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15. No evidence for a slow nucleation process has been detected in other well-observed events [D. C. Agnew and F. K. Wyatt, *Bull. Seismol. Soc. Am.* **79**, 480 (1989); M. J. S. Johnston, A. T. Linde, M. T. Gladwin, *Geophys. Res. Lett.* **17**, 1777 (1990)]. These observations limit the seismic moment of a slow process to about 0.5% of M_o. Thus, slow release of moment equivalent to M_o^ν would be unobservable in most instances.
16. The dynamic stress drop of the event is proportional to the slope of the velocity seismogram [J. Boatwright, *Bull. Seismol. Soc. Am.* **70**, 1 (1980)]. Propagation effects, such as intrinsic attenuation [M. T. Gladwin and F. D. Stacey, *Phys. Earth Planet. Inter.* **8**, 332 (1974)] and forward scattering (T. Mukerji, G. Mavko, D. Mujica, N. Lucet, *Geophysics*, in press) can distort the velocity pulse shape but will be quite small relative to the effects we observe at such short distances.
17. We measure the seismic moment, which is the product of the average slip, the faulted area, and the shear modulus μ (assumed to be 30,000 MPa). Although we use the static solution for a constant stress-drop circular crack ($M_o^\nu = 16\Delta\sigma r_\nu^3/7$), our estimates of the average slip and the faulted area are not strongly dependent on the circular geometry of the model.
18. See, for example, table 1 of C. H. Scholz [*Bull. Seismol. Soc. Am.* **72**, 1 (1982)].
19. Another observation that supports low mean rupture velocity is the distance between the initial hypocenter and the location of the point of breakaway, which has been determined for only a few earthquakes (*4*). In each of these cases, this distance divided by ν implies an average rupture velocity of 20 to 50% of the shear wave velocity.
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22. A plausible physical mechanism for delayed rupture is provided by the rate and state variable friction law. It is possible to explain the time decay of aftershocks, known as Omori's law, with such a model [J. H. Dieterich, *J. Geophys. Res.* **99**, 2601 (1994)]. This friction law also gives rise to stable preslip as part of the nucleation process.
23. Failure in both crack models [D. J. Andrews, *J. Geophys. Res.* **81**, 5679 (1976)] and frictional models [J. H. Dieterich, *ibid.* **84**, 2161 (1979)] of earthquakes is stable and is confined to a limited region of the fault until a critical dimension is achieved and the stiffness (stress drop per unit fault slip) falls below the critical level [J. R. Rice and J.-C. Gu, *Pure Appl. Geophys.* **121**, 187 (1983)].
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28. For example, low-frequency electromagnetic field variations were observed before the 1989 Loma Prieta earthquake [A. C. Fraser-Smith, A. Bernardi, R. A. Helliwell, P. R. McGill, O. G. Villard Jr., *U.S. Geol. Surv. Prof. Pap. 1550-C* (1993), p. C17.
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Late Triassic Turtles from South America

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Andrea B. Arcucci

The discovery of Triassic (Norian) turtles from the northwest part of Argentina extends the South American record of turtles by 60 million years. Two skeletons, one almost complete, represent a new genus and species of a basal turtle, *Palaeochersis talampayensis*. This turtle is a member of the family Australochelidae that was recently erected for *Australochelys africanus* from the Lower Jurassic of South Africa. Here, it is proposed that Australochelidae is the sister group of *Proterochersis* plus Casichelydia, that turtles were diverse by the Late Triassic, and that Casichelydia probably originated during the Jurassic.

Recent findings and restudy of previous collections have led to a new understanding of the origin of Casichelydia (pleurodires and cryptodires) and of turtle relations (*1–8*). A few German localities of Norian age have yielded complete skeletons of *Proganochelys quenstedti* (*7*) and the carapace, plastron, and girdles of *Proterochersis robusta* (*9*). Apart from these fossils, only extremely poor material from the Triassic attributed to *Proganochelys* has been reported worldwide (*10*). *Proterochersis* was previously identified as the oldest pleurodire (*9*). Therefore, pleurodires and cryptodires, the groups that include all living turtles, should have made their appearance during the Upper Triassic (*7, 9, 11*). This would place modern turtles among the wide array of taxa, including frogs, crocodiles, mammals, and dinosaurs, that originated around this time (*12*). On the basis of our fossils, we question the inclusion of *Proterochersis* in Pleurodira and accordingly the Triassic origin of Casichelydia. Here, we report the discovery of two partial turtle skeletons collected from the upper part of the Triassic Los Colorados Formation in northwestern Argentina. These fossils are associated with a tetrapod assemblage of Norian age (*13–15*) and they extend the South American record of turtles by 60 million years (*16*).

Palaeochersis talampayensis gen. nov. sp. nov. is represented by an unusually complete skeleton (Figs. 1 and 2) and additional material (*17*). *Palaeochersis* shows numerous primitive features present in *Proganochelys* or other nonturtle amniotes, including paired vomers, persistence of supratemporal and interpterygoid vacuities, and epiplastral processes (clavicles). However, the importance of *Palaeochersis* rests in the numerous characters shared with more advanced turtles (Fig. 3), such as the incipient middle ear cavity, the fusion between the pterygoid and the basicranium, and the fusion of the pelvis to the carapace; the latter is thought to be characteristic of pleurodires.

Although identification of a sister group to turtles remains controversial (*18*), *Proganochelys* is considered to be the sister group to all other known turtles (*7, 8, 10, 11*). We performed a cladistic analysis (*19*) of major turtle taxa, using *Proganochelys* as one of the outgroups (Table 1), and only one tree (*20*) was identified (Fig. 3). In this tree, *Palaeochersis* and *Australochelys africanus*, an Early Jurassic turtle from Africa, form a monophyletic assemblage, Australochelidae (*11*). The monophyly of Australochelidae is supported by the presence of large elongated nares (*21*), a nasal platform or bump, a wide occipital plate with depressions for neck muscles, and a temporal fossa that is partially closed by an overhanging flange of the skull roof. The geographic location of both members of Australochelidae suggests a Southern Pangaeic–Gondwanian distribution for the family.

Primitive amniote or chelonian charac-

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ters retained by *Palaeochersis*, and probably by *Australochelys*, include the presence of a long tail, supramarginal scutes, an extensive entoplastron (Fig. 2), a dorsal process of the clavicle (epiplastron), and the presence of cervical ribs. *Palaeochersis* and *Proganochelys* both have amphicoelous vertebrae, which preclude the retraction of the neck into the carapace. This defensive tactic so conspicuous in living turtles was accomplished in *Palaeochersis* by the dorsal extension of the carapace, whereas cervical ossifications gave protection in *Proganochelys*. Hence, the protection of the vulnerable neck was achieved through at least three different means during turtle evolution.

Two characters are shared only between *Proganochelys* and *Palaeochersis*. They are the presence of a hypoischium, an ossification unknown in any other tetrapod, and the presence of two phalanges in manual and pedal digits. The latter feature may be related to terrestrial habits, but the meaning of the former remains unclear.

The association in *Palaeochersis* of a fused pelvis and a skull lacking pleurodiran features resulted in our exclusion of *Proterochersis* from Pleurodira. The character "pelvic fusion" has a distribution that renders it a synapomorphy of Rhaptochelydia (*11*), with the surprising corollary that the free pelvis of cryptodires must be a reversion. Otherwise, it must have been acquired independently in *Palaeochersis*, *Proterochersis*, and pleurodires.

The relations of *Proterochersis* proposed here alter the timing for the origin of the Casichelydia, because Triassic turtles can no longer be attributed to this group. The oldest examples of Casichelydia would then be *Kayentachelys* (*1*) (Lower Jurassic) for Cryptodira and *Platychelys*-*Notoemys* (*22*) (Upper Jurassic) for Pleurodira. However, the position of *Kayentachelys* and *Platychelys* among casichelydians is weakly supported in our cladogram and in previous cladograms (*3*). The exclusion of *Kayentachelys* from Cryptodira, which would then become the sister group of Casichelydia, and the removal of *Platychelys* from Pleurodira to the same position would add only one step. These alternatives reflect the ambiguity of many characters, primarily because of the absence of skulls in *Proterochersis* and *Platychelys*. Furthermore, if *Kayentachelys* and *Platychelys* are to be accepted as casichelydians, the loss of the epiplastral process and supramarginal scutes must be assumed to be convergent in living pleurodires and cryptodires.

Despite the overall primitive aspect of the two genera of Australochelidae, the best supported node is Rhaptochelydia (Fig. 3). Twenty unequivocal synapomorphies account for this node, of which 18 are cranial (Fig. 3). Most of these traits can be related

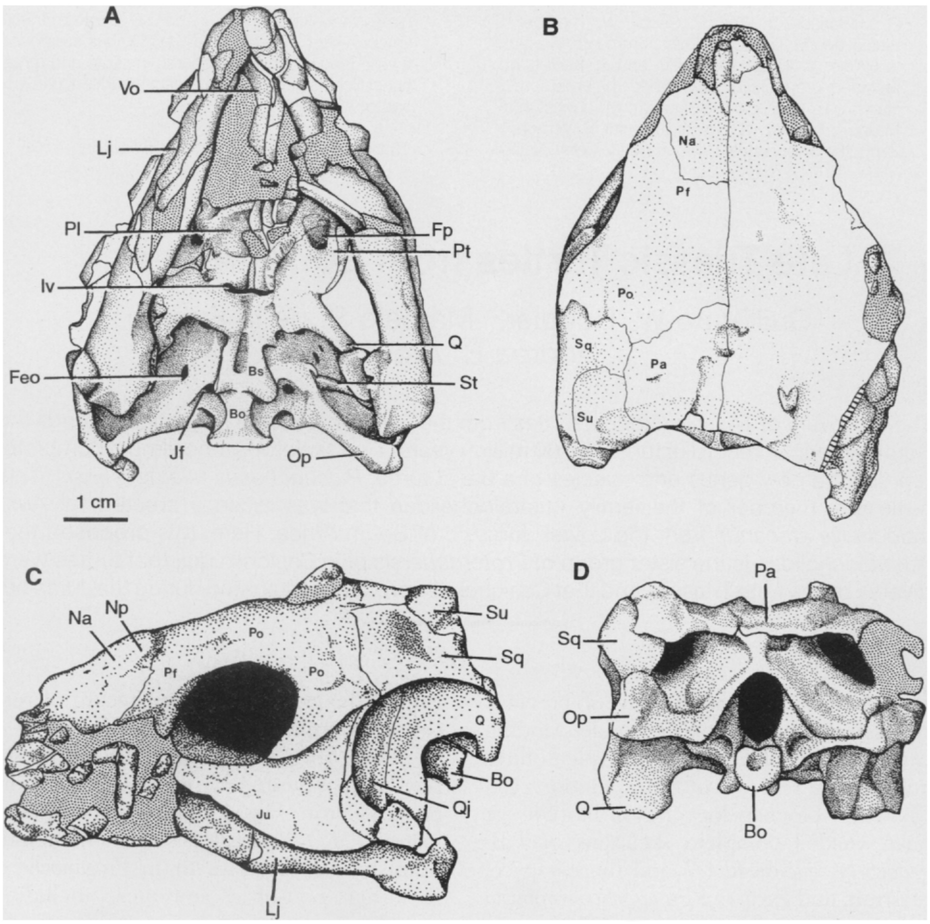

Fig. 1. Skull of *P. talampayensis*. (**A**) Ventral view; (**B**) dorsal view; (**C**) lateral view; (**D**) posterior view. Bo, basioccipital; Bs, basisphenoid; Feo, fenestra ovalis; Fp, foramen palatinum; Iv, interpterygoid vacuity; Jf, jugular foramen; Ju, jugal; Lj, lower jaw; Na, nasal; Np, nasal platform; Op, opisthotic; Pa, parietal; Pf, prefrontal; Pl, palatine; Po, postorbital; Pt, pterygoid; Q, quadrate; Qj, quadratojugal; Sq, squamosal; St, stapes; Su, supraoccipital; and Vo, vomer.

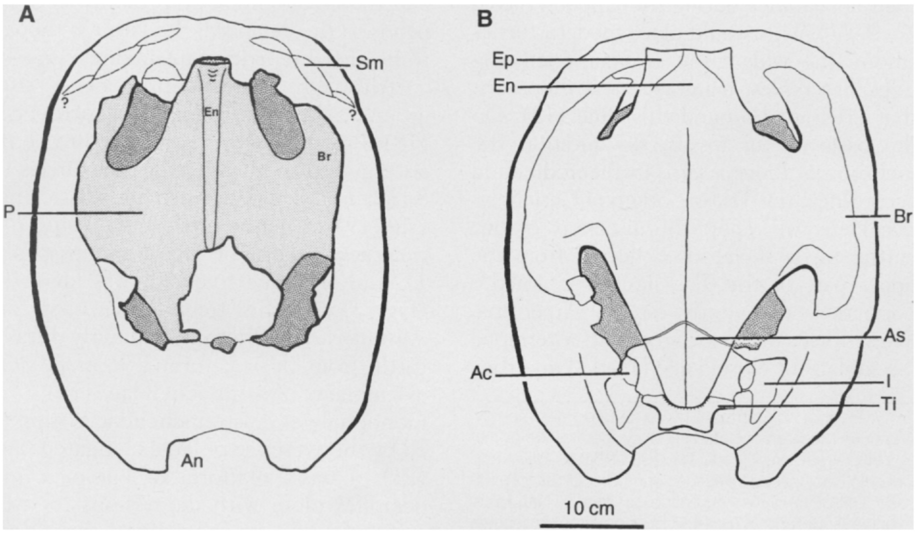

Fig. 2. Shell of *P. talampayensis*. (**A**) Dorsal view; (**B**) ventral view. Ac, acetabulum; An, anal notch; As, anal scute; Br, bridge; En, entoplastron; Ep, epiplastron; I, ilium; P, plastron; Sm, supramarginal; Ti, transverse ischial process; and ?, posteriormost identifiable border of a supramarginal scute (it is uncertain whether the supramarginal series continued posteriorly from this point). In (A) the central part of the carapace is missing, and the plastron and the large entoplastron (a primitive chelonian feature) are exposed. The pelvis is fused to the plastron through the posterior ischial shelf and the lateral pubic process, whereas the ilium is fused to the carapace through an extensive anteromedial process.

to the consolidation and modification of the palate or to the development of ear structures. Others seem to be related to modifications of the musculature of the posterior part of the skull and neck. Only two postcranial synapomorphies are identified. Even though most of the characters used are cranial (61%), it seems clear that the skull was more progressive than the postcranial skeleton during early turtle evolution.

Most turtle phylogenies have been based on cranial traits, and only a few postcranial features have been included. The resultant trees usually conform to the more numerous cranial data and lead to contradictions when only the postcranial features are considered. Such problems are outlined by *Palaeochersis*. If we had found an isolated skull of *Palaeochersis*, its systematic position would have been the same as that presented here. However, an isolated postcranium would have forced us to conclude that primitive pleurodires were present during the Triassic in Argentina as well as in Germany.

Homoplastic evolution seems to have been rampant in chelonian phylogeny, and the recovery of associated skulls and postcrania is a prerequisite for building a reliable phylogeny. By the end of the Triassic, turtles had already undergone an important radiation and were geographically widespread. Three different groups covered the southern and northern parts of Pangaea. This diversity suggests that turtles evolved much earlier during the Triassic.

The prospected upper part of the Los Colorados Formation shows extensive paleodunes and sporadically intercalated wadi deposits (*23*). The layer that yielded *Palaeochersis* may have been a mud flow covering an ephemerous channel. The paleoenvironmental setting and the anatomy of the extremities (reduction of the phalangeal number and fifth digit) suggest that these turtles were at least partially terrestrial, as has also been suggested for *Australochelys* (*11*). By the Triassic, turtles had attained a significant ecological diversity that included freshwater amphibious forms (such as *Proganochelys*) as well as more terrestrial forms (such as *Proterochersis* and probably the Australochelidae).

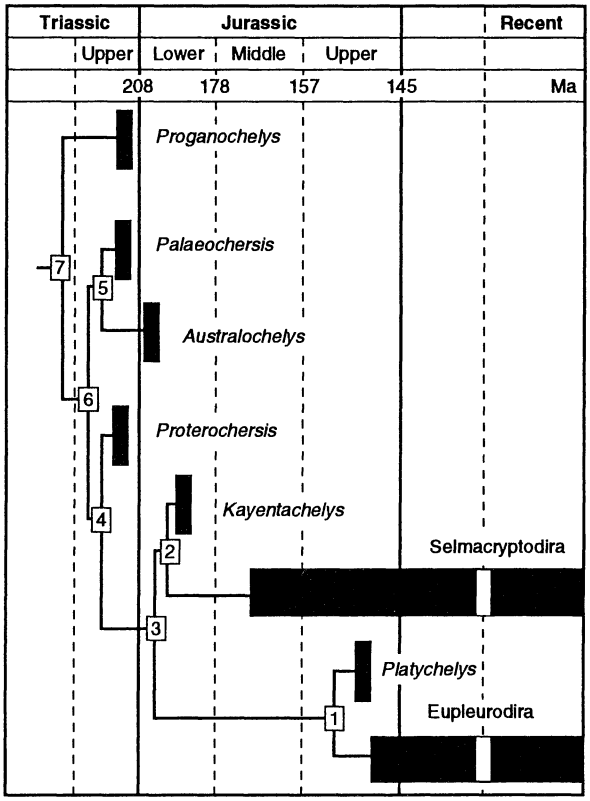

Fig. 3. Phylogenetic and temporal relations among basal turtles. Synapomorphies of each ingroup node are listed below. Equivocal characters are listed under the less inclusive level of generality, and the more inclusive node is shown between parentheses with the letter N. The condition of multistate characters is indicated with a hyphen. Characters 11, 12, and 25 were treated as unordered. Node 1, Pleurodira: 47, 48; equivocal 45-2(N3), 50(N4). Node 2, Cryptodira: 7, 13, 57-0; equivocal 41(N3), 12-1(N4). Node 3, Casichelydia: 42, 44, 46, 51, 59; equivocal 1, 4, 6, 11-2, 15-2, 26, 27, 28, 29, 35, 52, 53(N4), 25-2(N6). Node 4, unnamed: 43, 54, 56, 61; equivocal 39, 40, 49(N6). Node 5, Australochelidae: 2, 3, 31, 32; equivocal 25-1(N6). Node 6, Rhaptochelydia: 5, 8, 9-1, 10, 14, 16, 17, 18, 20, 21, 22, 23, 24, 30, 33, 34, 36, 37, 55, 57. Node 7, Testudines. Ma, millions of years ago.

Table 1. Character state matrix of the 61 characters used in this study (*19*). 0, primitive condition; 1 and 2, derived states; and ?, unknown.

Outgroup 1						
0000000000	0000000000	0000000000	0000000000	0000000000	0000000000	0
Proganochelys						
0000000000	0000000000	0000000000	0000000000	0000000000	0000000001	0
Australochelys						
011010??11	00?1011101	?111100001	1111??1???	??????????	??????????	?
Palaeochersis						
0110100111	1001111111	1111100001	11110111??	00000000?0	0000101101	0
Proterochersis						
??????????	??????????	??????????	????????11	001000??11	0??111110?	1
Kayentachelys						
1001111111	1111211101	?111211111	0011111111	1111110010	?111100??	?
Selmacryptodira						
1001111121	2111211101	1111211111	0011111111	1111210010	1111110010	1
Platychelys						
??????????	??????????	??????????	????????11	0111211111	???111101?	1
Eupleurodira						
1001110121	2201211111	1111211111	0011111111	1111211111	1111111010	1

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17. Etymology: *Palaeo*, early (Gk), and *chersis*, terrestrial turtle (Gk); *talampayensis*, after the provincial park of Talampaya, La Rioja, Argentina. We collected two specimens that are now housed at the Universidad Nacional de La Rioja. The type (UPVLR 68) is an articulated skeleton, complete except for the central part of the carapace. The specimen UPVLR 69 includes the endocranial cast, the right foot, and fragments of the carapace and plastron. Horizon and locality: Los Colorados Formation, Upper Triassic (Norian). Red siltstone with gypsum, 30 m below the top of the unit. Area between Quebrada de Los Jachaleros and La Esquina, about 6 km west of the 141 km marker, route 26, La Rioja province, Argentina. *Palaeochersis* is diagnosed by the following apomorphies: a quadratojugal that forms a large part of the cavum tympani; an angular with a strong ventral process; an anterior projection of the carapace beyond the margin of the plastron and overhanging most of the cervical vertebrae; an extensive transverse process of the ischium; a long hypoischium underlying about five caudal vertebrae; and an extreme reduction or loss of the fifth-digit phalanges.
18. Putative sister groups to turtles are captorhinomorphs (*4*), procolophonids (*5, 8*), and pareiasaurids (*6*).
19. Characters are enunciated according to the derived condition unless otherwise stated. **1**, External nares confluent; **2**, external nares large and elongated; **3**, narial platform; **4**, lacrimal bone and duct absent; **5**, orbital prominences and bosses absent; **6**, unpaired vomer; **7**, prefrontal-vomer contact; **8**, squamosal-jugal contact absent; **9**, palatal teeth on palatine and pterygoid (0), restricted to the medial portion of the pterygoids (1), absent (2); **10**, vomerine teeth absent; **11**, interpterygoid vacuity large and open (0), reduced (1), absent (2); **12**, trochlear process absent (0), otic (1), pterygoid (2); **13**, lateral vertical plate of pterygoid; **14**, acute quadrate margin; **15**, cavum tympani absent (0), moderately developed (1), deeply excavated (2); **16**, opisthotic covered laterally by quadrate; **17**, middle ear laterally walled; **18**, sinus cavernosus; **19**, facial nerve foramina separated from the sinus cavernosus; **20**, vertical fenestra ovalis; **21**, slender stapes; **22**, quadrate pocket absent; **23**, stapediotemporal canal anterior to fenestra ovaslis; **24**, basipterygoid articulation fused; **25**, basisphenoid-basioccipital? medial process unpaired (0), paired (1), absent (2); **26**, recessus scalae tympani and perilymphatic fenestra defined by bone; **27**, jugular posterior foramina defined by bone; **28**, small anterior jugular foramina; **29**, antrum postoticum; **30**, supraoccipital crest; **31**, wide transverse occipital plane with depressions for nucal musculature; **32**, temporal fossa roofed by overhanging process of skull roof; **33**, temporal roof extended posterior to opisthotic; **34**, procesus paraoccipitalis of opisthotic tightly articulated to squamosal and quadrate; **35**, supratemporal absent; **36**, occipital condyle neck; **37**, foramen magnum height greater than width; **38**, small Meckelian fossa; **39**, five vertebral scutes; **40**, eleven peripheral bones; **41**, supramarginal scutes absent; **42**, marginals not separated by an anal notch; **43**, plastron reaches posterior margin of ischium; **44**, epiplastral hooks absent; **45**, epiplastral processes articulating with carapace (0), present but without articulation (1), absent (2); **46**, large prominent entoplastral keel absent; **47**, articulation of cervical vertebrae concave or convex; **48**, cervical ribs absent; **49**, first dorsal rib smaller than second; **50**, tenth dorsal vertebra fused to sacrum; **51**, acromial process triangular plate (0), rodlike (1); **52**, extensive subrectangular and platelike coracoid (0), absent (1); **53**, coracoid foramina absent; **54**, elongated iliac neck; **55**, ventral ischial tubercle absent; **56**, hypoischium absent; **57**, fused pelvis; **58**, large anteromedial process of the ilium; **59**, large thyroid fenestra on ischium and pubis; **60**, phalangeal formula 2222?; and **61**, posterior ischial shelf absent.
20. The matrix of Table 1 was examined with the programs PAUP [D. Swofford, *Phylogenetic Analysis Using Parsimony* version 3.1.1 (Smithsonian Institution, Washington, DC, 1993)] and Hennig86 (J. Farris, version 1.5, 1988). The analysis yielded a tree length of 77, a consistency index of 0.87, and a retention index of 0.89.
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Serpentine Stability to Mantle Depths and Subduction-Related Magmatism

Peter Ulmer and Volkmar Trommsdorff

Results of high-pressure experiments on samples of hydrated mantle rocks show that the serpentine mineral antigorite is stable to ~720°C at 2 gigapascals, to ~690°C at 3 gigapascals, and to ~620°C at 5 gigapascals. The breakdown of antigorite to forsterite plus enstatite under these conditions produces 13 percent H_2O by weight to depths of 150 to 200 kilometers in subduction zones. This H_2O is in an ideal position for ascent into the hotter, overlying mantle where it can cause partial melting in the source region for calc-alkaline magmas at a depth of 100 to 130 kilometers and a temperature of ~1300°C. The breakdown of antigorite in hydrated mantle produces an order of magnitude more H_2O than does the dehydration of altered oceanic crust.

It has been repeatedly proposed (*1*) that H_2O liberated from a subducted lithospheric slab may cause partial melting in the overlying mantle wedge, thus giving rise to subduction-related volcanism. Hydrothermal alteration of mantle rocks near the Earth's surface produces serpentine. Alteration is extensive in ocean basins (*2*) and along continental margins (*3*). Fully serpentinized peridotites (serpentinites) contain about 13% H_2O by weight; subduction of this altered mantle may thus transport large quantities of H_2O to depths of arc magma genesis, provided that serpentine minerals are stable to high pressures and temperatures. Serpentinites are thus potentially a more important source of H_2O than hydrated mafic oceanic crust, which contains <2% H_2O by weight at 3.0 GPa and 700°C (*4*). Through field evidence it has been demonstrated (*5*) that serpentine minerals are stable under eclogite facies conditions (2.0 GPa, 550°C). We describe here the results of an experimental study to evaluate the stability of serpentinite under these and higher pressure conditions.

Serpentines [generalized formula $Mg_3Si_2O_5(OH)_4$] are trioctahedral phyllosilicates that have 1:1 octahedral-tetrahedral layer structures (*6*) and are composed of three basic minerals: chrysotile, lizardite, and antigorite. Experimental studies (*7*) have demonstrated that antigorite is the only serpentine mineral stable at conditions up to 1.5 GPa and 650°C. In nature, antigorite forms either through breakdown of less stable serpentine minerals or directly from peridotite. Our experiments were therefore carried out on antigorite.

Antigorite [typical composition $Mg_{2.82}Si_2O_5(OH)_{3.64}$] is composed of corrugated layers with a sinusoidal octahedral layer and a tetrahedral layer that reverses its polarity every half wavelength. The wavelength is variable and is expressed in terms of the number of tetrahedra (m) occurring along an entire wave. Some variations in composition and structure are common as a consequence of wavelike structural modulations (*8*). It is therefore crucial that in experimental investigations homogeneous material that is well characterized be used.

Such material cannot be obtained synthetically. We therefore chose a homogeneous natural antigorite [$m = 17$, ideal formula $Mg_{48}Si_{34}O_{85}(OH)_{62}$] that shows no structural or compositional modulations (*9*). This natural antigorite contains impurities (*10*). The calculated shift in the breakdown equilibrium curve of this antigorite with respect to a pure end-member, however, is in the range of experimental uncertainty (*11*). The sample separated from the rock (sample Mg159) consists of 85% antigorite and 15% brucite [$Mg(OH)_2$] by volume.

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