# The H6 Aarhus meteorite breccia: A new look at an old rock

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On 2 October 1951, a 750 g meteorite fell as two pieces over the Danish city of Aarhus. A sample of Aarhus is examined here using modern in situ analytical methods to reassess the meteorite's history, which was previously investigated in 1963 using petrography, wet chemistry and X-ray diffraction. It is here confirmed to be an H6 ordinary chondrite based on the textural characteristics and the homogenous olivine (olivine (#$Fa_{19.9±0.5}$) and orthorhombic low-Ca pyroxene (enstatite, $Fs_{17.6±0.7}$) compositions. The meteorite's pyroxene Mn/Fe ratios align with the trend of those for non-differentiated planetary bodies and thus support the assumption that the parent body largely retained a chondritic composition. Aarhus preserves textural evidence for a phase of brecciation pre-dating the major metamorphic recrystallisation phase and so occurred early on in the parent body history, possibly during the asteroid's construction. The main metamorphic textures are then overprinted by shock fracturing of olivine and pyroxene and the formation of maskelynite after plagioclase, which may relate to the catastrophic disruption of the parent body. Aarhus is similar to the Danish meteorites Ejby (H5/6), which landed on Copenhagen in 2016, and Dueodde (H5), which was recovered from a roof on Bornholm in 2017.

*Keywords:* Denmark, meteorite, mineral chemistry, olivine, ordinary chondrite

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At 18:15 on 2 October in 1951, a bright fireball was observed over Denmark (Buchwald 1992). This bright meteor dropped two meteorite fragments: Aarhus I and Aarhus II (Fig. 1). Aarhus I, at 300 g, was found in Risskov shortly after the fireball, although it had broken into four fragments (Nørby 2013). The fall was a significant event in the city's history, with scientific and cultural institutions urging people to participate in efforts to locate fragments of meteorite and reconstruct its trajectory (Nielsen 1953). A second stone, Aarhus II at 420 g, was found two weeks later a few kilometres away. The classification of Aarhus as an ordinary chondrite was made by Mason (1963) and although olivine compositions were inspected, the analyses were by X-ray diffraction, only a single Fe/(Fe+Mg)*100 value is reported, and no other minerals were chemically analysed. The H6 classification first reported in Grady (2000) appears to be based upon the van Schmus and Wood (1967) criteria and Mason's (1963) olivine value coupled with thin section images in Callisen *et al.* (1963). Since the 1963 publications, geological interpretations regarding meteorites, and the tools to investigate them, have evolved, which means that a modern look at the mineralogy could provide new insights. Here, we present new electron beam chemical analyses of Aarhus, assess the existing classification, and compare it with similar Danish meteorites.

## Methods

The main masses of Aarhus II and fragments of Aarhus I are housed at the Natural History Museum Denmark in Copenhagen as part of the Danish Meteorite collection. The largest fragment of Aarhus I, however, is stored at the Natural History Museum of Aarhus. With their permission, a small fragment (3×2×1.5 cm) was cut off a corner and mounted in epoxy resin. The sample was then polished and carbon coated for analysis with a TESCAN scanning electron microscope at the Department of Geoscience at Aarhus University. The SEM was used with an energy beam configuration of voltage 20 keV and current of 20 nA at a fixed working distance to measure the mineral compositions and obtain backscattered electron images and maps. The beam was calibrated regularly with pure copper metal, and the chemical data standardized against the default factory standards. Measurements were obtained using the Oxford Instruments Aztec software. To confirm that our SEM data are robust, minerals in the same fragment were re-analysed by wavelength dispersive spectrometry using an JEOL JXA-8200 superprobe electron microprobe at the Department of Geosciences and Natural Resource Management at University of Copenhagen. The microprobe was operated with a beam diameter of 5 micrometers, an accelerating voltage of 15 KeV and a beam current of 15 nA. Elements were standardized against in house reference materials including corundum (Al), Marjalathi olivine (Mg), albite (Na), orthoclase (K), rutile (Ti), hematite (Fe), Mn-Ti-oxide (Mn), chromite (Cr), Ni-metal (Ni), and wollastonite (Si and Ca). In-house secondary silicate standards (fayalite and pyrope garnet) were also analysed for quality control. Counting times were 20 s on peak and on backgrounds for all elements excluding Na and K (10 s). Matix corrections were performed using the phi-rho-z method (Goldstein *et al.* 2017).

# Results

Aarhus I has a slightly cracked dark fusion crust and a broken face that exposes the pale interior (Fig. 2a). The pale interior is composed of less than 1 cm-sized angular clasts set within darker areas (Fig. 2b, c). A few relict chondrules can be found in the matrix, which has olivine and low-Ca pyroxene as main phases (Fig. 3a, b, c). The chondrules are slightly elongated and approximately 0.4 by 1 mm in average size, with two displaying a barred texture comprising olivine and plagioclase (likely maskelynite, which is plagioclase glass). The main minerals in the meteorite are olivine and low-Ca pyroxene, accompanied by maskelynite, kamacite and taenite-tetrataenite (Fe-Ni alloys), troilite (FeS), diopside, chromite, merrillite ($Ca_9NaMg(PO_4)_7$) and apatite (Figs 3, 4, 5). Ca-pyroxene is relatively rare and found primarily as smaller skeletal grains (< 100 µm), often occurring with maskelynite and fine-grained troilite. Kamacite is up to 500 µm in size and is by far the most abun-


**Fig. 1.** The fall sites of Aarhus I and II on a map of Aarhus from 1953-1976 with orthophoto from 2024 as background (Klimadatastyrelsen 1953–1976; GeoDanmark 2024). The current location of the Department of Geoscience is marked for reference. The site of Aarhus I marks the location of the memorial stone for Aarhus I, which fell within 100 m.

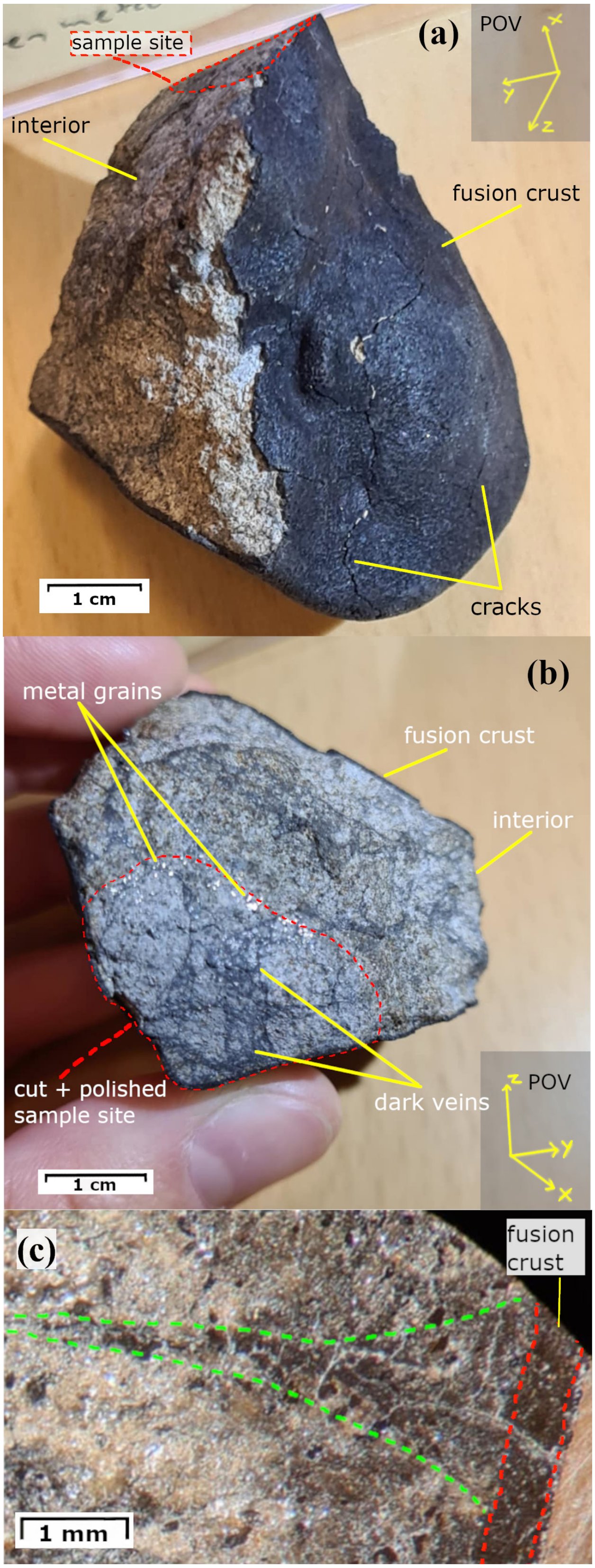


**Fig. 2.** Images of the Aarhus I meteorite hand specimen (A) and sampled section (B, C). plg, plagioclase glass; tr, troilite.

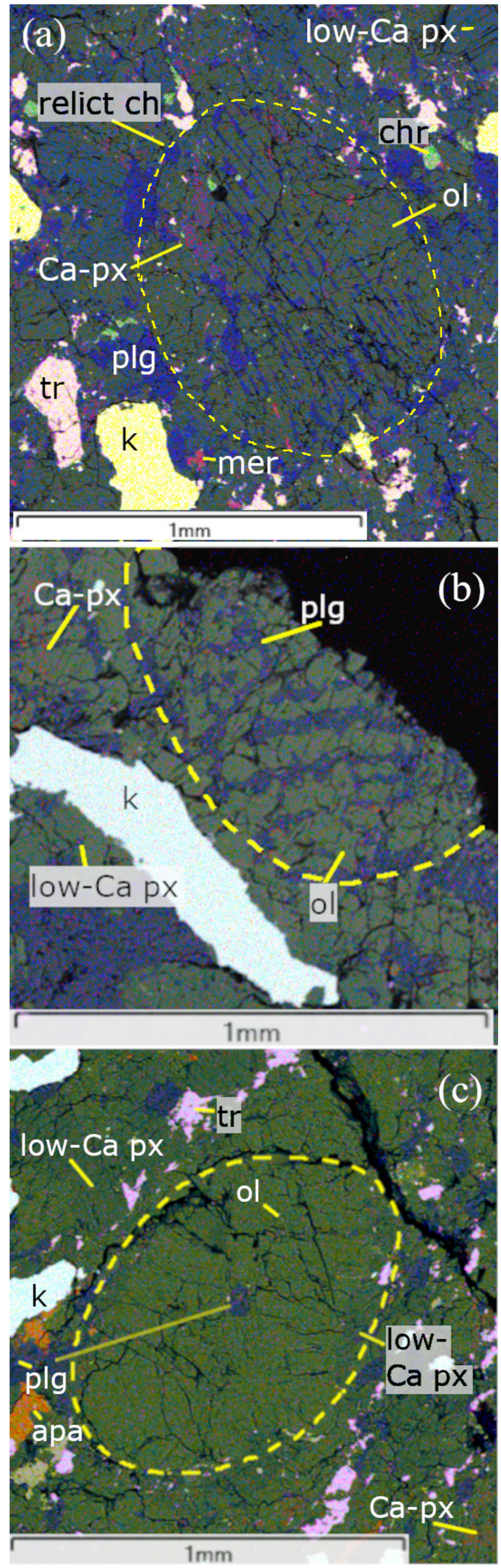


**Fig. 3.** Examples of relict chondrules in Aarhus. The colours are false-coloured. Px, pyroxene; plg, plagioclase (maskelynite); apa, apatite; ol, olivine; tr, trolite; k, kamacite; Chr, chromite; mer, merrillite; ch, chondrule.

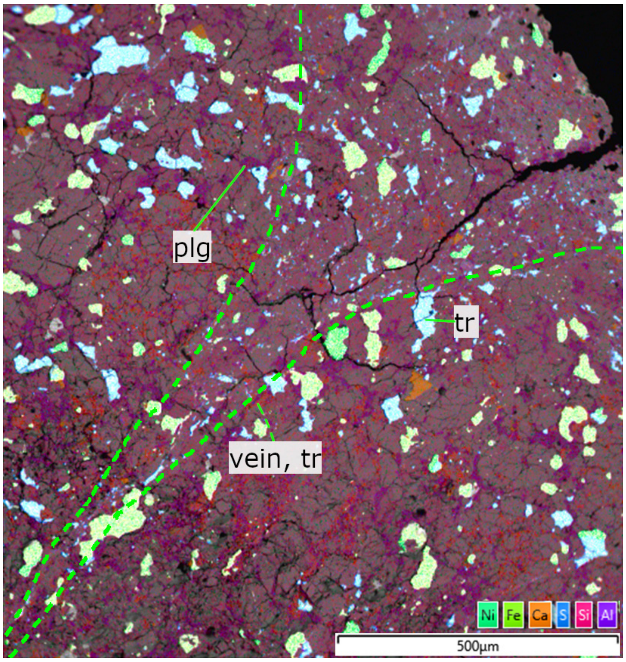


**Fig. 4.** False-coloured element map of the occurrence of a vein or zone of finer-grained troilite within the meteorite. The dashed green lines correspond with the zone visible in figure 2C.

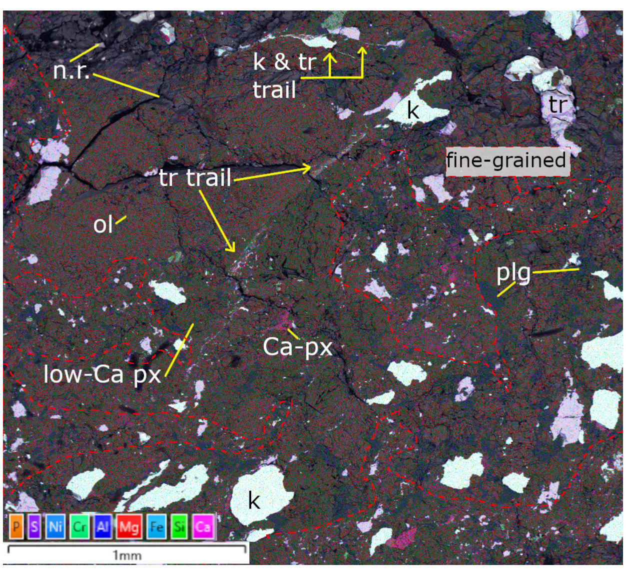


**Fig. 5.** False-coloured scanning electron microscope EDS map and backscattered electron image showing the different zones of grainsize in the meteorite. K, kamacite; tr, trolite; ol, olivine; plg, plagioclase glass; px, pyroxene; n.r., fractures in the polished sample.

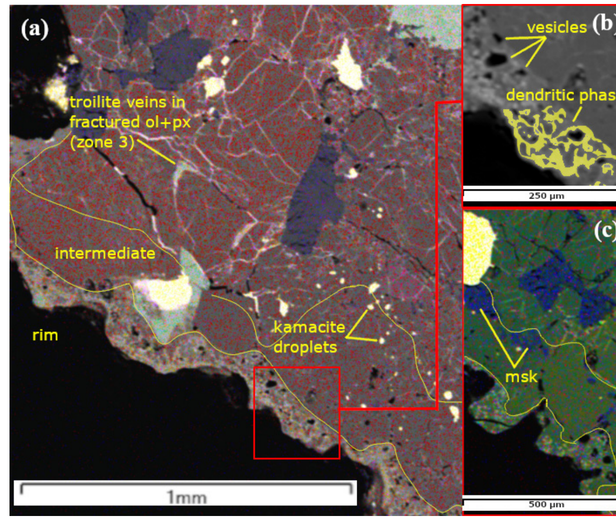


**Fig. 6.** False-coloured images from the margin of the meteorite showing the occurrence of a fusion crust and consecutive zones of alteration of the meteorite.

dant metal phase (Figs 4, 5). Troilite is also abundant and generally either found as grains up to 200 µm or forming very fine trails (< 5 µm; Fig. 5). The fusion crust of the meteorite can be split into three distinct textural domains (Fig. 6a, b, c). The rim is the ~ 0.1 mm thick exterior part of the meteorite that was last melted during its passage through the atmosphere, and is characterized by glass, dendritic olivine and small vesicles (< 30 µm (Fig 6b). The intermediate zone is the ~0.3–0.4 mm wide area adjacent to the rim and is characterized by sparse droplets of metal phases and some larger maskelynite grains (Fig 6c). Vesicles are also found here to a lesser extent than at the rim. Zone 3 is the third textural position counting from the rim towards the centre of the sample, and contains distinct troilite veins filling fractures in the olivine-pyroxene groundmass (Fig. 6a). The thickness varies from 0.5 to 1.5 mm.

## Mineral compositions

The mineral compositions are important for classifying the meteorite in the ordinary chondrite group (H, L, or LL) and are not readily available other than a note that the olivine has a #Fa of '18' (Mason 1963). The olivine chemically varies depending on textural position. Our measurements of dendritic olivine in the fusion crust's outermost zone have a higher content of Fe and are unrepresentative for the original olivine in the rock prior to atmospheric entry. Excluding those data, a total of 35 analyses acquired by scanning electron microscope from further inside the meteorite, from chondrules and matrix, gives a mean composition of $\#Fa_{19.9\pm0.5}$ (Table 1), with a range between 18.8 and 22 and a mean deviation of 2%. The microprobe data give $\#Fa_{19.8\pm0.7}$, which confirms the SEM results (Supplementary 1).

Of the pyroxenes, the low-Ca pyroxene is enstatite, with SEM data yielding compositions between 15.7 and 19.6 mol% but with an average Fs-content of

**Table 1.** Mean chemical compositions of the main mineral constituents of Aarhus I

| wt% | Olivine (*n = 35*) | Low-Ca pyroxene (*n = 44*) | Ca pyroxene (*n = 22*) | Plagioclase (*n = 49*) | Apatite (*n = 12*) | Merrillite (*n = 16*) | Chromite (*n = 13*) |
|---|---|---|---|---|---|---|---|
| $SiO_2$ | 38.6 | 55.7 | 53.4 | 64.5 | 0.00 | 0.82 | 0.00 |
| $TiO_2$ | 0.00 | 0.20 | 0.52 | 0.00 | 0.00 | 0.00 | 1.90 |
| $Al_2O_3$ | 0.00 | 0.24 | 0.85 | 21.6 | 0.00 | 0.00 | 6.97 |
| $Cr_2O_3$ | 0.00 | 0.17 | 1.16 | 0.09 | 0.00 | 0.00 | 55.2 |
| FeO | 18.6 | 11.8 | 4.30 | 0.78 | 0.79 | 1.26 | 29.0 |
| MnO | 0.49 | 0.53 | 0.22 | 0.00 | 0.00 | 0.00 | 1.00 |
| MgO | 41.9 | 30.4 | 16.6 | 0.00 | 0.12 | 3.59 | 3.13 |
| CaO | 0.00 | 0.69 | 22.0 | 2.50 | 51.9 | 46.4 | 0.00 |
| $Na_2O$ | 0.00 | 0.10 | 0.64 | 8.91 | 0.44 | 2.56 | 0.00 |
| $K_2O$ | 0.00 | 0.00 | 0.00 | 0.90 | 0.00 | 0.00 | 0.00 |
| $P_2O_5$ | 0.00 | 0.00 | 0.00 | 0.00 | 40.9 | 45.1 | 0.00 |
| Total | 99.59 | 99.71 | 99.69 | 98.29 | 94.15 | 99.80 | 97.20 |
| Oxygens | 4 | 6 | 6 | 8 | 12.33 | 56 | 4 |
| Si | 0.99 | 1.98 | 1.96 | 2.86 | 0.04 | 0.25 | 0.00 |
| Ti | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.05 |
| Al | 0.00 | 0.01 | 0.04 | 1.13 | 0.00 | 0.00 | 0.29 |
| Cr | 0.00 | 0.00 | 0.03 | 0.00 | 0.00 | 0.00 | 1.54 |
| Fe2+ | 0.40 | 0.35 | 0.13 | 0.03 | 0.06 | 0.34 | 0.86 |
| Mn | 0.01 | 0.02 | 0.01 | 0.00 | 0.00 | 0.00 | 0.03 |
| Mg | 1.60 | 1.61 | 0.91 | 0.03 | 0.01 | 1.87 | 0.17 |
| Ca | 0.00 | 0.03 | 0.87 | 0.12 | 4.78 | 18.0 | 0.00 |
| Na | 0.00 | 0.01 | 0.05 | 0.77 | 0.07 | 1.73 | 0.00 |
| K | 0.00 | 0.00 | 0.00 | 0.05 | 0.00 | 0.00 | 0.00 |
| P | 0.00 | 0.00 | 0.00 | 0.00 | 2.96 | 13.7 | 0.00 |
| Total | 3.00 | 4.02 | 4.01 | 4.99 | 7.92 | 35.89 | 2.94 |
| Fa | 19.9 ± 0.5 | | | | | | |
| Fs | | 17.6 ± 0.7 | 6.9 ± 0.7 | | | | |
| Wo | | 1.3 ± 0.2 | 45.4 ± 0.1 | | | | |
| An | | | | 13 ± 1.4 | | | |
| Or | | | | 5 ± 1.6 | | | |

Fa = 100*Fe/(*Mg* + *Fe*). Fs = 100* Fe/Fe+Mg+Ca), Wo = 100*Ca/(Fe+Mg+Ca). 100*An = Ca/(Ca+Na+K), 100*Or = K/(Ca+Na+K).

$Fs_{17.6±0.7}$ (n = 44; Fig. 7a; Table 1). The microprobe data yield an average of $Fs_{17.7±0.8}$, again confirming the SEM results. The Ca pyroxene is diopside, bordering on augite, and has a mean Fs-content of $Fs_{6.9±0.7}$ (n = 22; Table 1).

The plagioclase composition phase, which we believe is most likely maskelynite because plagioclase melts at lower temperatures compared to olivine and orthopyroxene (Stöffler *et al.* 2018) and is unfractured compared to the adjacent olivine and orthopyroxene, has a general oligoclase composition of $Ab_{82±0.8}An_{13±1.4}Or_{5±1.6}$ (n = 49; SEM data; Fig. 7b). Microprobe data yield compositions of $Ab_{82±0.6}An_{12±2.6}Or_{6±2.6}$, once again confirming the results obtained by SEM. There is some variation in the An and Or components, but the cause of this is unclear. It does not relate to chondrule versus matrix textural position, and maskelynite can be heterogeneous, probably due to the incomplete mixing of former feldspar zoning during the glass forming stage (Chen & El Goresy 2000; Burgin *et al.* 2023).

The chemical compositions of the minor mineral phases apatite, merrillite and chromite are given in Table 1. Generally, the minor phases occur sparsely either very fine-grained (< 10 μm) or as moderate grain sizes (50–100 μm), although in one area a large (> 1 mm) chromite and merrillite assemblage bridges the fusion crust rim with the interior of the meteorite sample. Kamacite has a mean Ni-composition of 6.3 wt% (n = 30), taenite a mean of 35.9 wt% Ni (n = 6), and tetrataenite has a mean of 44.9 wt% Ni (n = 2). The analysed tetrataenite is primarily found bordering kamacite or as an exsolution from kamacite.

# Discussion

## Classification

The existing classification of the Aarhus meteorite is an H6 ordinary chondrite (Gradey 2000), which appears to have been derived from Mason's (1963) unpublished olivine X-ray diffraction analysis and Callisen *et al.*'s (1963) petrographic observations. The H indicates that it is a high iron ordinary chondrite, with the 6 indicates that is displays a very high degree of metamorphic equilibration. Of the ten classification criteria for chondrites based on petrologic type (van Schmus & Wood 1967), the ones deemed most relevant are the composition and homogeneity

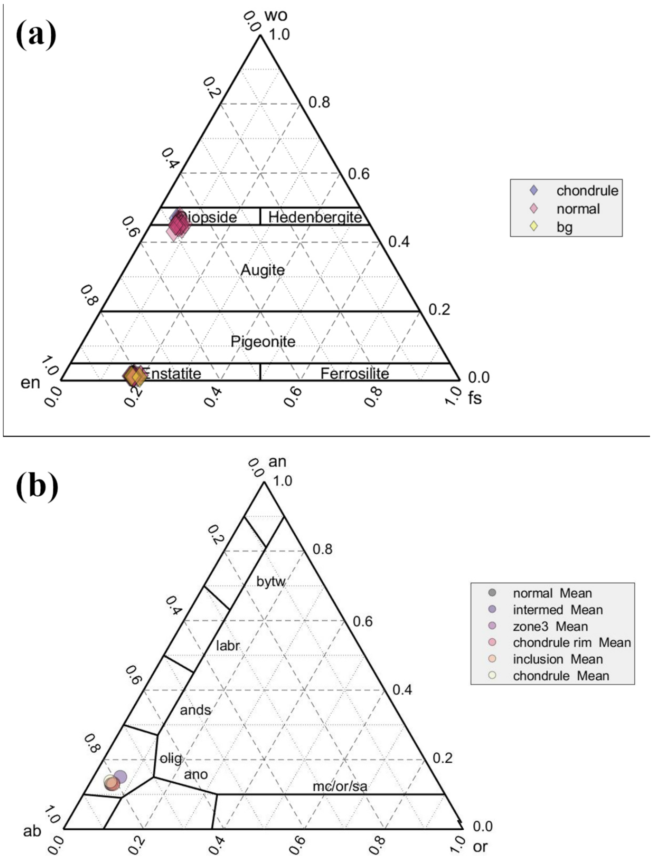


**Fig. 7.** Classification diagrams of the pyroxene (A) and plagioclase (B) in Aarhus.

of olivine, nature of the feldspar grains, texture of the matrix, and the chondrule-matrix integration. Our olivine data show the mean olivine composition to be *Fa#* = 19.9 and strongly supports the classification as H-type (Fig. 7). The olivine compositions have a mean deviation of $\sigma_{\mu,2sd}$ = 2%, which corresponds to petrological type 5 or 6 (Van Schmus & Wood 1967).

The low-Ca pyroxenes analysed are of enstatite composition (Fig 7a) and thus orthorhombic. This low-Ca pyroxene structural state is diagnostic of the petrologic types 6-7 (Hazen 2021). Diopside undergoes coarsening with an increasing grade of thermal metamorphism (Huss *et al.* 2006) and occurs as a minor phase in equilibrated ordinary chondrites, which also supports the classification as a type 6 (Hazen 2021).

The size of the plagioclase (maskelynite) grains is diagnostic of the petrologic type (van Schmus & Wood 1967). For either type 5 or 6, this phase should be found as products of metamorphism rather than relict grains incorporated into the meteorite during assembly. In type 6 chondrites, it should exist abundantly as 50–100 μm sized interstitial grains (van Schmus & Wood 1967), whereas in type 4–5 it is found as 2–50 μm sized grains (Hutchison 2004). In

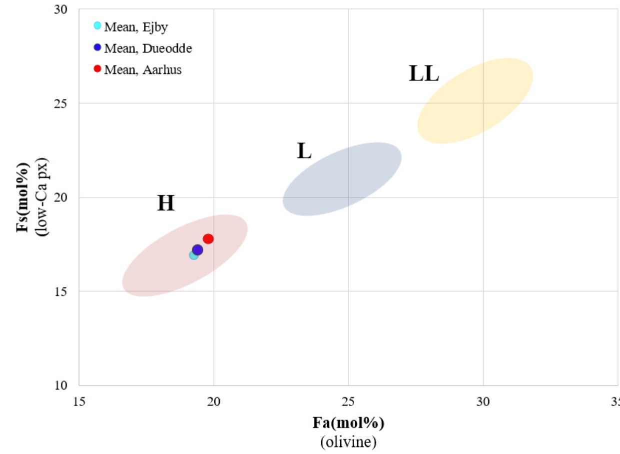


**Fig. 8.** Classification diagram of the H, L and LL ordinary chondrite fields based upon olivine and orthopyroxene composition. Data for Ejby are from Haack *et al.* (2019), and Dueodde are taken from unpublished results presented on the Meteoritical Bulletin (https://www.lpi.usra.edu/meteor/metbull.cfm).

Aarhus, the plagioclase is found in great abundance with large grains of > 50 μm but also smaller grains of 5–25μm. The occurrence of the larger grains indicates classification as type 6. The coarse-grained texture of the matrix and the poor delineation of the chondrules, which are also diagnostic for the petrologic type 6, were likely caused by thermal heating of the rock caused by radioactive decay of abundant short-lived isotopes whilst in an early Solar System parent body.

## Shock effects and brecciation

The Aarhus meteorite has undergone shock metamorphism, as evident from the fractures in olivine and pyroxene, and the occurrence of maskelynite. The occurrence of maskelynite indicates a shock class of S5 and indicates shock pressures of at least 30–45 GPa (Stöffler *et al.* 2018). The shock textures appear to be superimposed upon an earlier phase of brecciation. The darker zones surrounding clasts, seen best macroscopically (Fig. 2b, c), are slightly richer in fine-grained troilite and metal sulphide than the clasts, and have textures indicate there was a degree of healing and grain boundary growth (Fig. 4) prior to the last major shock event. This may mean that this phase of coarse brecciation occurred on the parent body, probably early in the rock's history, and before the rock was statically thermally equilibrated at H6 conditions. Thus, this metamorphosed breccia texture is not related to the shock event that fractured olivine and orthopyroxene and melted plagioclase that may be related to the catastrophic disruption of the parent body.

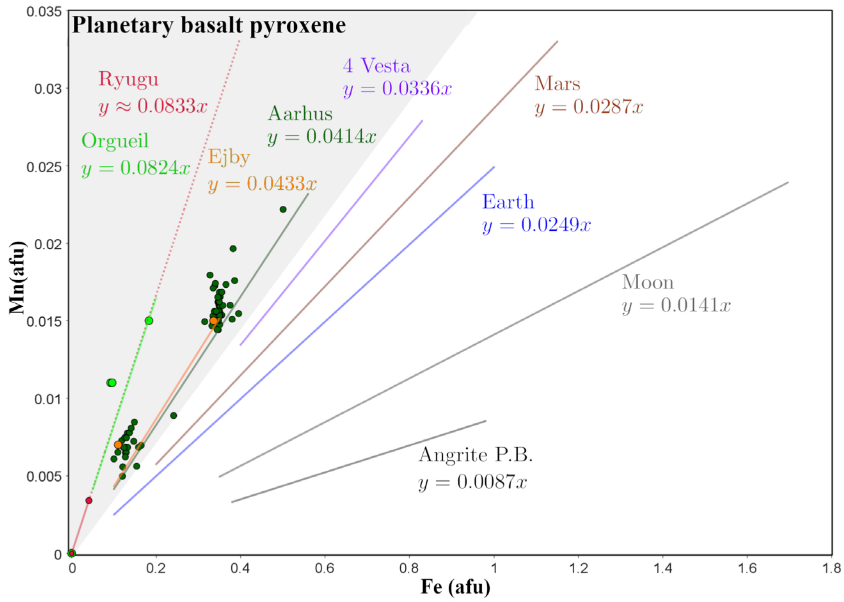


**Fig. 8.** Mn versus Fe diagram for orthopyroxene and clinopyroxene data in various meteorites. The diagram is modified from Papike *et al.* (2003).

*Comparison with Danish H-chondritic meteorites*

There are two further known H meteorites in Denmark. The H5/6 Ejby meteorite fell over Copehagen in 2016 (Haack *et al.* 2019), and Dueodde, an H5, is reported in the Meteoritical Bulletin to have been recovered from Bornholm in 2017 after probably having lain there for several years. There is currently insufficient mineral data for Dueodde to undertake a comparison. However, for the mineral phases stated in Table 1 the residuals, Δ, between Aarhus and Ejby and the relative percentagewise deviation, $\Delta_{\%}$, relative to Aarhus have been calculated by $\Delta = C_{oxide,Aarhus} - C_{oxide,Ejby}$, and $\Delta_{\%} = \Delta_{abs}/C_{oxide,Aarhus}$, and , where is the wt% of a given oxide. Generally, Aarhus and Ejby are very similar: olivine, low-Ca pyroxene and feldspar, with relative deviations of 0-3% for oxides. An exception is the plagioclase (maskelynite) of Aarhus that contains less $Na_2O$ than Ejby. The metals are similar in Aarhus and Ejby with relative deviations of ~0% for kamacite, taenite and troilite in the substantial elements: Fe and Ni for kamacite and taenite, and Fe and S for troilite. Tetrataenite is somewhat different in Fe and Ni composition between Aarhus and Ejby, although within ~10% relative deviation. The fact that the three known meteorites found thus far in Denmark are similar is consistent with H meteorites being the most commonly found type – not that Denmark especially attracts them!

## Origin of the Aarhus meteorite

There are different methods of linking meteorites to an asteroidal parent body. The HED meteorites, for example, are commonly argued on the basis of spectra data to come from the asteroid 4Vesta (McSween *et al.* 2013). For chondrites, most attempts at identifying parent bodies based on astrophysical data will be inconclusive (Sears 2004). An exception is a recent interpretation of the asteroid Ryugu as a C-type asteroid based on near-infrared reflectance observations, which was confirmed from returned material (Yada *et al.* 2022). Although isotopic data such as O isotopes form a common means of estimating the parent body of a meteorite, a less expensive method is the geological comparison of major and minor elemental ratios in mineral phases, such as pyroxene, olivine, and feldspar (e.g., Papike *et al.* 2003). The Fe/Mn ratio, which the change of behaviour in geochemical affinity from lithophile to siderophile for Mn during the core-formation process (Ringwood 1991; (Gessmann & Rubie 2000), can be used to differentiate some parent bodies.

The ratio of Mn/Fe in pyroxene in Aarhus are plotted in Figure 9, along with the those for basalt pyroxenes of Earth, Mars, the Moon, 4 Vesta, the angrite parent body from Papike *et al.* (2003), and the carbonaceous chondrites Ryugu (Nakamura *et al.* 2022) and Orgueil (Leshin *et al.* 1997), as well as the Danish H5/6 Ejby (Haack *et al.* 2019). The trend of pyroxene Mn/Fe ratios of Aarhus is and is distinct from any of the differentiated bodies (Vesta, Mars, Earth, the Moon and angrite parent body) but overlaps with that of Ejby (Fig 9). The trends of Aarhus, Ejby, Orgueil and Ryugu are steeper than that of Earth, whose mantle is known to be depleted in Mn, and less depleted than 4 Vesta, Mars, and the angrite parent. The Aarhus and Ejby pyroxene compositions therefore confirm that these meteorites are probably very little modified from their primary composition. This comparison indicates that an area can be marked on this mineral composition diagram that shows whether or not a parent body of an analysed meteorite has undergone differentiation and/or element mobility and could be usefully employed in cases where there is very little volume of material available for geochemical analyses.

## Conclusions

The Aarhus meteorite has been analysed for the first time since 1963 and now has a comprehensive suite of mineral analyses. The mineral assemblage confirms it to be an ordinary chondrite, with the olivine and orthopyroxene compositions supporting a 'H' (high iron) classification. The petrologic type 6 is indicated by the homogeneous olivine compositions, orthorhombic low-Ca pyroxene, large feldspar grains, a recrystallized matrix, and poor chondrule delineation. Aarhus originates from an undifferentiated parent body, which is supported by the Fe/Mn trend found in pyroxenes. Texturally, brecciation predates metamorphism, and thus was probably brecciated very early on in the Solar System history. The shock metamorphic history later was later superimposed on this rock. These results upscale the transmitted light microscope observations made by Callisen *et al.* (1963) and thus provide new insights into this old rock.

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