GEOPHYSICAL RESEARCH LETTERS, VOL. 11, NO. 10, PAGES 951-954, OCTOBER 1984

AGE OF OCEANIC PLATES AT SUBDUCTION AND VOLATILE RECYCLING

Dallas Abbott and Mitchell Lyle

College of Oceanography, Oregon State University

Abstract. The age of the subducting plate as it enters the trench controls the maximum depth of volatile transport by the downgoing plate. As the slab descends and heats up, decarbonation and dehydration reactions cause alteration minerals and sediments to release volatiles. Our calculations show that subducting oceanic plates <11 m.y. old in oceanic arcs and <34 m.y. old in continental arcs heat up so rapidly that no H_2O or CO_2 can return to the asthenosphere. Instead, these volatiles rise into the over-riding lithospheric plate. CO_2 and H_2O are released differently during subduction. A thickly-sedimented plate subducting beneath an oceanic arc will return H_2O to the asthenosphere only if the subducting plate is older than 11 m.y. and CO_2 only if it is older than 25 m.y. If Archaean oceanic lithosphere had a maximum age of 30-50 m.y. and an average age of 10-18 m.y., then the amount of volatile recycling to the asthenosphere could have been much lower than at present, despite a greater total consumption rate.

Introduction

The maximum penetration depth into the mantle of seismically active subducting plates and the age (thermal thickness) of the oceanic plate at subduction are closely related [Vlaar and Wortel, 1976; Molnar et al., 1979]. The subduction of older plates produces a longer seismic zone because older plates have a higher convergence rate [Carlson et al., 1983] and a greater initial thermal thickness [McKenzie, 1969].

The temperature of the subducting oceanic plate also affects phase changes and consequent volatile loss [Ringwood, 1974; Anderson et al., 1976; Fyfe, 1981]. Because thermal structure is dependent upon the age of the slab and geophysical and geochemical changes in the slab are strongly dependent upon temperature, the age of the oceanic plate at the start of subduction is a major control on volatile release from the slab [Delong et al., 1979]. We have used a simple conductive model [McKenzie, 1969] and average subduction rates [Carlson et al., 1983] to evaluate quantitatively the effect of the age of the descending plate upon reheating and consequent volatile release.

Evidence for Volatile Recycling

Back-arc basin basalts quite often have higher vesicularity and higher contents of H_2O and CO_2 than analogous mid-ocean ridge basalts [Taylor and Karner, 1983]. Furthermore, only 10% of all subducted H_2O is released in the form of subduction zone magmatism [Ito et al., 1983]. The remaining H_2O must therefore be stored in the subduction zone complex or be returned to the asthenosphere. Recent isotopic measurements of δC^{13} values on back-arc basin basalts are 1.7 to 10.3 per mil lighter than magmatic C (-6.0) [Mattey et al., 1984] implying that isotopically light C (perhaps sedimentary organic C) is recycled from the nearby subducting slab. Another possible source of recycled C is vein calcite within the oceanic crust. Direct evidence for recyling of vein calcite is more difficult to obtain because the average δC^{13} of vein calcite is -5.8 [Cocker et al., 1982], similar to magmatic C. However, the range of δC^{13} of the vein calcite is 0 to -19.0 and 1/3 of the measurements are lighter than magmatic C. Therefore, vein carbonate is formed from at least three different reservoirs; seawater, magmatic and isotopically lighter C.

Sources of Volatiles Subducted into the Mantle

The dominant volatiles in the subducting slab are H_2O and CO_2. The most likely source of H_2O and CO_2 to the asthenosphere is the hydrothermally altered upper layer of the oceanic plate (Figure 1).

Stable isotopic studies of ophiolites have found that hydrothermal circulation extends to the base of the crustal section, a stratigraphic thickness of 5 to 7 km [Gregory and Taylor, 1981; Cocker et al., 1982]. Furthermore, geophysical evidence suggests that hydrothermal alteration may cause the low velocity zone beneath the Moho which occurs in the Pacific. Where the plate is 1-3 m.y. old, the base of the zone follows the 450°C isotherm and Lewis [1978] has suggested that it is caused by the serpentinization of olivine. Low velocity zones are difficult to detect seismically, so, for our calculations, we have estimated that the maximum depth of hydrothermal hydration is just below the Moho at 8 km.

The maximum depth of hydrothermal carbonation of the oceanic lithosphere, primarily by precipitation of calcite, lies at ~6 km. Carbonation does not extend as deeply into the plate because vein calcite commonly precipitates at temperatures less than 200°C [Stakes and O'Neill, 1982]. Temperatures in actively convecting hydrothermal systems are proportional to the logarithm of the depth [CRRUST,1981]. Therefore, the maximum depth of hydrothermal carbonates and of the 200°C isotherm will lie at ~6 km.

Sediments compose the upper 0.5 to 5.2 kilometers of the subducting oceanic plate. The minimum thickness of subducting sediment is ~0.5 km, estimated from the relief of block faults in the Peru-Chile trench [Schweller and Kulm, 1978]. Maximum sediment thickness is a

Paper number 4L6268.
0094-8276/84/004L-6268$03.00

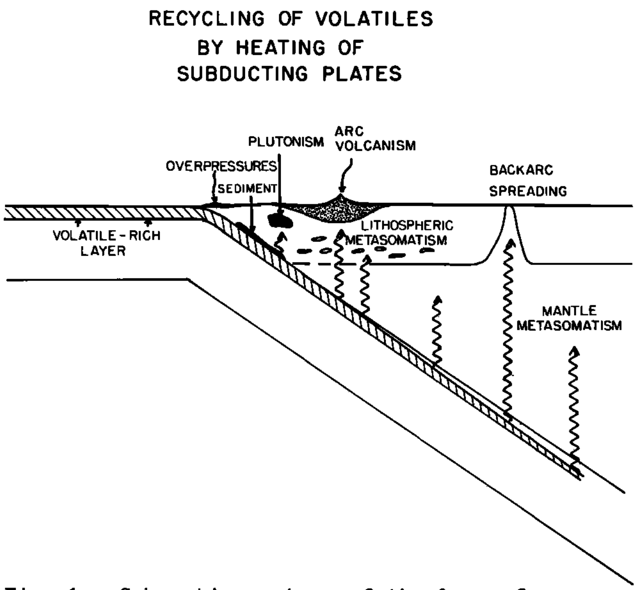

Fig. 1. Schematic cartoon of the loss of volatiles by a subducting plate and its overlying sediments. Initially, most of the volatiles come from the sediments. At depth, all of the degassed volatiles come from the hydrothermally altered plate. Also shown are the reservoirs which may receive volatiles from a subducting slab.

function of trench relief; sediment which spills over the top of the trench is unlikely to be subducted. Trench relief is caused by lithospheric flexure and increases as the log of lithospheric age, from ~1 km on a 1 m.y. old oceanic plate to ~5.2 km on a 180 m.y. old plate [Grellet and Dubois, 1982]. Volatiles will be subducted in the sediment pile, but because sediments form the upper layer of the descending plate, they will heat up and degas rapidly. Therefore, subducted sediments may not represent a major source of recycled volatiles to the mantle.

Estimates of Temperatures of Volatile Loss

Common dehydration reactions in the subducting plate include the breakdown of clay minerals, serpentine, amphiboles, micas, and garnet. The breakdown of garnets [Rossman and Aines, 1983] and some micas is probably insignificant for the recycling of water to the mantle. The highest temperature reactions which could deliver significant quantities of H_2O to the region overlying the slab are the breakdown of amphibole (often derived from serpentine) at <30 kb and the incipient melting of layer 3 at >30 kb, both of which occur at ~1000°C [Basaltic Volcanism Study Project, 1981; p. 540-543]. Decarbonation is more complicated. Between 0 and 25 kb, the temperature of breakdown of calcite increases almost linearly from ~600°C to ~1000°C [Basaltic Volcanism Study Project, 1981; p. 543]. At higher pressures, calcite becomes unstable at ~1000°C.

Mathematical Modeling

We use a simple two dimensional conductive model of the reheating of the slab as it enters the mantle [McKenzie, 1969]. This has the advantage of being analytic, unlike finite element models, which are ordinarily inaccurate on scales of less than 2-10 km. Phase changes and friction are both ignored as heat sources or sinks because these are second order effects compared to conductive heating [Toksoz et al., 1971]. Frictional effects are much smaller than previously supposed [Bird, 1978; Yuen et al., 1978] and it is likely that the effects of endothermic phase changes nearly balance frictional heating [Anderson et al., 1976].

We also assume that the asthenosphere above and below the subducting slab has the same potential temperature of 1300°C. This assumes that the material in the asthenospheric wedge between the subducting and over-riding plate is being convectively removed and replaced. Convection in the asthenospheric wedge is supported by observations of seismic attenuation and volcanic continuity [Sacks, 1984]. Our estimate of the mantle temperature is within the 1260-1500°C range imposed by the solidus of pyrolite [Green and Ringwood, 1969]. Our other major assumptions follow Molnar et al. [1979] and McKenzie [1969]. We have tested the validity of the thermal model by comparing the predicted seismic zone length to actual observations. Assuming a cutoff potential temperature for seismic activity of 700-800° C [Weins and Stein, 1983], a convergence rate of 8.2 cm/yr and a plate age of 105 m.y. (parameters for the Japan trench), we calculate a seismic zone length of 1022-1468 km. This correctly brackets the observed length of 1300 km [Molnar et al., 1979].

The model of McKenzie [1969] was run for different boundary temperatures. The results indicate that the plate center will take about 70% longer to reach 1000°C when the subducting plate is overlain by lithosphere rather than asthenosphere. Some uncertainty is introduced by assuming that these results apply uniformly to the upper few kilometers of the slab. However the uncertainty is much smaller than the differences in thermal behavior between subducting plates of differing ages.

We can also estimate the thickness of the hydrated, carbonated zone when the slab arrives at the lithosphere-asthenosphere boundary. As shown in Figure 2, plates younger than 11 m.y. will not return H_2O or CO_2 to the mantle. Instead, the volatiles will rise into the overlying lithosphere, which will undergo extensive metasomatism and/or pluton emplacement. Intermediate ages of subducting oceanic lithosphere (11-25 m.y. for oceanic arcs and 34-42 m.y. for continental arcs) will almost invariably recycle H_2O but not CO_2 into the actively convecting mantle. Thinly sedimented subducting plates which are as old as 53 to 79 m.y. will deliver only H_2O to the asthenosphere. Only the oldest subducting plates (>25-79 m.y., depending upon subduction rate and sediment cover) will recycle CO_2 into the mantle.

Implications for Early Mantle Degassing

Assuming that the maximum age of the oceanic lithosphere at subduction has increased linearly since 3.8 b.y. ago [Abbott and Hoffman, 1984], the average age of Archaean oceanic lithosphere at subduction would have been 10-18 m.y. and all

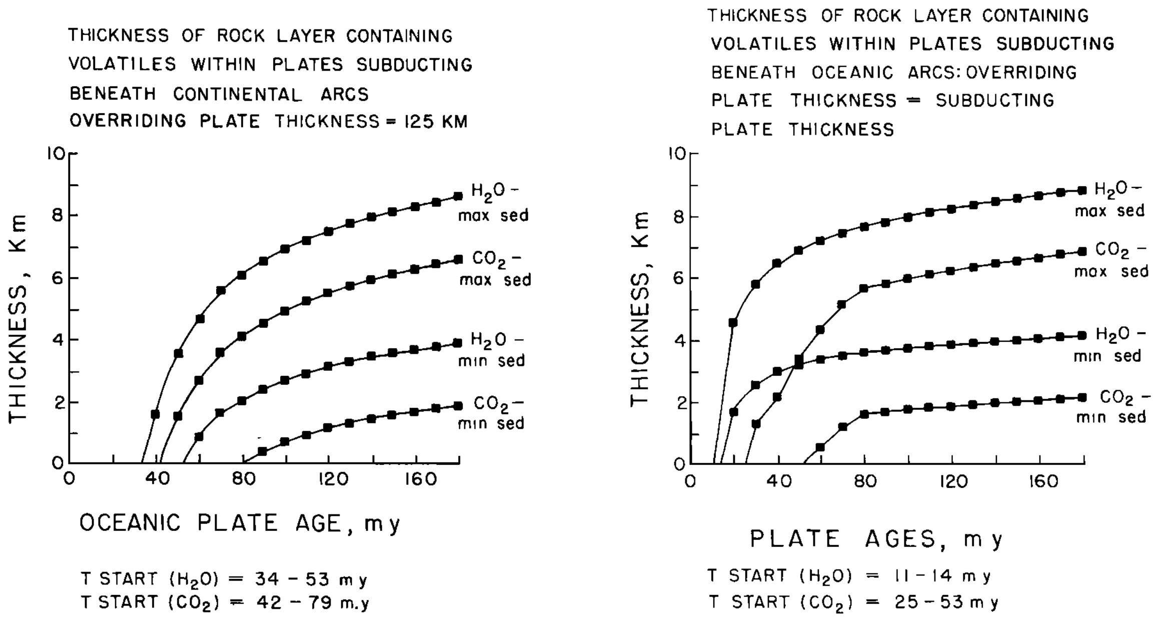

Fig. 2. Thickness of the layer of rock and sometimes sediment which has not completely degassed by the time the subducting plate has an overlying asthenospheric wedge. Left: Model results for oceanic arcs. Right: Model results for continental arcs. TSTART indicates the minimum ages of oceanic lithosphere which can transport CO_2 and H_2O into the mantle given average subduction rates and maximum and minimum values of sediment cover.

would have been subducted before 30-50 m.y. Therefore, our calculations imply that no volatiles were returned into the asthenosphere during early Earth history. If no volatile recyling occurred, then mantle degassing at spreading ridges caused a rapid increase in the amount of volatiles at the Earth's surface. Degassing later in Earth's history, when older oceanic lithosphere was subducted more often, has been balanced somewhat by the return of volatiles to the asthenosphere at subduction zones. Estimates of the terrestrial heat loss and consequent seafloor creation rate required to produce a 'catastrophic' initial degassing of the mantle thus may be much smaller than previously supposed.

Acknowledgements. We thank the members of the Archaean local group for helpful advice and discussion. We also thank M. Fisk, R. Heath and S. Hoffman for internal review. We thank the College of Oceanography (Abbott) and NSF Grant #OCE-8217250-01 (Lyle) for research support.

References

Abbott, D.H. and S.E. Hoffman, Archaean Plate Tectonics Revisited - Part I: Heat flow, spreading rate and the age of the subducting oceanic lithosphere, and their effects on the origin and evolution of continents, in press, Tectonics, 1984.

Anderson, R.N., S. Uyeda and A. Miyashiro, Geophysical and geochemical constraints at converging plate boundaries - part I: Dehydration in the downgoing slab, Geophys. J. R. Astron. Soc., 44, 333-357, 1976.

Basaltic Volcanism Study Project, Basaltic Volcanism on the Terrestrial Planets, Pergamon Press, New York, 1288 pp., 1981.

Bird, P., Stress and temperature in subduction shear zones: Tonga and Mariana, Geophys. J. R. Astron. Soc., 55, 411-434, 1978.

Carlson, R.L., T.W.C. Hilde and S. Uyeda, The driving mechanism of plate tectonics: relation to age of the lithosphere at trenches, Geophys. Res. Lett., 10, 297-300, 1983.

Cocker, J.D., B.J. Griffin and K. Muehlenbachs, Oxygen and carbon isotope evidence for seawater-hydrothermal alteration of the Macquarie Island ophiolite, Earth Planet. Sci. Lett., 61, 112-122, 1982.

CRRUST, Geothermal regimes of the Costa Rica Rift, east Pacific rise, investigated by drilling, DSDP IPOD Legs 68,69, and 70, Geol. Soc. Am. Bull., 93, 862-875, 1981.

Delong, S.E., W.M. Schwarz and R.N. Anderson, Thermal effects of ridge subduction, Earth Planet Sci. Lett., 44, 239-246, 1979.

Fyfe, W.S., Geosphere interaction and earth chemistry, in Evolution of the Earth, R.J. O'Connell and W.S. Fyfe, Geodynamics Series, 5, A.G.U., 82-86, 1981.

Green, T.H., and A.E. Ringwood, in The Earth's Crust and Upper Mantle, edited by P.J. Hart, Geophys. Mono. 13, 489-494, 1969.

Grellet, C., and J. Dubois, The depth of trenches as a function of the subduction rate and age of the lithosphere, Tectonophysics, 82, 45-56, 1982.

Gregory, R.T., and H.P. Taylor, An oxygen isotope profile in a section of Cretaceous oceanic crust, Samail ophiolite, Oman: evidence for δO^{18} buffering of the oceans by deep (> 5 km) seawater-hydrothermal circulation at mid-ocean ridges, J. Geophys. Res., 86, 2737-2755, 1981.

Ito, E., D.M. Harris, and A.T. Anderson, Jr., Alteration of oceanic crust and geologic

cycling of chlorine and water, Geochim. Comochim. Acta, 47, 1613-1624, 1983.
Lewis, B.T.R., Evolution of ocean crust seismic velocities, Ann. Rev. Earth Planet. Sci., 6, 377-404, 1978.
Mattey, D.P., L.P. Carr, I.P. Wright, and C. T. Pillenger, Carbon isotopes in submarine basalts, Earth Planet. Sci. Lett., in press, 1984.
McKenzie, D.P., Speculations on the consequences and causes of plate motions, Geophys. J.R. Astron. Soc.,18, 1-32, 1969.
Molnar, P., D. Friedman and J.S.F. Shih, Lengths of intermediate and deep seismic zones and temperatures in downgoing slabs of lithosphere, Geophys. J.R. Astr. Soc., 56, 41-54, 1979
Ringwood, A.E., The petrological evolution of island arc systems, Jour. Geol. Soc. Lond., 130, 183-204, 1974.
Rossman,G.R. and R.D. Aines, The water content of mantle garnets, EOS Trans. AGU, 64, 903, 1983.
Sacks, I.S., Subduction geometry and magma genesis, in Explosive Volcanism: Inception, Evolution and Hazards, edited by F.R. Boyd, National Academy Press, Washington, D.C., 34-46, 1984.
Schweller, W. J. and L.D. Kulm, Extensional rupture of oceanic crust in the Chile Trench, Marine Geology, 28, 271-291, 1978.
Stakes, D. S. and J. R. O'Neill, Mineralogy and stable isotope geochemistry of hydrothermally altered oceanic rocks, Earth Planet Sci. Lett., 57, 285-304, 1982.
Taylor, B. and G. D. Karner, On the evolution of marginal basins, Rev. Geophys. Space Phys., 21, 1727-1741, 1983.
Toksoz, M.N., J.W. Minear, and B.R. Julian, Temperature field and geophysical effects of a downgoing slab, J. Geophys. Res., 76, 1113-1061, 1971.
Vlaar, N.J. and M.J.R. Wortel, Lithospheric aging, instability and subduction, Tectonophysics, 32, 331-351, 1976.
Weins, D.A. and S. Stein, Age dependence of oceanic intraplate seismicity and implications for lithospheric evolution, J. Geophys. Res., 76, 6455-6468, 1983.
Yuen, D.A., L. Fleitout, G. Schubert and C. Froidevaux, Shear deformation zones along major transform faults and subducting slabs, Geophys. J.R. Astr. Soc., 54, 93-119, 1978.

D. Abbott and M. Lyle, College of Oceanography, Oregon State University, Corvallis, OR 97331.

(Received June 29, 1984;
revised August 21, 1984;
accepted August 24, 1984.)