Aridity, Continental Weathering, and Ground-Water Chemistry

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ABSTRACT

Naturally occurring acid ground water is more abundant than previously thought and appears to have been important in the geologic past. Acid (pH <4) saline ground-water and lake systems are found across southern Australia, are abundant as alkaline-hypersaline systems in East Africa, and are thought to represent processes associated with laterization, red-bed formation, authigenic potassium feldspar formation, and the formation of trace metal, bauxite, and opal deposits. The basic problems in understanding modern acid systems and their importance in the past are the cause and maintenance of the acidity. The extensive nature of these systems in Australia indicates that the stage of continental denudation and climates may be important variables. As continents evolve through denudation, there are changes in the minerals available to be weathered, the geomorphology of the weathered surface, the availability of water, and the types and rates of biogeochemical processes. We hypothesize that as a consequence of these changes, the chemistry of terrestrial water must change and that during late-stage continental denudation with appropriate climate conditions, dramatic changes can occur in the chemistry of terrestrial water. The acid-saline to hypersaline conditions of ground-water and playa systems in Australia may be an example of the type of changes that could occur.

INTRODUCTION

Without anthropogenic interferences such as acid-mine drainage and acid rain, the acidification of natural water has been thought to be uncommon (Drevet, 1988). However, increasing evidence indicates that naturally occurring acid ground water is more abundant than previously thought and has been important in the geologic past.

There are natural acid ground-water systems in Bowman County, North Dakota; Paint Pots, British Columbia; Engineer Creek, Yukon Territory; and in a region northeast of Fort Norman, Northwest Territories (van Everdingen et al., 1983). This type of environment is found in the southern United States (Goslin, 1966) and Summit County, Colorado (McKnight and Cenicola, 1980; Kimball et al., 1992). An intriguing example is the acid ground-water and lake system, Colour Lake, on Axel Heiberg Island in the high Canadian Arctic. The pH of the dike NaCl, H2O, lake water and the major ions feeding it is 3.7 (Allan et al., 1987).

On a much larger scale, numerous acid systems are found across the southern half of the Australian continent from Victoria and New South Wales in the east to South Australia and Western Australia (Bettaney et al., 1964; McLaughlin, 1966; Williams, 1970; Johnson, 1960; Mann, 1983; 1985; Macumber, 1983; 1992; Lyons et al., 1987; Lock, 1988; McArthur et al., 1989, 1991; Kling, 1990). These systems are characterized by acid ground water (pH <4) discharging onto playa lakes (Lock et al., 1992a; McArthur et al., 1989, 1991). Australian acid-hypersaline systems appear to be as abundant as alkaline-hypersaline systems in East Africa (Eugster and Jones, 1979). Not all hypersaline systems in southern Australia are acidified, but in South Australia there are at least 22 acid-lake systems (Lock, 1988), and in Western Australia there are at least 12 (Lyons et al., 1987). Because the playas are ground-water discharge zones, vast areas of ground water in these areas are acid. For example, the Murray Basin in Victoria, New South Wales, and South Australia covers an area of 10 km², and much of its saline ground water at intermediate depth is acid. These Australian systems are thought to represent processes associated with laterization, red-bed formation, authigenic potassium feldspar formation, and the formation of trace-metal, bauxite, and opal deposits (e.g., Brimhall et al., 1988; Duffin et al., 1989; Long and Lyons, 1990; Thiry and Milnes, 1991).

The basic problems in understanding modern acid systems and their importance in the past concern the cause and maintenance of the acidity (DeDeckker, 1983; Mann, 1983; 1988).
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McArthur et al., 1989). Some insight into this problem can be obtained from small-scale examples of acid systems, whether natural or anthropogenic (e.g., Filipek et al., 1987). In most cases the drive for acidification is the oxidation minerals and sediments (e.g., Nordstrom, 1982; Raischer and Fritz, 1991). Acidity is maintained in the systems because its production is greater than its dilution. The relative rates of production of acidity and alkalinity are a function of the abundance of dissolved oxygen and/or the buffer capacity of the rock and soil (Caldey and Cowling, 1978; Drever, 1988). The basic principles learned from the study of acid systems caused by anthropogenic

processes could be useful in understanding the acid systems in Australia. However, the extensive nature of acid ground water and aquatic systems in Australia and only local cases of active systems in other continents indicate that the stage of continental denudation and climate also may be important vari-
ables on a large scale. As continents evolve through denudation, there are changes in the minerals available to be weathered, the geology of the weathered surface, the availability of water, and the types and rates of biogenic processes (e.g., Barron et al., 1989). We hypothesize that because of these changes, the chemistry of terrestrial waters will be different and that late-stage continental denudation with appropriate climatic conditions, drainage changes can occur in the chemistry of terrestrial water. This paper investigates this hypothesis through the idea that the acid-like conditions of ground-water and playa lakes in Australia may be an example of the type of changes that could occur.

ACID SYSTEMS AND CONTINENTAL WEATHERING

The most intensely studied acid ground-water-lake system is Lake Tyrell in Victoria (Figs. 1 and 2). The initial research on this location was done by Macumber (1983, 1991). A more detailed geochronological description of the waters in the ground-water basin is in Lyons et al. (1992).

The lake and sediments of lakeshore acid ground water with acid ground water are of low, acid-

buffering capacities and include the Parklands in Victoria graywackes and gneisses of Archean age greenstone belts in the Tilgarn block of Western Australia, and Proterozoic age gneissic terrane movements, (2) stratigraphy and paleogeography, (3) magmatism, and (4) structure, geophysics, and tec-
tonics of the Jurassic arc and inboard areas.

This conference is organized to involve every participant. Each session begins with a talk summarizing the main problems and identifying the main problems and presenting information. Two-hour poster sessions follow within which all participants present data rele-

vant to the topic of that session. A short time is allowed for brief oral presentations. At the end of the session, the keynote speaker plus other participants will summarize the session and promote discussion among the conference participants.

Participation in the conference is limited to 60 persons. Additional persons in 1992 will be invited for the 1993 conference. Additional participants should apply by submitting a short summary of their contributions and their proposed topics for the confer-

ence and the tentative session by November 6, 1992, to Dave Miller, U.S. Geological Survey, 345 Middlefield Road, Menlo Park, CA 94025, phone (415) 329-4923, fax 415-393-4936. The registration fee is $100 (non-residents) and includes all transportation from Phoenix to the site at Havasu City and return (except double occupancy), and all costs associated with the conference field trips. Applicants who are attending regarding procedures for payment of deposits for formal registration.© 1992, The Geological Society of America, Inc. GSA Today is copyrighted. Copyright notices are not available. However, all text content is fully available to the public.

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Penrose Conference on North American Cordilleran Reworked

The postended Penrose Conference, "Continental Tectonics and Mag-

mination of the Jurassic North American Cordillera" (originally scheduled for March 1992) was rescheduled for Febru-
ary 27 to March 4, 1993, in Havasu City, Arizona. The conveners are Dave Miller, (415) 329-4923, and Dick Tos-


All participants accepted for the 1992 conference will be contacted automatically for the rescheduled conference. Meeting arrangements are available, so additional applications are encouraged.

The intent of this conference is to examine the first magmatic-tectonic events, from when continental-margin subduction started extruding the Mesozoic, to extensively affect conti-
nental crust far inland of the mag-

astic arc and to produce voluminous magmas both in and behind the arc. Accordingly, we expect to focus on the ~180-130 Ma interval of the Mid-

dle and Late Jurassic, but earlier Jurassic events are critical for understanding the regional tectonic and volcanic collage outboard of native North America. Our primary goal is to understand con-
tinental tectonics at the natural magmatic arc and inland (to the east) as a response to plate-tectonic processes, including tectonic movements and accretional events.

The conference will focus on mag-

ization and isotopes, the cratonic paleo-

geographic record, structure and tec-
tonics, and geophysics as they apply to understanding continent-scale tectonic-

tics and lithospheric processes. Not only does magnatitization identify the tectonic activity as subduction-related, but also study of the magma provides clues for deep-lithosphere processes, the ultimate source of energy for most conti-
nental tectonics. Because the Jurassic continental tectonics was the first widespread orogeny of the Mesozoic subduction system, depositional patterns in the continental interior contain a complete record of the tectonic, providing a unique opportunity to study paleogeographic information from stratigraphy with tectonics and magnatitization. Comparing tectonic styles, magmatic characteristics, and timing of events along the Cordillera from Mex-

ico to the Yukon should provide much information about interactions with oceanic plates, effects of continental crust composition, and effects of magnatitization.

The conference begins on Saturday evening, February 27, in Phoenix, Ariz-

a, with a welcoming gathering and introduction. Two days of field trips will traverse the Jurassic magmatic arc of Arizona and southern California. Voluminous pyroclastic volcanic rocks and calc-alkaline plutons that charac-
terize the Jurassic arc, examples of intru-

sive deformation, and the sedimentary rocks that record the erosion of arc activity and its subsequent degradation will be examined. Days of confer-

ence sessions in Havasu City are divided among four broad but interrelated-topics: (1) global tectonics and
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Table 1. Comparison of Selected Australian Acid-Hypersaline Ground-Water Lakes System

<table>
<thead>
<tr>
<th>Lake</th>
<th>K (M)</th>
<th>Ca (M)</th>
<th>Fe (mM)</th>
<th>Minerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tyrell</td>
<td>7.5</td>
<td>4.3</td>
<td>225</td>
<td>Alunite</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Alunite oxides</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Jarosite</td>
</tr>
<tr>
<td>Gilmore</td>
<td>6.0</td>
<td>4.3</td>
<td>61</td>
<td>Alunite</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Iron Oxides</td>
</tr>
<tr>
<td>Chandler</td>
<td>4.8</td>
<td>15.0</td>
<td>11</td>
<td>Alunite</td>
</tr>
</tbody>
</table>

100 m in some places on the Yilgarn block in Western Australia (Webster and Mann, 1984). Although aridity appears to have become well established in Australia by at least the Pleistocene, processes similar to lateritization may still be occurring in arid regions of Australia (Gleadow, 1982). Little chemical weathering is occurring on the Australian continent today, except in a small band of tropical and semiarid regions of north-central and northeastern Australia. Garrels and Mackenzie (1971) showed that the six ice-free continents, Australia has the lowest annual chemical denudation rate, 12 times lower, per unit area, than the next lowest continent, Africa (2 and 24 t/km², respectively) (Fig. 6). Aridity must be a factor in slowing the rate of chemical denudation. However, Garrels and Mackenzie (1971) also showed that for stream discharge vs. continental area, Australia falls near the trend line for all continents (Fig. 7). Sufficient water is available, when compared to other continents, for chemical weathering, even though the continent is largely arid. The lack of chemical weathering today presupposes that the regime of Australia has been extensively weathered in the past. We believe that these acid-hypersaline systems occur in such large geographic areas because of both climatic and tectonic conditions. Much of Australia appears to be in the last stages of land surface reduction associated with a long period of tectonic stability. The waters are acid simply because the continent has been weathered to the point where only relatively unreactive residues are left and therefore there is little to titrate the acid in the system. What causes the acidity in these systems continues to be debated (McArthur et al., 1991; Macumber, 1992). Change from humid to arid conditions after lateritization and the preservation of the continent has led to the retention of solutes in the landscape and the formation of hypersaline solutions. The conditions in present-

Figure 4. Evaporitic jarosite (yellow) and iron oxides (red) in sediments of a spring zone.

Figure 5. Iron oxides in sediments of a spring zone.

Figure 6. Annual chemical denudation of the continents (from Garrels and Mackenzie, 1971).

Annual denudation (metric tonnes/km)

<p>| | | | | |</p>
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<tbody>
<tr>
<td>0</td>
<td>50</td>
<td>100</td>
<td>150</td>
<td>200</td>
</tr>
</tbody>
</table>

North America | South America | Asia | Africa | Australia

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day Australia may be one of the last stages of terrestrial development under arid and semiarid conditions.

GEOLoGIC IMPoRTANCE oF AciD SYStEMS

Recently Ollier (1988) and Mab- 
but (1988) have argued that the condi-
tions found in Australia would be simi-
lar to the geomorphic conditions that existed in the interiors of ancient su-
cretosol catching soils and aridlla.
These supercontinents would have had interior regions great distances from the oceans, and rivers would have been long and would have had low gradients (Ollier, 1988). Land surfaces would have been flat and, late in their history, highly weath-
ered. If these supercontinents then became arid, conditions similar to those observed today in Australia could have existed over extensive areas of Earth in the Mesozoic and even into the Paleo-
zoic. For example, the Archean deposits may provide a model for for-
mation of ferrites surrounding shal-
low-water lake margins in the Strelitz of southwest Ireland and in the Per-
imian-Carboniferous of Spain that are associated with cherts and carbonaceous sediments (V. P. Wright, 1990, personal communication). As pointed out above, in the hyperarid systems, major sedimentary pro-
tects are the minerals halite, gypsum, 
ate, arse, jordate, feric oxideo-
ildes, and ferric hydroxides (sider-
pens to these "tellurite" minerals when the acid systems are gone? In some cases, a portion of these minerals can be preserved—e.g., silica, ferric-oxide-hy-
droxide, gypsum. The best samples of this preservation are the middle, younger and central South America are currently the major-oldest-period producing region of the world, as well as one of the oldest regions of the world. Lastly and Milnes (1991) have argued that marine in South America was produced by epigenetic processes in an acidic environment in which Al as is retained in the form of Alp and 
ate commonly present in the opal-rich deposits (Thiry and Milnes, 1991). Alunite in the South Australian opal fields both predate and postdate opalization. Recently, K/A dating of these alunite suggest ages of formation ranging from 18 to 4 Ma (Morey and Binning, 1991). Deutoclonal values of these alunite indicate that the alunite was formed in equilibrium with meteoric waters (Bird et al., 1989); all the avail-
able data suggest that alunite forma-
tion either occurred at the end of the Mesozoic weathering event, described

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Figure 7. River discharge versus continental area (from Garrels and Mackenzie, 1977).

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