ORIGIN OF ALLENDE CHONDRULES; H. Palme1, B. Sippel1, G. Kurat2 and E. Zimmer3;  
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The origin of chondrules is still not completely understood although major progress has been made in recent years (1). Since chondrules were, by definition, once molten droplets their original structure is destroyed and one has to rely primarily on chemical composition when attempting to unravel their formation history. We have analysed 34 Allende chondrules by INAA techniques and performed subsequent petrographic investigations on thin sections prepared from the analysed chondrules. Conclusions from subsets of this suite have been presented earlier (2,3).

Chondrules in Allende and other chondrites are notoriously inhomogeneous in chemical composition (e.g., Fig. 1). Correlations between chemical composition, texture and size are absent. Low bulk Fe contents of chondrules and large variations in chemical composition of individual chondrules rule out formation by remelting of matrix in a single step. It is conceivable that several cycles of melting of fine-grained matrix, crystallization of coarse-grained chondrules and subsequent collisional destruction and reassembly to new chondrules could ultimately lead to the observed coarse-grained, inhomogeneous, Fe-poor objects. However, the chemical composition of Allende and other chondrules excludes this possibility and shows that they have not been subject to geochemical processing, thus clearly pointing to a nebular formation origin, as earlier emphasized by Grossman (1):

1) Loss of a major fraction of metal during chondrule formation is excluded: (a) by reasonably good correlations and chondritic ratios among Fe, Ni, Co and (b) an approximate correlation of the refractory metal Ir with lithophile refractory elements (Sc, REE) and the complete absence of a Ni-Ir correlation.

2) Lack of lithophile element fractionation is evident from: (a) Correlations between incompatible and compatible refractory elements. Several remelting episodes would, for example, destroy the good correlation of Sc with Sm (Fig. 2) as Sc is partly compatible with olivine but Sm is not. This is apparent from the distribution of Sc and Sm within chondrules as determined by ion-probe analysis (see abstract by Kurat et al., this volume). Scandium and Sm data of olivine and chondrule matrix are shown in Fig. 2. The corresponding bulk compositions plot on the CI-line. Olivine has some Sc but no Sm while chondrule matrix has high Sm and lower Sc as expected from closed system melting. Separation of olivine and chondrule matrix would inevitably destroy the good correlation for chondrules. (b) Mg/Si variations among chondrules require olivine and/or pyroxene fractionation. However, chondritic bulk Sc/Si (Fig. 2) ratios exclude any pyroxene fractionation, since Sc has strong preference for pyroxene and involvement of this mineral would fractionate Sc (and V) from incompatible elements. Even large radiating pyroxene chondrules have chondritic Sc/Si ratios (2) excluding any magmatically produced pyroxene as precursor. At the time of Mg/Si fractionation (pyroxene formation) both, Sc and Sm, must have been completely condensed. (c) Absence of Eu- and Sr anomalies rules out any plagioclase fractionation. (d) Occasionally volatility related REE-patterns are found in chondrules, including a single chondrule analysed here. Consequently, the chemical inhomogeneity of Allende chondrules must be a result of condensation and aggregation in the early solar nebula.

From Fe-Cr (Fig. 1) a complementary relationship between matrix (including related dark inclusions) and chondrules is inferred. It even appears that chondrules from various parts of Allende are different in composition indicating a closed system behaviour for bulk Allende material (3).

The bulk Allende Sc/Ni-ratios in chondrules (this work and (4)), matrix, dark inclusions and various grain size fractions (5) in Fig. 3 argue against loss of volatiles during chondrule formation or reflect condensation of volatile Se (chemically similar to S) into Ni-containing phases. It is suggested that Ni, Co, Se and partly Fe in chondrules reflect incorporation of variable amounts of a matrix component. It is important that all Allende components have essentially bulk Allende Sc/Ni ratios. Redistribution of Se by volatility related processes is virtually absent.

Model: Chondrules formed from aggregates containing previously condensed mineral grains (forsterite, enstatite, Ca, Al-oxides) and some fine-grained dust (matrix). Variations in chondrule composition must be the result of random sampling of these components. A more or less continuous variation in abundances of refractories in Allende chondrules, from the level in matrix (Fig. 2) to that in CAIs, suggests isolation of aggregates at various nebular temperatures. The low bulk Fe content of Allende chondrules (Fig. 1) indicates that formation of aggregates occurred above the condensation temperature of the major fraction of Fe and Ni. This can is easily be achieved at higher than solar oxygen fugacities, since there is a considerable increase in the condensation temperature of forsterite, but not metal, with increasing fO2 (6).

While fine-grained matrix formed in an environment of rapid temperature decrease and high supersaturation: many small forsterite grains condensed (also at elevated oxygen fugacity) on tiny condensation nuclei of refractory oxides and metals, possibly in a region above or below the central plane of the accretion disk. Matrix, predominantly olivine, contains all cosmochemical components (refractory metals, refractory lithophiles etc.) in nearly bulk Allende proportions (5). Higher temperatures and slower cooling in the central plane of the accretion disk would produce larger grains and aggregates, potential precursor components of chondrules.
Turbulent mixing caused mixing of fine grained matrix and coarse grained aggregates. Some fraction of the dust accreted to aggregates before they were converted to chondrules (by a yet unidentified mechanism). A mineralogically and texturally (but not compositionally) unusual fragment of Allende (ALL-AF) contains unmelted aggregates that are good candidates for chondrule precursors (7,8,9).

The essential point in the present model is that coarse grained chondrule precursor material and fine grained matrix are both products of processes that occurred in the solar nebula. The chemical complementarity of these two components (Fig. 1) requires a closed system (except for exchange with gas of different oxygen isotopic composition). The inferred nebular processes must have occurred in a small nebular region thus providing evidence for a highly turbulent nebula with large local variations in temperature, oxygen fugacity and cooling rates. This view is inherent in our notion of unequilibrated chondrites, which are generally thought to represent the most primitive meteorites and thus record a variety of nebular processes (10). A slowly cooling nebular environment would produce equilibrated meteorites. The present model implies a significant time difference between formation (accretion) and melting of aggregates (chondrule formations).

Fig. 1
Cr vs. Fe in Allende Chondrules

Fig. 2
Sm vs. Sc in Allende Chondrules

Fig. 3
Se vs. Ni in Allende Components

RIDGE AND TROUGH TERRAIN AND THE ORIGIN OF MIRANDA'S CORONAE;
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Tectonic and magmatic models have been investigated for the formation of sets of subparallel ridges and troughs, termed ridge and trough terrain (RTT), observed on Miranda, and the results indicate that most of Miranda's ridges and troughs formed in extensional-tectonic environments, with magmatism as a common association [1]. Normal faulting models are favored based upon the morphologies, geologic settings, and associations of ridges and troughs as well as the relative ease of extensional failure of Miranda's crust [2]. Compression, if involved in shaping RTT, was of local extent. The results shed light upon the origin and evolution of Miranda's three coronae, indicating that mantle upwelling was probably the most important contributor to the formation of the coronae [3]. Despite this common thread, however, the origin and evolution of each corona may have been in many ways unique.

Arden Corona. Surrounding Arden's Inner Region of smooth terrain is the Outer Region composed of a Central Band that exhibits ridges and troughs of uncertain origin and the Southeastern Band containing ridges and troughs created by domino-style normal faulting. Arden may have originated as an impact basin, subsequently modified by volcanism and tectonism [4]. Basin formation may have fractured and thinned the crust to a great extent, permitting Inner Region volcanism, but the timing and process of Outer Belt formation may be different. Consistent with this idea, Arden's Southeastern Band shows a relatively fresh morphology, indicating relatively late tectonic activity at the corona's periphery.

Beginning from the premise that a large impact initiated Arden's evolution, an evolutionary scenario is proposed that could account for the corona's present morphology. Modeling of the stress field resulting from internal flow induced by relaxation of an icy satellite basin shows that the most commonly predicted flow pattern induces near-surface stresses that are extensional near the crater center, compressional in the region straddling the crater rim, extensional at roughly twice the crater radius, and extensional but relatively small near the basin antipode [5]. Comparison of this stress pattern has been made to mirandian geomorphology observed radially from the presumed center of Arden Corona toward Elsinore Corona, considering the extent and inferred formational stress of each region. Excepting Inverness Corona, the possible independent origin of which is discussed below, the comparison is favorable if Arden's Central Band is of compressive origin. Conversely, the comparison argues for a compressional paleo-stress in this band if we accept the likelihood of Arden as a relaxed and modified impact site. Predicted stress magnitudes of \( \leq \) a few bar [5] are not large enough to create deep faults on Miranda, but could cause motion on pre-existing structures to depths \( \leq \) a few km if the shear strength of Miranda's crust is very small [2]. A large impact into a thin, weak lithosphere can produce multiple normal faults concentric to the resultant crater [6], and such fractures could have been reactivated by relaxation-induced stresses to create ridges and troughs of the Arden Outer Belt. Thus, formation of the hypothetical Arden Basin with possible concentric fractures, plus subsequent viscous relaxation, fracture reactivation, and Inner Region resurfacing could have shaped Arden to its present form.

Inverness Corona. At least four observations suggest that Inverness represents the mirandian equivalent of a rift zone. First, extensional-tectonic bands, expressed as cross-sectionally asymmetrical ridges and troughs that likely originated as domino-style fault blocks, bound three sides of Inverness. Second, two RTT types identified within Inverness are believed to have had a normal-faulting origin as graben and domino-style tilt blocks. Third, topographically high shoulders of cratered terrain bound the north and western edges of the corona, likely due to isostatic rebound resulting from adjacent rifting. Fourth, flood volcanism likely occurred within Inverness, and volcanism may have contributed to the formation of an unusual RTT type in northwestern Inverness which may have originating as striae on diverging lobes of a late-stage viscous extrusion [7].

The rift zone analogy presents a simple explanation for the seemingly unusual shape of the Inverness chevron. Large-scale domal uplifts usually produce three rifts that diverge from the crestal region at similar angles; two arms of such terrestrial triple-rift junctions typically become zones of normal faulting and volcanism, while activity halts on the third arm [8]. On Miranda, the two branches of the Inverness chevron are believed to mark sites of ancient normal faulting and volcanism, and both arms were likely active at similar times. Verona Rupes, which joins the chevron at a common apex, shows no volcanism and may represent the failed arm of a triple-rift junction. If so, the apex of the chevron marks the site of ancient deep upwelling that triggered doming and active rifting of the mirandian crust.

Careful examination of the topography data of [9] shows that the dark apex of the Inverness chevron stands high relative to the light unit to the north and east. This relationship may have resulted from a sequence of normal faulting of the presumably older dark unit along both active rift arms with relative
downdrop of the northern and eastern blocks, followed by infill of the chevron-shaped rift depression by a mobile light material that now forms the bright chevron. In this "hot spot" model of northern Inverness's evolution, migration of a mantle plume toward the southwest over time could account for an apparent shift of volcano-tectonic activity from the presumably oldest area of activity, where the Inverness chevron intersects Verona Rupes, to beneath the corona's northwest region, where ridges and troughs appear to be relatively young and may owe their origin to late-stage extrusion. While terrestrial rifting is invoked here as an analogue to mirandan rifting, "plate tectonics," which involves the physical separation of crustal plates with formation of newer crust in between, is not suggested to have operated on Miranda; instead a single-plate rifting model is invoked [1].

In summary, the history of Inverness probably began with mantle upwelling producing crustal doming and active rifting, creating the Verona-chevron triple junction. Normal faulting and fissure volcanism ensued in the corona's inner region, where extension, crustal thinning, and volcanism were most intense, producing the bright chevron and short-wavelength ridges and troughs of the Inverness Inner Region. The primary hot spot migrated during this time toward its final position beneath northwestern Inverness. Extrusion there might have created an unusual RTT as striae on diverging extruded lobes while causing local compression of the northwest corner of Inverness, creating folds there and in adjoining cratered terrain. Normal faulting of thicker crust surrounding the Inner Region created the relatively large wavelength ridges and troughs of the Inverness Outer Belt, increasing the lateral dimensions of the corona; however, the degree of extension and availability of magma were not great enough to permit volcanism there.

**Elsinore Corona.** Adjacent to the Elsinore Inner Region of intersecting ridges and troughs, the Outer Belt consists of the north-south trending "Grooved Band," simply explained as regularly-spaced grabens in a volcanically resurfaced rift, and the east-west trending "Ridged Band," containing the prominent "Elsinore Ridges" [10]. Diapirism or fissure volcanism may have shaped the Elsinore Ridges [10, 11, 4]. If so, they may have formed as viscous linear extrusions which formed a chilled caprace that inflated as magmatism continued beneath. We find such a magmatic origin likely only in combination with normal faulting. Elsinore Ridges may have formed within grabens, in some cases only partially resurfacing them to leave bounding troughs, in a manner analogous to that proposed for some ridges on Ariel [12]. This style of volcanism only in the Ridged Band suggests extrusion of a more viscous magma compared to that which resurfaced the Grooved Band, and its eruption may have been aided by a greater degree of extension and crustal thinning of the Ridged Band.

Elsinore's Outer Belt represent further expressions of mirandan rifting, as the constituent bands have experienced volcanism and extensional tectonism. Elsinore's position opposite the candidate Arden basin invites speculation that disruption due to concentration of seismic energy at the impact antipode [13] and concentrated fracture near the antipode of the viscously relaxing basin [5] might have created an initial region of fracture and volcanism where large-scale upwelling ultimately became concentrated.

**Implications for general corona evolution.** The preceding suggests both similarities and differences in the formation and evolution of Miranda's three coronae. All are of volcano-tectonic origin, with extensional stresses being predominant, suggesting that mantle upwelling was involved in their formation. Arden's activity may have been triggered by an initial impact that induced relaxation flow, Inverness probably developed over an upwelling mantle plume, and Elsinore may have been created by an upwelling plume localized by Arden's formation. All three coronae appear to have grown outward over time from an initial core of tectonic deformation and volcanism. Both active and passive rifting probably contributed to corona development, as formation of core regions by active rifting above large-scale diapiric upwellings might have complemented satellite expansion in triggering passive formation of the outer belts. The squared shape of each corona likely reflects a satellite-wide pattern of ancient near-orthogonal structures which influenced the development of later tectonic structures.