New Rules for AAAS–Newcomb Cleveland Prize

The AAAS–Newcomb Cleveland Prize, which previously honored research papers presented at AAAS annual meetings, will henceforth be awarded annually to the author of an outstanding paper published from September through August in the Reports section of *Science*. The second competition year under the new rules starts with the 2 September 1977 issue of *Science* and ends with that of 25 August 1978. The prize is $5000; the winner also receives a bronze medal.

To be eligible, a paper must be a first-time presentation (other than to a departmental seminar or colloquium) of previously unpublished results of the author's own research. Reference to pertinent earlier work by the author may be included to give perspective.

Throughout the year, readers are invited to nominate papers appearing in the Reports section. Nominations must be typed, and the following information provided: the title of the paper, issue in which it is published, author's name, and a brief statement of justification for nomination. Nominations should be submitted to the AAAS–Newcomb Cleveland Prize, AAAS, 1515 Massachusetts Avenue, NW, Washington, D.C. 20005. Final selection will rest with a panel of scientists appointed by the Board of Directors.

The award will be presented at a session of the annual meeting at which the winner will be invited to present a scientific paper reviewing the field related to the prizewinning research. The review paper will subsequently be published in *Science*. In cases of multiple authorship, the prize will be divided equally between or among the authors; the senior author will be invited to speak at the annual meeting.

Reports

Fluid Inclusion Assemblages of the Stratiform Broken Hill Ore Deposit, New South Wales, Australia

Abstract. *Minerals of the Broken Hill lode in New South Wales, Australia, have a rich assemblage of fluid inclusions. Most typically they contain a high-salinity aqueous liquid and a high-density carbon dioxide and methane gas. Northerly trending shear zones in the area are characterized by a distinct assemblage of inclusions. The inclusions provide a record of the sequence of metamorphic fluids since the period of high-grade metamorphism. Inclusions from the period of ore formation have been eliminated by repeated deformation and recrystallization.*

A large proportion of all ores are deformed or metamorphosed to some degree. One of the major outstanding problems of fluid inclusion research into the genesis of ore deposits is the effect of subsequent deformation and metamorphism on inclusions which were trapped during the period of ore formation. It is likely that inclusions of ore-forming fluids are modified and overprinted by later metamorphic inclusion assemblages, and in extreme cases entirely eliminated. This raises the question of what useful information may be obtained from the study of fluid inclusions in highly metamorphosed ore deposits.

An example is the Broken Hill lead-zinc deposit situated in Proterozoic high-grade metamorphic rocks in western New South Wales. It is one of the largest ore bodies of its type and of considerable historical significance, as work on the deposit has resulted in major advances in understanding the mode of origin of stratiform ore bodies (*1*). Despite a vast scientific literature (*2*), including much discussion of the role of fluids in the formation of the ore body and alteration of the surrounding rocks, there is still no significant reference to the fluid inclusions. Nevertheless they are abundant and widespread, especially in the gangue silicates, carbonates, and fluorite.

In a deposit of this type, the major problem in making use of the fluid inclusions is to establish when they were trapped relative to known episodes in the geological history of the area. Homogenization temperatures and pressures are of limited value in this stage of the investigation because large and unknown corrections may be required. The metasediments and metavolcanics which enclose the ore body have had a complex deformational and metamorphic history. At least three episodes of folding are associated with granulite facies metamorphism (F_1, F_2 prograde, and F_3 retrograde) at about 1700 million years (*3*, *4*). Shear zones trending north-northwest and northeast are a major expression of retrograde metamorphism in the area.

Where blue quartz of the lode is recrystallized, early fluid inclusions have been destroyed (Fig. 1a). Fluid inclusion elimination must have accompanied each episode of deformation and recrystallization. Critical data relevant to the time of emplacement of the ore body indicate that the ore body was formed before or during the high-grade metamorphism (*5*), although the latter possibility is not seriously entertained in one recent review (*6*). These considerations suggest that the fluid inclusions now remaining are unlikely to provide useful information on ore genesis.

With the important exception of blue quartz in the siliceous lode rocks, fluid inclusions are commonly clearly aligned along healed fracture surfaces which often cut grain boundaries. Most of these inclusions have therefore been introduced after the final adjustment of grain boundaries. While the fractures persisted they would have facilitated movement of fluids and the development of an alteration zone in the wall rocks (*7*, *8*). With presumed low fluid flow rates, intergranular spaces and fractures would hold fluid containing dissolved chemical species in equilibrium with local mineral assemblages (*9*). To reduce this problem, quartz has been selected as the host mineral for a comparison of the fluid inclusion content of rocks of different generations (Table 1). Carbonate from late minor fault zones is included for comparison as quartz was not available.

Blue quartz in the siliceous lode rocks contains a complex assemblage of small (< 10 μm) fluid and solid inclusions. Rutile needles are especially characteristic (*10*). The fluid inclusions are variable in content and difficult to classify. Some have extreme salinities, estimated to be 60 to 70 percent based on the volumes occupied by NaCl and other phases which have formed during cooling (Fig. 1b). By contrast, adjacent recrystallized quartz contains few inclusions, the inclusion assemblage tends to be simple, and the inclusions associated with individual healed fractures have a uniform composition. Although some variability is apparent, fluid inclusions from the lode pegmatite quartz are similar to those from the lode blue quartz. Sulfide-bearing quartz veins (*11*) contain an inclusion assemblage similar to that of recrystallized quartz of the siliceous lode rocks. The veins are discordant to the layering of the lode rocks and to the garnet-rich rocks which, in places, are present at the lead lode–silicate rock inter-

Table 1. Fluid inclusion assemblages in Broken Hill rocks. The survey was based on approximately 100 representative samples. Abundances: r, rare; c, common; and a, abundant. Phases at 25°C are as follows: (type 1) NaCl cube, at least one other crystal, aqueous solution, and gas; (type 2) at least one birefringent crystal (no NaCl cube), aqueous solution, and gas; (type 3) NaCl cube, aqueous solution, and gas; (type 4) at least a rounded isotropic crystal (?NaCl), up to five other crystals, aqueous liquid, and gas; (type 5) aqueous solution, CO_2-rich gas, with or without CO_2 liquid; (type 6) aqueous solution and gas rich in CO_2 and CH_4; (type 7) aqueous solution and low-density gas; (type 8) liquid CO_2 and < 5 percent aqueous solution; (type 9) high-density, low-critical-temperature gas; and (type 10) aqueous liquid.

Occurrence	Abundance of inclusion type									
	1	2	3	4	5	6	7	8	9	10
Relic lode blue quartz	a	a	c		r	?c			r	c
Lode pegmatite quartz	c	a	r			a	?r			r
Recrystallized lode quartz			c	r		?a				c
Discordant vein quartz			a	r		a	r		r	c
Retrograde shear zone quartz			c	c	r			c	c	c
Late minor fault zone carbonate							a			

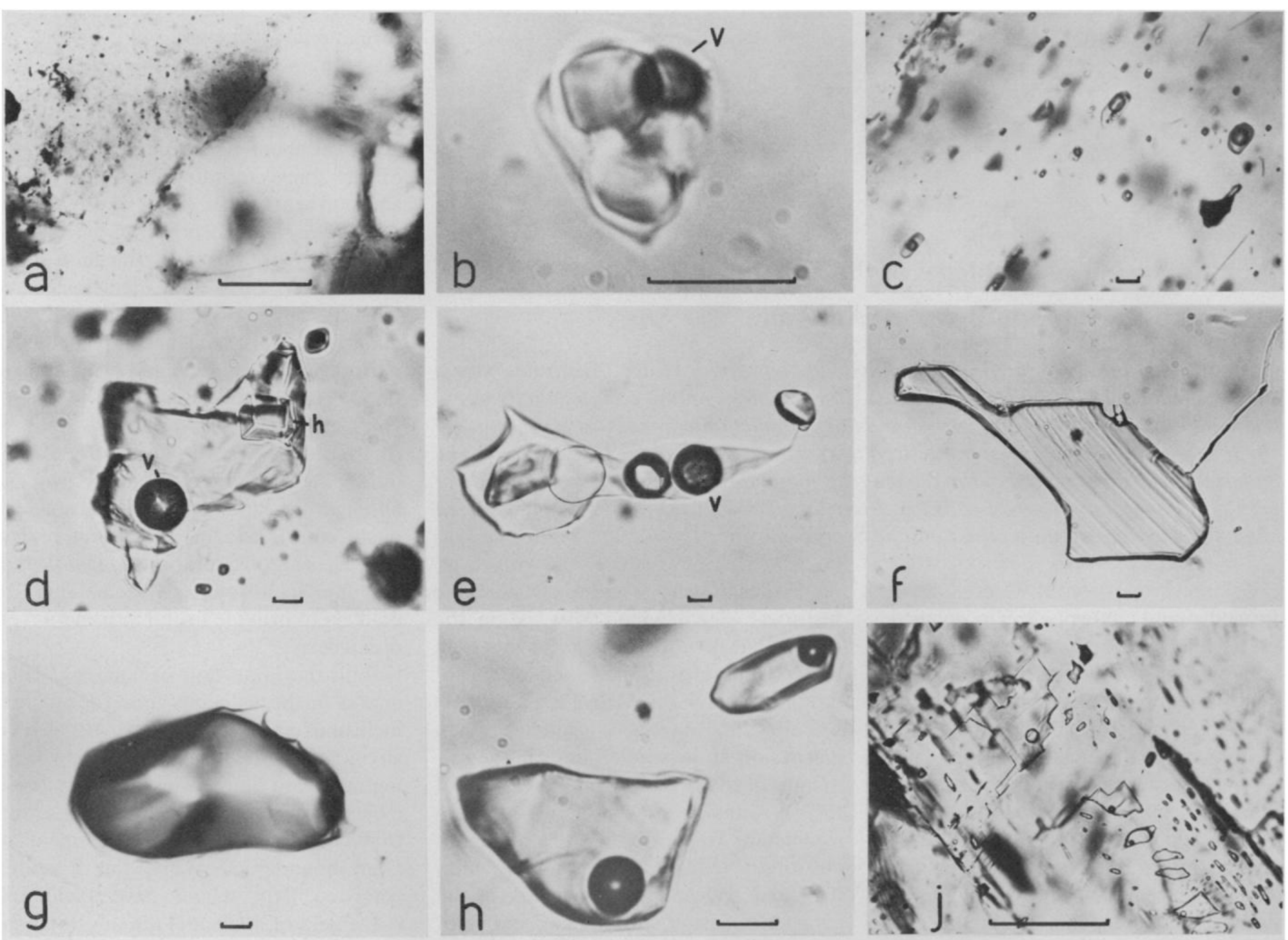

Fig. 1. Photomicrographs of Broken Hill fluid inclusions in transmitted light at 25°C. All bar lengths are 10 μm, except in (a) and (j) where the bar represents 100 μm. (a) Inclusion-free polygonally recrystallized quartz against inclusion-rich relic (blue) quartz; No. 3 lens ore, Zinc Corporation mine. (b) Type 1 multiphase inclusion with four daughter crystals and vapor bubble (*v*); blue quartz, No. 3 lens ore, Zinc Corporation mine. (c) Fluid inclusions, types 2 and 6, and rutile needles in lode pegmatite quartz. Pegmatite internal to B lode, level 14, New Broken Hill Consolidated mine. (d) Type 3, multiphase inclusion with halite daughter crystal (*h*) and vapor bubble (*v*) in discordant vein quartz, level 27, North mine. (e) Type 4, multiphase inclusion with unidentified daughter crystals and vapor bubble (*v*); in quartz from vug, level 21, New Broken Hill Consolidated mine. (f) Type 9, high-density gaseous inclusion from the same crystal as (e). (g) Type 8, CO_2-rich liquid inclusion in quartz from the same vug as (e). Note the thin layer of aqueous liquid on the cavity walls. (h) Type 6, aqueous liquid plus (CO_2 + CH_4) rich gas inclusion in quartz; same sample as (d). (j) Type 7 fluid inclusions in late minor fault zone calcite. West fault, level 27, North mine.

face. They appear to have been emplaced during F_3 or later (*12*) and rarely contain deformed but recognizable crystals showing the $\{10\bar{1}0\}$, $\{10\bar{1}1\}$ and $\{01\bar{1}1\}$ forms of α-quartz.

The fluid inclusions in blue quartz of the siliceous lode rocks are too small for satisfactory microscopic study, but abundant inclusions in lode pegmatite (Fig. 1c) and discordant vein quartz (Fig. 1h) contain a gas phase which is indicated by low-temperature phase equilibria (*13*) to be mainly CO_2 and CH_4. The gas composition has been confirmed by gas chromatography. Aqueous solutions in the same inclusions have a wide range of salinity between that equivalent to 5 percent NaCl and saturation, but low-temperature microscopic observations are difficult because of the formation of voluminous clathrate hydrates. It is important to note that despite this range, fluid composition is almost constant along individual healed fracture surfaces, after allowance is made for "necking down" of inclusions, which sometimes results in the presence of a larger or smaller gas bubble.

The period between the high-grade metamorphic event at about 1700 million years and an event recorded at 500 million years in the mica ages (*14*) is not well known. However, it is clear that at least some of the shear zones were active during a substantial part of this period (*7, 15*). Kyanite-, staurolite-, and chloritoid-bearing assemblages have been described from the shear zones (*15*). Fluid inclusions which may be characteristic of the north- to northwest-trending shear zones have been identified from the British and Pine Creek shear zones, and also in quartz in vugs associated with calcite, apophyllite, and laumontite (*16*) from level 21 of the New Broken Hill Consolidated mine in a related situation. They include liquid CO_2 inclusions (type 8, Fig. 1g); highly saline inclusions with up to six daughter crystals but without an NaCl cube which homogenize up to 450°C (type 4, Fig. 1e); and a high-density gaseous fluid which homogenizes at temperatures between $-90°$ and $-125°C$ (type 9, Fig. 1f), with some inclusions exhibiting critical phenomena. Inclusion types 4 and 9 are sometimes found occupying distinct areas within the same fracture surface, showing that the fluids were immiscible at the time of healing of the fracture.

Early workers held that the ore body originated by selected hydrothermal replacement of favorable horizons, the fluids emanating from a deep magmatic source with the major retrograde shear zones acting as possible channelways (*17*). Dominant inclusions (types 4, 8, and 9) of the retrograde shear zones are not restricted to these rocks, but wherever they are found in lode rocks outside the major shear zones the preexisting assemblage has not been obliterated. Samples from the intersection of the British shear zone with the ore body contain relic quartz with an assemblage of fluid inclusions typical of the siliceous lode rocks outside the shear zone. Recrystallized quartz in the same samples contains the distinctive shear zone assemblage of fluid inclusions and not the assemblage found in recrystallized quartz elsewhere in the lode.

Although the evidence is slender, the majority of fluid inclusions in the lode pegmatites, the recrystallized lode quartz, and the discordant vein quartz appear to have formed during early retrograde metamorphism. The same holds for inclusions in the gangue Ca-Fe-Mn silicates and fluorite. This view is supported by the widespread occurrence of clinopyroxene–fluid inclusion complexes in bustamite. A case can be made for the exsolution of clinopyroxene by a process of solution growth through the fluid inclusions to which they are attached (*18*). I surmise that these fluid inclusions were present before solvus temperatures were attained. If this conclusion is correct, it follows that brittle deformation has been significant from the same period.

The fluid inclusions compare well with those described from high-grade metamorphic rocks elsewhere, especially in the common occurrence of a high-density CO_2 and CH_4 gas phase (*13, 19*). Some indication of the sequence of fluids pervading the ore body can be deduced from Table 1 if it is borne in mind that any later fluid may invade any earlier quartz. As immiscibility relationships between the fluid types are further established, and the compositional variations of continuous fluids in equilibrium with the different mineral assemblages become better known, it will become possible to determine the relative age of individual healed fractures.

There seems to be no easy way of proving that early-formed inclusions have not developed their present compositions by diffusive loss of water or other components during the long period of retrograde metamorphism. This applies especially to the highly saline inclusions in the lode blue quartz. Nevertheless, rather clearly defined inclusion types are found over distances of some kilometers, and within individual healed fractures there is usually consistency of composition as far as can be judged from freezing stage data. The present study suggests that stratiform ore bodies in metamorphic terranes at least as old as middle Proterozoic provide an ideal environment for the collection of samples of fluids of metamorphic origin. The complex nature of the fluid phase and its changes in composition with time must be taken into account in any study of the metamorphism at Broken Hill.

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