils are rare on a worldwide basis (Berry & Boucot 1973). The apparent gap in the graptolite succession of Saudi Arabia is probably not due to events peculiar to the Arabian platform. It is tempting to consider the euxinic black shale as well as the condensing or absence of the early Llandovery graptolite zones as in some way related to the glaciation event. Cessation or drastic restriction of fluvial flow regimes and consequent constriction of clastic input due to tie-up of water in glacial ice may have resulted in stagnant, euxinic conditions in more distal intra-platform areas on what was already a cold water, carbonate-starved platform. Fig. 2 presents outcrop and subsurface correlations within the Tabuk Formation.

Thus, a firmer calibration of a time scale with depositional and climatic events and faunal occurrences is essential to define more precisely the nature of the Ordovician–Silurian boundary on the Arabian platform and correlate it with sequences elsewhere. The evidence accumulated to date, however, is informative, and the following conclusions can be tentatively made.

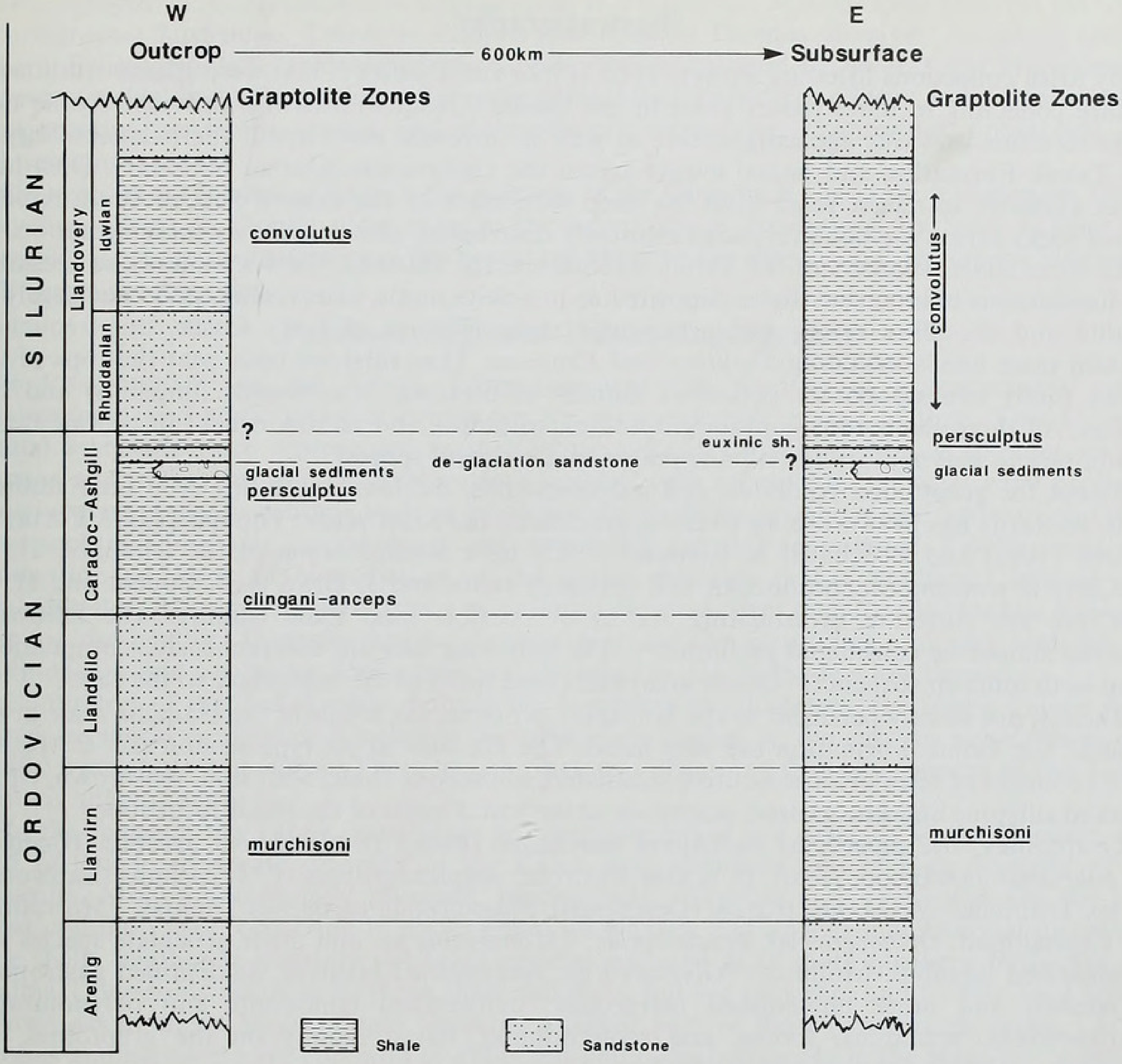

Fig. 2 Section comparing the Tabuk Formation in the outcrop of NE Saudi Arabia (left) with that in the subsurface to the east (right). The three shale horizons at outcrop are termed Hanadir (Llanvirn), Ra'an (Caradoc to basal Llandovery) and Qusaiba (Middle Llandovery). The Idwian Stage shown is now regarded as the lower part of the Aeronian Stage. The base of the Tabuk Formation is at the base of the Llanvirn.

1. Rates of sediment deposition may have varied on the Arabian platform across the Ordovician–Silurian boundary and can probably be attributed to the effects of glaciation. Land-derived clastic input may have been drastically restricted, resulting in euxinic, starved and stagnant areas, but:

2. No regionally significant depositional hiatus is evident and the contact between the Ordovician and Silurian may be considered conformable.

3. Nothing except glaciation happened at the boundary to upset significantly the mode of deposition characteristic throughout the Tabuk Formation of prograding sandstone, tidal flats, delta cycles and intermittent marine incursions on a tectonically stable structural platform.

4. The graptolite succession across the boundary appears normal, the apparent gap of early Llandovery graptolite zones being probably attributable to world-wide events and not intraplatform activity.

5. The significant boundary event on the Arabian platform appears to have been the glaciation at the end of the Ordovician that affected sedimentation rates and faunal suites.

Biostratigraphy

Early fossil collections listed by Powers *et al.* (1966) and Powers (1968) were sparse. Additional surface collecting in more recent years in the Qasim (Qusaiba) area has provided fossils that serve to refine previous age assignments as well as to reveal more about the palaeobiology of the Tabuk Formation and faunal events across the Ordovician–Silurian boundary. Drill hole cores available in recent years from the deep subsurface of the eastern part of Saudi Arabia, where rocks across the boundary are extensively distributed, also provide useful information.

All three shale members of the Tabuk Formation, the Hanadir, the Ra'an, and the Qusaiba, are fossiliferous holomarine shales deposited as pro-delta muds. Intervening sands are largely of tidalite and shoreface origin and are mostly unfossiliferous of body fossils, but frequently contain trace fossils including *Skolithos* and *Cruziana.* Thin siltstone beds near the tops of the shales rarely contain poorly preserved moulds of bivalves, brachiopods (lingulids) and trilobites. All three shale units contain graptolites, trilobites, and an assortment of benthic fauna in addition to palynomorphs (chitinozoans, acritarchs, and spores).

Except for graptolites, trilobites, and palynomorphs, the fossil suite has been little studied. R. B. Rickards has been working with the graptolites in recent years; Thomas (1977), Fortey & Morris (1982) and El-Khayal & Romano (1985) have studied some of the trilobites, H. A. McClure is working on chitinozoan and acritarch suites and J. Gray, A. J. Boucot and H. A. McClure are currently investigating spores of possible land plant affinity. The following analysis should be considered preliminary. The following lists are comprehensive compilations from both outcrop sequences (Qasim area) and cored holes of the subsurface to the east.

Though not strictly pertinent to the boundary problem, the fossils of the Hanadir shale at the base of the Tabuk Formation are also listed. The Hanadir at its type section (26° 27′ N, 43° 27′ E) consists of 60 m of varicoloured, laminated, micaceous shale, with thin, red-brown, ripple marked siltstone and fine grained sandstone at the top. Fossils of the Hanadir include:

Graptolites: *Didymograptus murchisoni murchisoni* (Beck), *D. murchisoni geminus* (Hisinger), *D. pakrianus* Jaanusson, *D.* aff. *D. acutus* Ekstrom, *Amplexograptus* cf. *A. coelatus* (Lapworth), *A.* sp. Trilobites: *Neseuretus tristani* (Desmarest), *Plaesiacomia vacuvertis* Thomas, ?*Marrolithus* sp. Cephalopod: *Orthoceras* sp. Brachiopods: ?*Monobolina* sp. and other articulate species and unidentified lingulids. Molluscs: ?*Glyptarca* sp., unidentified bivalves, unidentified gastropods. Beyrichids and other unidentified ostracodes; unidentified conodonts and palynomorphs (chitinozoans, acritarchs, spores, and scolecodonts). Based mainly on the graptolites, the Hanadir is Llanvirn in age, *murchisoni* Zone.

The Ra'an shale contains the following fossils, derived mainly from several thin zones at the base and toward the top from outcrop and from cores of the subsurface: Graptolites: *Glyptograptus persculptus* (Salter) *s.s.*, *Orthograptus amplexicaulis* Hall *s.s.*, *Orthograptus* sp. nov., *Diplograptus* sp., *Climacograptus angustus/normalis*, ?*Dictyonema* sp., ?*Climacograptus miserabilis* and ?*Diplograptus modestus.* Trilobites: *Kloucekia* sp. and *Onnia* sp. Brachiopods: *Comatopoma* sp. or *Hirnantia* sp., others (mostly lingulids). Molluscs: unidentified gastropods and bivalves and the cephalopod *Orthoceras* sp.; unidentified conodonts and palynomorphs (chitinozoans, acritarchs, spores, and scolecodonts).

The range of *Orthograptus amplexicaulis* is from the *clingani* to the *anceps* Zones. *Glyptograptus persculptus* places the top part of the Ra'an in the *persculptus* Zone.

The Qusaiba shale contains the following: Graptolites, Suite 1: *Climacograptus scalaris* (Hisinger), *C.* aff. *C. rectangularis* Törnquist, *Glyptograptus* aff. *G. incertus* Elles & Wood, *G. tamariscus tamariscus* (Nicholson), *G.* (*Pseudoglyptograptus*) sp., *Lagarograptus* sp., *Monograptus capis* Hutt, *M. communis* Lapworth, *M. convolutus* (Hisinger), *M. decipiens* Törnquist, *M. gregarius gregarius* Lapworth, *M. lobiferus* (M'Coy), *M.* cf. *M. delicatulus* (Elles & Wood), *M.* ex gr. *tenuis* (Portlock), *Orthograptus cyperoides* Törnquist, *Petalograptus ovatoelongatus* (Kurk), *P.* sp., *Pristiograptus regularis* (Törnquist), *Pseudoclimacograptus* (*Clinoclimacograptus*) *retroversus* Bulman & Rickards, *P.* (*Pseudoclimacograptus*) sp. nov., *Rastrites spina* Richter, *Retiolites perlatus* (Nicholson), *Rhaphidograptus tornquisti* Elles & Wood. Graptolites, Suite 2: *Climacograptus tamariscus s.l.*, *Coronograptus gregarius* cf. *C. minisculus* Obut & Sobolovskaya, *Climacograptus* cf. *C. rectangularis*, *Diplograptus* cf. *D. magnus*, *Monograptus lobiferus* (M'Coy), *Pristiograptus ?concinnus*. Trilobite: *Platycoryphe dyaulax* Thomas. Bivalves: *Nuculites*, among others. Bellerophontids, unidentified gastropods; the cephalopod *Orthoceras* sp.; brachiopods: '*Camarotoechia*' and other unidentified articulates. Unidentified conodonts and palynomorphs (chitinozoans, acritarchs, spores, and scolecodonts); ostracodes, *Tentaculites*, ophiuroids and fish remains.

On graptolite evidence of Suite 1, the outcrop of the Qusaiba is Llandovery, Aeronian Stage, *convolutus* Zone. A slightly older zone in the subsurface is represented by Suite 2, from the *gregarius* Zone, approximately on the boundary between the *magnus* and *leptotheca* Subzones, still within the Aeronian.

Palaeoecology and Palaeobiogeography

The fossil content of the Tabuk Formation was the product of a remarkably stable environment and static physical conditions for a considerable period of time. Two kinds of faunal association are represented in the Tabuk suite: (1) planktic, with graptolites, chitinozoans and acritarchs, and (2) level-bottom benthic, with an epifauna of what were probably mostly vagrant shelly benthos such as brachiopods, molluscs, trilobites and ostracodes. Other taxa such as conodonts, scolecodonts and ophiuroids are also represented. Fine layering and lamination and lack of bioturbation of the shales indicates that a significant infauna was probably not present. In general terms, population densities were high for the planktic level and low for the benthic. Diversity was moderately high for the graptolites and very high for the chitinozoans and acritarchs. Shelly benthics identified to date indicate a low diversity.

Continuity of the Tabuk suite extends for hundreds of kilometres, the fossils known from cored sequences in deep drill holes in the subsurface further to the east do not differ significantly from those of outcrop. There are no obvious indications that any element of the Tabuk biota is allochthonous.

In the shales of the Tabuk, graptolites are common but of low diversity in the Hanadir, rare and of low to moderate diversity in the Ra'an, and abundant and of high diversity in the Qusaiba. Molluscs (especially bivalves), brachiopods, trilobites and ostracodes are the next most common taxa, occurring in about equal abundance and approximately equal diversities. The shelly benthos is certainly not brachiopod-dominated as in more northern biogeographic realms. Conodonts occur in all three shale members, but are very rare and to date very little is known about them. Scolecodonts occur as a minor part of the palynomorph suites. Chitinozoans and acritarchs are common to abundant and of high diversity in the Hanadir, comparatively rare and of comparatively low diversity in the Ra'an and abundant and of high diversity in the Qusaiba. Spores, including tetrahedral tetrads that possibly represent early vascular land plants, are rare to common in the palynomorph suites. Ophiuroids are very rare; only several specimens of less than 0·5 cm size are recorded from the Qusaiba. *Tentaculites* occurs rarely in the Qusaiba. *Orthoceras* is rare but ubiquitous in all three shales, being more common and robust in the Qusaiba. In one limited locality, near the base of the Ra'an, it is concentrated in small planoconvex lenses of calcareous debris associated with algal nodules. (This is the closest resemblance to the *Orthoceras* limestone lenses recorded as widespread in the Silurian of north Africa by Berry & Boucot, 1973. The Arabian occurrence possibly represents a storm event.)

All the shelly benthic species are small, brachiopods and molluscs being rarely more than one centimetre in maximum dimension. Shelly specimens appear to have been weakly calcified or subjected to early dissolution. Most of the material is composed of moulds of the composite type on poorly defined bedding planes and laminae. As in the case of composite-type moulds (McAlister 1962), fine interior and external morphological features are often well preserved. Although taxonomic diversity is generally maximised in shallow marine environments (Boucot 1981), this is not the case with the Tabuk fauna. The condition of the shelly benthics of the Tabuk shales may indicate the influence of low salinity, but cold-water conditions (especially marked during the glaciation at the end of the Ordovician) was most likely the over-riding control. Fortey & Morris (1982) regard the trilobite genus *Neseuretus*, present in the Llanvirn (Hanadir) of the Tabuk, to be a reliable and sensitive indicator of inshore facies in cold water.

Planktics do not appear to have been affected by some cold, but were clearly affected by the excessive glacial cold conditions at the end of the Ordovician. An extensive platform covered with hyposaline water can exist if an adjacent continent has a river system adequate to provide a steady influx of fresh water. In such environs today, there is a low taxic diversity, and there is no reason to think that extensive river regimes of the past flowing off large land masses may not have had the potential for producing similar hyposaline environments with appropriate faunal consequences (Boucot 1981). This condition may have prevailed on the Arabian platform during Ordovician and Silurian times. Outcrop sequences of the Tabuk sands, silts, and shales are oxidized to shades of red, pink, yellow and green. However, subsurface equivalents invariably range from light grey to dark grey and black. Tidalite sands are especially rich in carbonaceous laminae, each lamina possibly representing nutrient material transported by a single tidal event. Tabuk shales in the subsurface are usually medium grey to dark grey and black, the extreme case being the black, highly radioactive, 'sooty' shale of the subsurface *persculptus* Zone.

Some of the palynological samples yield a distinct tetrahedral tetrad type of suspected land origin. This kind of evidence for vascular land plants may be recorded as early as the Llanvirn (Hanadir shale) in the Arabian Tabuk section. Berry & Boucot (1973) suggest that a black, radioactive shale at the 'base of the Silurian' in north Africa could be due to blooms of plants in mud flats and lagoons at this time. An apparently synchronous event occurs across much of north Africa and Arabia. A readily accessible and presumably useable supply of nutrients might therefore be assumed for both planktic and bottom benthics. Nutrient kind and availability may have been a significant factor in the palaeoecology of chitinozoans and acritarchs especially, and perhaps also graptolites.

Temperature is probably the most important variable affecting both plant and animal distribution of the present and continental glaciation episodes of the end of the Ordovician and Permian–Carboniferous are associated with global diversity gradients (Boucot 1981). The change in faunal composition associated with the Ordovician glaciation is now well documented (Berry 1973; Berry & Boucot 1973). A Silurian warming followed the Ordovician cold in the area and this may be reflected in taxa of the Qusaiba fossil suite being relatively more diverse and populations denser, especially planktic ones.

In summary, the Tabuk palaeogeography and palaeoenvironment was probably that of a broad pro-delta mud substratum on a shallow-water, clastic-fed, carbonate-starved, tectonically stable platform area, with sediment and high nutrient input derived from a low, rapidly eroding landmass, possibly with primitive plant cover, and transported via extensive fluvial, tidal and deltaic systems. Conditions of low salinity and cold-water temperatures probably controlled diversity and density of parts of the faunal community. Conditions may be considered to have been optimum for planktic taxa such as chitinozoans and acritarchs, favourable for graptolites, and generally unfavourable for benthics.

Lovelock *et al.* (1981) record chitinozoans and acritarchs, trace fossils, ?dalmanellid brachiopods, and the trilobite ?*Neseuretus* from Early and Middle Ordovician rocks of the Amdeh Formation of Oman. Rocks of southern Jordan of age equivalent to the Tabuk Formation are sandstones, shales and siltstones bearing graptolites, brachiopods, bivalves and gastropods, nautiloids, *Conularia* and trace fossils such as *Cruziana* and *Skolithos* (Bender 1975). Exact equivalents in these two areas to individual units of the Tabuk Formation, the precise definition of the Ordovician–Silurian boundary, and the comparison with the Tabuk fauna remain yet to be worked out.

Conclusions

Pending further study and documentation of the palaeobiology of Arabian Ordovician–Silurian fossil suites, the following conclusions are presented:

1. The fossils of all three Tabuk shales are similar in composition, diversity, population density and abundance levels and may be taken to represent one community.

2. Two trophic levels are readily identifiable: (a) planktic—consisting of graptolites, chitinozoans and acritarchs, and (b) benthic—consisting largely of vagrants on a flat-bottom mud

substratum.

3. Water temperature was probably the main environmental control on the community.
4. Salinity was possibly a secondary control on the community.
5. Nutrient material was readily available and may have played a significant role in the palaeocology.
6. An extensive pro-delta mud platform provided the main palaeogeographical control for the bulk of the Tabuk fauna; inshore sandy facies and tidal flats were less important features.
7. The main event that affected the biological community across the Ordovician–Silurian boundary was stress imposed by glaciation at the end of the Ordovician. Otherwise, the conditions that affected the community throughout deposition of the Tabuk were also operative in boundary times.
8. Similarities in the palaeobiology, palaeogeography and palaeoecology occur in the platform rocks of the north African Silurian sections.

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Note added in page proof. The *atavus* Zone (Rhuddanian) has recently been documented in the Arabian Silurian section. *Atavograptus atavus* (Jones) is present in both the Tabuk area of outcrop and the deep subsurface of eastern Saudi Arabia. In the outcrop section, it occurs with *Climacograptus normalis* Lapworth.