Integrated ammonite biochronology and U-Pb geochronometry from a basal Jurassic section in Alaska

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ABSTRACT

New results from integrated biochronologic and geochronometric studies on the basal Jurassic section at Puale Bay (Alaska Peninsula) improve the calibration of the Early Jurassic time scale. Previously, the interval around the Triassic-Jurassic system boundary was poorly dated, which hampered our understanding of geologic and biotic events, e.g., the end-Triassic mass extinction and subsequent recovery. Published suggestions for the presence of the earliest Hettangian (Planorbis Zone) and a continuous boundary section at Puale Bay are not substantiated. Although the Kamishak Formation is likely to contain an uninterrupted sedimentary record, pre-middle Hettangian strata are locally faulted, resulting in an apparent Rhaetian to early Hettangian gap in the fossil record. The Hettangian ammonite zonal schemes developed locally for Nevada and the Queen Charlotte Islands permit reliable correlation with Alaska, but have limited applicability. The faunal succession recorded at Puale Bay is useful in the development of a regional zonation for North America.

We obtained three U-Pb zircon dates that are tied into an ammonite biochronology at the zonal level. A middle Hettangian tuff layer from near the top of the Kamishak Formation is dated at 200.8 +2.7 /–2.8 Ma. Tuffs from the overlying Talkeetna Formation are bracketed by middle and late Hettangian ammonites and yield crystallization ages of 197.8 ±1.2 /–0.4 and 197.8 ± 1.0 Ma. These new calibration points require that the Hettangian-Sinemurian boundary be younger than 199 Ma. The Triassic-Jurassic boundary is likely to fall between 200 and 205 Ma. Similar studies are needed for the uppermost Triassic to obtain tighter constraints. Zircon U-Pb systematics of two samples revealed strong correlations with the Hettangian ammonite zonal schemes developed locally for Nevada and the Queen Charlotte Islands permit reliable correlation with Alaska, but have limited applicability. The faunal succession recorded at Puale Bay is useful in the development of a regional zonation for North America.

INTRODUCTION

This study is aimed at improving the Early Jurassic time scale in the North American Cordillera through U-Pb dating of volcanic units whose ages are well constrained by ammonite biochronology. The establishment of an Early Jurassic time scale has been problematic; fossiliferous lowermost Jurassic marine sediments are scarce, and key biostratigraphic indicators—ammonites—are known from only a few localities. Age estimates for the Triassic-Jurassic boundary, which marks one of the five most significant Phanerzoic mass extinction events (Raup and Sepkoski, 1982), range from 213 to 200 Ma in time scales published during the past 15 yr (Pálfy, 1995). The imprecision is due to a small number of relevant isotopic ages. Here we present results from our study of the Puale Bay, Alaska, section. This outcrop is said to contain the Triassic–Jurassic transition (Newton, 1989). The work presented here is part of a larger project directed at refining the Jurassic time scale for the North American Cordillera (Pálfy et al., 1995).

The Puale Bay section has long been known to contain fossiliferous uppermost Triassic and lowermost Jurassic sedimentary strata and volcanic rocks (Capps, 1923; Kellum et al., 1945; Martin, 1926; Smith and Baker, 1924). The monographic treatment of its Hettangian ammonoids by Inlay (1981) indicated the presence of earliest Jurassic faunas. Continuous Triassic–Jurassic sequences are rare globally (Hallam, 1990).

The section studied here is located on the southeastern shore of Puale Bay, on the rugged coastline of the Alaska Peninsula, across the Shelikof Strait from Kodiak Island (Fig. 1). A wave-cut intertidal platform and adjacent coastal bluffs provide excellent exposures. Beds dip moderately to the northwest, and their continuous erosion by waves aids macrofossil collecting.

We collected ammonoids and other macrofauna from 26 levels in the Hettangian–Sinemurian strata, measured the basal Jurassic stratigraphic section, and sampled potentially zircon-bearing volcanic units for U-Pb dating.

In this report we (1) document the Early Jurassic ammonoid succession in the Puale Bay section based on the new collections, (2) establish a biochronologic framework to constrain the dated volcanic units at the zonal level, (3) report three new zircon U-Pb ages, (4) discuss the significance of new data in comparison with recent time scales, and (5) reconsider the status of the Puale Bay section as a Triassic–Jurassic boundary section.

GEOLOGIC SETTING AND PREVIOUS WORK

South-central Alaska is a collage of tectonostatigraphic terranes. The three largest terranes—Alexander, Peninsular, and Wrangellia—are thought to have amalgamated into the Wrangellia composite terrane prior to their accretion to North America during Cretaceous time (Nokleberg et al., 1994, 1996).
and references therein). The Puale Bay area forms part of the Peninsular terrane, also known as the Alaska Peninsula terrane (Wilson et al., 1985). Its Triassic and Jurassic stratigraphy records the geological evolution of a volcanic island arc (Wang et al., 1988) that is closely linked to Wrangellia on the basis of shared shallow marine carbonate, clastic, and volcanic (mainly volcaniclastic) sequences.

The Puale Bay section was recognized as one of the most complete and relatively undeformed Triassic and Jurassic successions in south-central Alaska. Early work was summarized by Imlay and Detterman (1977). Based on a comprehensive evaluation of all Early Jurassic ammonite collections made in the area (including neighboring Alinchak Bay), Imlay (1981) demonstrated the presence of Hettangian rocks. The underlying Upper Triassic sequence was studied in detail by Wang et al. (1988). A complete (Upper Triassic to Upper Jurassic), measured stratigraphic section is found in Detterman et al. (1985). The most recent stratigraphic summary is given by Nokleberg et al. (1994).

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The Upper Triassic Kamishak Formation is the oldest Mesozoic unit at Puale Bay. It comprises some 700 m of shallow marine, biogenic carbonate that is, in its upper part, interbedded with basaltic volcanic rocks (Wang et al., 1988). Wilson and Shew (1992) obtained an imprecise whole-rock K-Ar age of 197 ± 12 Ma (1σ) for the basalt. Dark gray, organic-rich, thin-bededded, siliceous limestone in the upper part of the formation yielded ammonites (Metasibirites, Rhabdoceras), bivalves (Monotis spp.), and a hydrozoan, Heterastridium, that indicate a late Norian age (Silberling in

![Figure 1. Location map of the Puale Bay section. F—fault.](image-url)
The Hettangian–Sinemurian section is truncated by a fault that juxtaposes the Talkeetna Formation and the several-hundred-meter-thick dark shale sequence of the Kialagvik Formation. The oldest ammonites from the latter unit occur merely 6 m above the fault. From this level, Imlay (1981) identified Haugia cf. compressa of middle Toarcian age, which was later revised as Pleydellia maudensis, a guide ammonite of the latest Toarcian Yakouensis Zone (Jakobs, 1997; Jakobs et al., 1994). Our collection of Pleydellia sp. confirms the presence of uppermost Toarcian. Beds a few meters upslope from this uppermost Toarcian level yielded Tnetoceras, a characteristic Aalenian genus. Stratigraphically younger parts of the Puale Bay section are beyond the scope of this study.

**HETTANGIAN–SINEMURIAN BIOCHRONOLOGY**

Ammonoids are the predominant megafossils in the Lower Jurassic section at Puale Bay. More than 100 specimens were collected from 26 levels in a measured stratigraphic section (Fig. 3). Bivalves, plant fossils, and nautiloids also occur, but they do not rival the abundance and stratigraphic importance of the ammonoids and thus are not discussed here. The ammonoids are moderately to poorly preserved internal molds that suffered postdepositional compression to varying degrees. In most cases, much important morphologic information such as whorl cross section, ventral features, and suture lines are lost. The set of characteristics available for identification is commonly restricted to resolution, whorl expansion rate, and ornamentation. The less-than-ideal preservation necessitates frequent use of open nomenclature (Bengtson, 1988). In several cases a form can only be assigned to a group of taxa which share the observed characters. The absence of preserved distinguishing features, however, precludes a more precise identification. In some cases, comparable species have been attributed to more than one genus. We indicate this by a question mark appended to the genus considered the most likely. The low morphologic diversity among Hettangian ammonoids, especially the narrow range of ornamentation (Liang, 1994), hinders precise identification. Homeomorph is common among Hettangian ammonoids that record post-extinction recovery from limited root stocks (Tozer, 1971). In case of heterochronous homeomorphs, care was taken to avoid using stratigraphic inferences in the identification. All possible homeomorphs known from the Hettangian and Sinemurian were considered to ensure unbiased biochronologic dating.

**Local Ammonite Ranges**

Observed ranges of ammonite taxa are shown in Figure 3. Uncertainty in identification, as discussed above, is indicated. Detailed taxonomic remarks are given in the Data Repository.

Good ammonite biostratigraphic control exists in three intervals of the Hettangian–Sinemurian section. The first interval occurs in the basal 55 m above the fault at the base of the measured section. Here calcareous mudstones yielded an abundant and diverse ammonoid fauna (levels 1–14). Kammerkaries? cf. frigga (Fig. 4, B, E, F, and H) is the most common form in the lowest 30 m (levels 1–11). Discamphiceras occurs throughout with D. cf. silberlingi (Fig. 4, A and D) appearing first (levels 2–12) and apparently replaced by D. aff. reissi (Fig. 4C; levels 13–14). Less common but stratigraphically important forms include, in order of their first appearance, K. ex gr. megastoma (Fig. 4R), Saxoceras? sp. (Fig. 4, G and J), S.? ex gr. portlockii (Fig. 4I), Pleuroacanthites ex gr. mulleri (Fig. 4L), and Mullerites cf. pleuroacanthitoides (Fig. 4, N and O). Several poorly understood forms such as Franziceras? sp. (Fig. 4M), a psilo-

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1 GSA Data Repository item 9980, taxonomic remarks, is available on the Web at http://www.geosociety.org/pubs/ftpyrs.htm. Requests may also be sent to Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301; e-mail: editing@geosociety.org.
Figure 3. Measured lowest Jurassic stratigraphic section showing fossil collection levels, ammonite ranges, and U-Pb sample sites at Puale Bay, Alaska. Bold italic font denotes taxa with higher confidence in species and/or genus identification. Light Courier font denotes tentative identifications where a genus may be only provisionally suggested. Zonal correlation with zones and informal assemblages of the Hettangian (Tipper and Guex, 1994), Sinemurian (Pálffy et al., 1994), and Toarcian (Jakobs et al., 1994) of Queen Charlotte Islands is indicated. TR.—Triassic; RH.—Rhaetian; TO.—Toarcian; P.d.—Pseudoaetomoceras doetzkircheni assemblage; Ya.—Yakounensis Zone; Kl. FM.—Kialagvik Formation.
Figure 4. Middle Hettangian ammonite fauna of Puale Bay. Collection levels are shown in Figure 3. Specimens are deposited in the type collection of the Department of Earth and Ocean Sciences, University of British Columbia, under the type numbers with the prefix UBC. (A) *Discamphiceras* cf. *silberlingi* Guex, level 7, UBC 018; (B) *Kammerkarites*? cf. frigga (Wähner), level 5, UBC 019; (C) *Discamphiceras* aff. *reissi* (Tilmann), level 13, UBC 020; (D) *Discamphiceras* cf. *silberlingi* Guex, level 12, UBC 021; (E) *Kammerkarites*? cf. frigga (Wähner), level 10, UBC 022; (F) *Kammerkarites*? cf. frigga (Wähner), level 8, UBC 023; (G) *Saxoceras*? sp., level 8, UBC 024; (H) *Kammerkarites*? cf. frigga (Wähner), level 7, UBC 025; (I) *Saxoceras*? ex gr. *portlocki* (Wright), level 6, UBC 026; (J) *Saxoceras*? sp., level 4, UBC 027; (K) *lytoceratid* indet., level 14, UBC 028; (L) *Pleuroacanthites* ex gr. *mulleri* Guex, level 9, UBC 029 (note parabolic nodes); (M) *Franziceras*? sp., level 8, UBC 030; (N and O) *Mullerites* cf. *pleuroacanthitoides* Guex, level 11, UBC 031 and UBC 032; (P and Q) *psiloceratid* indet., level 9, UBC 033 (counterparts of the same specimen, note nodes on inner whorls); (R) *Kammerkarites* ex gr. *megastoma* (Gümbel), level 3, UBC 034.
ceratid (Fig. 4, P and Q), *Euphyllites* sp., and a lytoceratid (Fig. 4K) occur in the upper part of the interval.

The second fossiliferous interval occurs in sandstone from 180 m to 240 m above the base of the measured section. These beds are separated from the lower fossiliferous unit by more than 100 m of dominantly volcaniclastic strata. A single specimen of *Sunnistes*? sp. (Fig. 5, A and B) was recovered near the lowest epiclastic beds (level 16). It is overlain by a moderately diverse assemblage of *Badouxia* (showing an apparent succession of *B. canadensis* [Fig. 5I] followed by *B. columbiæ* [Fig. 5G]), *Eolytoceras* cf. *tasekoi* (Fig. 5D), *Paracaloceras* (including *P. rursicostatum* [Fig. 5C]), and a single large schlotheimiid specimen.

The third ammonite-bearing interval is found within the top 80 m below the fault contact with Toarcian strata, where sparsely fossiliferous sandstone and minor shale interbeds yielded a monogenic *Arnioceras* fauna (Fig. 5, J and K).

**Correlation and Biochronologic Dating**

The standard chronostratigraphy of the Jurassic is based on the north-west European ammonite succession. North American Early Jurassic ammonite faunas are different enough from those of northwest European to warrant independent regional standard zonations, as demonstrated for the pliensbachian and Toarcian (Smith et al., 1988; Jakobs et al., 1994). To date, no regional North American zonal scheme has been proposed for the Hettangian, but local biostratigraphy has recently been elaborated for two areas with the most complete faunal succession: Nevada (Guex, 1995) and the Queen Charlotte Islands (Tipper and Guex, 1994). We first compare the Alaskan faunas with these areas, and they indeed exhibit great faunal similarity. Next we consider the South American and Alpine regional zonal schemes that are useful for correlation on the basis of a host of common taxa. Finally, we attempt a correlation with the standard chronozones (i.e., northwest European zones) through a web of interregional correlation and a few direct links. Figure 6 shows a global compilation of Hettangian ammonite zonations and their approximate correlation.

The stratigraphic distribution of the Alaskan Hettangian taxa known from other regions is summarized in Figure 7. Vertical ranges are shown at zonal resolution except for Nevada and the Queen Charlotte Islands, where data are available to further confine ranges to certain parts of zones. It is evident that the lower fauna from Puale Bay correlates with middle Hettangian units worldwide. This lower fauna may be further constrained to the lower part of the middle Hettangian (i.e., Portlocki Subzone equivalents). Direct correlation with northwest Europe using *Saxoceras* ex gr. *portlocki* and *Kammerkaries* ex gr. *megastoma* corroborates this conclusion. The only species that apparently contradicts this correlation is *Mullerites pleuroacanthisoides*, which is known only from a single bed in Nevada representing a slightly higher stratigraphic position within the middle Hettangian.

The second fauna contains East Pacific elements to such an extent that there is a conspicuous lack of direct links to European faunas. Nevertheless, a placement within the late Hettangian through Hettangian-Sinemurian boundary interval is undoubted. *Sunnistes*, occurring in the lowest bed of this fauna, suggests the lower part of the late Hettangian because the genus appears at this level in North and South America. Somewhat higher, the association of *Badouxia, Eolytoceras*, and *Paracaloceras* is characteristic of the Canadensis Zone (Frebold, 1967; Pálfy et al., 1994), but the first representatives of these genera may appear earlier (Guex, 1995; Tipper and Guex, 1994). Correlation of the Canadensis Zone is difficult. Several workers favor its placement straddling the Hettangian-Sinemurian stage boundary (Pálfy et al., 1994; Riccardi et al., 1991; Taylor, 1990). The correlation of this zone with the Alpine Marmorea Zone is more conclusive, but the position of the Marmorea Zone itself is debated (Bloos, 1983; Guex and Taylor, 1976; Taylor, 1986). Recent studies by Bloos (1994, 1996) provide evidence supporting the placement of the Marmorea Zone in the Hettangian. In Alaska as well as in the Queen Charlotte Islands, the first appearance of *Badouxia columbiæ* postdates that of most other elements of the Canadensis Zone, and thus it can be pragmatically used to approximate the base of the Sinemurian.

The third fauna contains *Arnioceras* only, *A. cf. arnouldi* being the only species identified. It is a guide fossil of the Arnouldi Assemblage recognized in the lower Sinemurian of the Queen Charlotte Islands (Pálfy et al., 1994). Although *Arnioceras* is known to range up to the lower part of the upper Sinemurian, monogeneric faunas typically occur in the upper lower Sinemurian. The global record of this cosmopolitan genus also suggests that the standard Semicostatum Zone is the most likely correlative of this fauna.

**U-Pb GEOCHRONOMETRY**

**Analytical Methods**

U-Pb analytical work was done at the Geochronology Laboratory of the University of British Columbia. Zircon was obtained from 8 to 25 kg samples using crushing, grinding, wet shaking, and heavy liquid separation. Fractions were handpicked on the basis of differences in magnetic susceptibility, size, and crystal morphology. Whenever possible, the least magnetic and best quality grains (i.e., free of cracks, inclusions, and visible cores or zoning) were used for the analyses. In all but one sample with the smallest zircon yield (95JP4), the fractions were strongly air-abraded using the technique of Krogh (1982) to minimize or eliminate the effect of surface-correlated Pb loss. Details of techniques employed in chemistry and mass spectrometry are given by Mortensen et al. (1995). During the course of this study, U and Pb procedural blanks were 0.6–2.5 and 5–9 pg, respectively. Blank isotopic compositions, crucial in the calculation of 207Pb/235U and 206Pb/205Pb ages, were carefully monitored.

Analytical data are reported in Table 1. The age calculations are based on the decay constants recommended by Steiger and Jäger (1977); the correction for initial common Pb follows the model of Stacey and Kramers (1975). The analytical errors are propagated through the age calculations using the method of Roddick (1987). In some analyzed zircon fractions, U-Pb systematics are affected by Pb loss and inheritance. The rationale for assignment of the crystallization age and its associated error at the 2σ level is described separately for each sample.

**Age Determinations**

The lowermost sample (95JP1) was collected from a conspicuous, 1-cm-thick, pink, coarse-grained, crystal tuff layer interbedded with the siliceous marl sequence (Fig. 3). A small, <10 kg sample yielded abundant and excellent-quality zircons. The apparently homogeneous population consisted of pale brown, mainly euhedral, multifaceted, doubly terminated prisms with varying aspect ratio, ranging from stubby to needle-like grains.

Seven of the analyzed nine fractions are concordant to nearly concordant (Fig. 8A). The 206Pb/238U ages range from 194.7 to 198.3 Ma, and many of them overlap. Slight Pb loss not entirely removed by air abrasion is indicated for these fractions, perhaps with the exception of fraction A, which is concordant and yields the oldest 206Pb/238U age (198.3 ± 0.7 Ma). Notably, fractions E and F abraded to a lesser degree, yielded the youngest 206Pb/238U ages. Since the concordance and age of fraction A has not been duplicated, we calculated a seven-fraction discordia line through the origin (MSWD = 1.98) that yields an upper intercept age of 200.4 ± 2.7 Ma, and only requires a 0.1 Ma extension to include the 206Pb/238U age of A and its range of error. Thus, a conservative best estimate for the age of the rock is 200.4 ± 2.8 Ma.
Ma. Fraction J was not considered because it is reversely discordant, and it clearly represents an inferior analysis. Fraction D differs from all other fractions by its older $^{206}\text{Pb} / ^{238}\text{U}$ age, which is interpreted as a result of a small amount of inherited older Pb component, likely as undetected, cryptic cores. Unequivocal evidence for inherited or xenocrystic zircon will be presented in the following section for samples stratigraphically higher in the section. On this basis, fraction D was also omitted from the final age calculation.

Three samples were collected from the main volcaniclastic unit. The lowermost of these, 95JP5, is from a nearly 6-m-thick bed of green to red, unaltered, crystal-rich tuff. Common phenocrysts include plagioclase, biotite, and hornblende. Abundant, gem-quality zircon was recovered from this sample. Colorless to pale brown, euhedral, doubly terminating prismatic grains form a single population ranging continuously from needles with simple, square cross section to more multifaceted, stubby crystals.

Six of the analyzed seven fractions intercept or touch the concordia line and overlap one another (Fig. 8B). Fraction H, which yielded the youngest $^{206}\text{Pb} / ^{238}\text{U}$ age, is slightly discordant, likely due to Pb loss not completely removed by abrasion. The other six fractions yield a weighted mean $^{206}\text{Pb} / ^{238}\text{U}$ age of 197.8 ± 0.4 Ma. Allowing for the possibility of slight Pb loss in some of these fractions, we extend the error to include the oldest $^{206}\text{Pb} / ^{238}\text{U}$ age of the concordant fraction B (198.6 ± 0.4). Thus, the best age estimate of this sample is 197.8 ± 0.4 Ma.

Sample 95JP4 was collected from a green, resistant, 10-cm-thick, likely somewhat reworked tuff layer that contains rare plagioclase and biotite phenocrysts, devitrified glass, and lithic fragments. A 20 kg sample yielded less than 0.1 mg zircon, which was divided into two fractions. Both contained subhedral grains of good quality with no visible cores or zoning. Abrasion was prohibited by the small quantity of grains. Both fractions show a strong inherited Pb component (Fig. 8C). A discordia line yields a lower intercept of 113 ± 29 Ma. The deviation from the expected crystallization age could result from Pb loss and/or mixing of inherited Pb of different ages. Results from our other samples suggest that Pb loss is expected for unabraded zircons. The upper intercept of 1270 ± 68 Ma points to a Proterozoic zircon component that was not detected as cryptic cores or xenocrysts.

The stratigraphically highest sample, 95JP3, was collected from massive, soft, poorly lithified, plagioclase-phyric water-laid tuff with green, some-
what altered groundmass. Zircon in this sample was not abundant, but the recovered material was sufficient to analyze five fractions. Colorless to pale brown grains of good to excellent clarity were separated into fractions of euhedral or dominantly subhedral to anhedral crystals. Fractions A and D, both containing euhedral prisms, are overlapping and slightly discordant to concordant, whereas the other three fractions reveal variable amount of inherited Pb. It is possible that some resorbed grains are xenocrysts or cryptic zircon cores and remained visually undetected. When plotted on a composite concordia diagram (Fig. 8C), these three fractions and the two discordant fractions of sample 95JP4 fail to define a single chord. It is therefore likely that mixing of inherited Pb of varying ages occurred in both samples. A bounding chord through fractions A, D, and C defines an older upper intercept age of 2775 ± 30 Ma. The other bounding chord through A, D, and E yields an upper intercept age of 1094 ± 30 Ma. The crystallization age of the tuff is estimated from the 206 Pb/238 U age of fractions A and D, which are virtually free of inheritance and Pb loss. An estimate of 197.8 ± 1.0 Ma is derived from the weighted mean 206 Pb/238 U age with its error extended to encompass the error range of both fractions.

**DISCUSSION**

In this study we identified 20 ammonite taxa from new collections as compared to the nine taxa reported by Imlay (1981), whose work is based on all previous collections from the same area. Table 2 summarizes the revised taxonomy in comparison with that of Imlay (1981). Only two previously known species have not been found in the new collection. *Laqueoceras* cf. *sublaqueus* is a serpenticone alsatitid characteristic of the upper part of the Liasicus Zone or its equivalents. *Schlotheimia* sp., with the genus ranging from the middle through the late Hettangian, can also be easily accommodated within the stratigraphic framework outlined above.

The biochronologically most important revision concerns *Psiloceras* cf. *planorbis* in Imlay (1981). Similar, midvolute, unornamented forms occurring in the lower fauna are now tentatively interpreted as *Euphyllites* sp. Also similar is a large, smooth whorl fragment at the top of the lower fauna, which is probably a lytoceratid. Both these identifications are in accordance with the middle Hettangian age assignment. There appears to be no firm evidence for the presence of early Hettangian faunas. The youngest proven Triassic is the Norian *Cordilleranus* Zone, and the oldest proven Jurassic is the Liasicus Zone equivalent. Between the two at Puale Bay are several tens of meters of strata containing only trace fossils (Newton, 1989) and a fault. The presence of middle Hettangian ammonites in the lowest beds of the hanging wall and the lack of significant lithological change across the critical interval suggest that deposition may have been continuous throughout the Triassic-Jurassic boundary, but the basal Jurassic is faulted out. The Puale Bay section is therefore ruled out as a continuous Triassic-Jurassic boundary section. However, outcrops at neighboring Alinchak Bay should be scrutinized as they may contain an uninterrupted record spanning the boundary.
Figure 7. Ranges of Hettangian ammonite taxa known from Puale Bay as established in other regions. Numbered biochronologic units are the same as in Figure 6. All taxa listed in the taxonomic remarks (see Data Repository item 9980, and footnote 1) as included in the identified species groups are considered. Bars in lighter shade denote taxa of uncertain generic assignment. Black bars indicate taxa occurring in the lower faunal level, double bars indicate taxa from the middle faunal level at Puale Bay. SIN.—Sinemurian. Genus abbreviations: B—Badouxia; D—Discamphiceras; E—Eolytoceras; F—Franziceras; K—Kammerkarites; M—Mullerites; P—Pleuroacanthites; Pc—Paracaloceras; S—Saxoceras. Sources: G95—Guex (1995); GF90—Guérin-Franiatte (1990); H90—Hillebrandt (1990); H91—Hillebrandt (1991); H94—Hillebrandt (1994); L52—Lange (1952); P94—Pálffy et al. (1994); R91—Riccardi et al. (1991); R93—Rakús (1993); TG94—Tipper and Guex (1994); W—Wähner (1882–1898).
The detailed documentation of ammonoid ranges in the Puale Bay section is an important step toward the development of a regional standard zonation for the North American Hettangian. The main stratigraphic relationships known from Nevada and the Queen Charlotte Islands were upheld. Our new observations underscore the need for the study of several sections before the biochronologic significance of certain taxa can be fully understood. The lower fauna is not easily amenable to subdivision, yet it contains elements of four local zones from Nevada (Guex, 1995) and two from the Queen Charlotte Islands (Tipper and Guex, 1994). The occurrence of Discamphiceras cf. silberlingi below D. aff. reissi is the reverse of the succession in Nevada. A more substantial overlap exists in the ranges of Mullerites in the second fauna supports the idea that this lineage is the most useful for subdividing the late Hettangian and the Hettangian–Sinemurian transition in North America.

The isotopically dated levels are firmly constrained by the ammonite palynostratigraphy (Fowell et al., 1994). The new U-Pb ages do not correspond to the Hettangian in most of the recently published time scales, although they fall within the range of error proposed for the terminal Hettangian boundary (Fig. 9). Based on the new results, the Hettangian–Sinemurian boundary cannot be older than 199 Ma. The age of the Triassic–Jurassic boundary cannot be directly derived from our data. Many time scales (e.g., Harland et al., 1990; Gradstein et al., 1995) yield similar results, the Hettangian–Sinemurian boundary cannot be older than 199 Ma. The age of the Triassic–Jurassic boundary cannot be directly derived from our data. Many time scales (e.g., Harland et al., 1990; Gradstein et al., 1995) yield similar

### TABLE 1. U-Pb ANALYTICAL DATA

| Sample and fraction | U (ppm) | Pb²⁺ (ppm) | 206Pb²⁺ (pg) | 207Pb²⁺ (pg) | 208Pb²⁺ (pg) | 238U²⁺ (pg) | 207U²⁺ (pg) | 206Pb²⁺/238U²⁺ | 207Pb²⁺/206Pb²⁺ | 206Pb²⁺/235U²⁺ | 207Pb²⁺/206Pb²⁺ | Calculated ages [12n Ma]²³ |
|---------------------|---------|------------|---------------|--------------|--------------|-------------|-------------|----------------|----------------|----------------|----------------|-----------------|-------------------|
| 95JP1††† A          | 0.175   | 233        | 7             | 9493         | 8            | 8.4         | 0.03124 ± 0.17% | 0.2156 ± 0.16% | 0.05006 ± 0.08% | 198.2 ± 0.5   | 197.0 ± 0.3   | 195.3 ± 0.3      |
| 95JP1††† B          | 0.095   | 277        | 9             | 4331         | 12           | 8.9         | 0.03105 ± 0.10% | 0.2147 ± 0.21% | 0.0515 ± 0.12% | 197.1 ± 0.4   | 202.2 ± 5.5  | 204.2 ± 5.5      |
| 95JP1††† D          | 0.143   | 261        | 7             | 7805         | 10           | 8.9         | 0.03206 ± 0.25% | 0.2227 ± 0.29% | 0.05308 ± 0.11% | 203.4 ± 1.0   | 212.4 ± 5.0  | 204.3 ± 5.0      |
| 95JP1††† E          | 0.062   | 324        | 10            | 4360         | 9            | 10.1        | 0.03089 ± 0.10% | 0.2136 ± 0.20% | 0.0516 ± 0.12% | 196.1 ± 0.4   | 204.2 ± 5.5  | 204.3 ± 5.5      |
| 95JP1††† F          | 0.083   | 239        | 7             | 1868         | 21           | 9.4         | 0.03066 ± 0.11% | 0.2117 ± 0.24% | 0.0506 ± 0.15% | 194.7 ± 0.4   | 198.0 ± 7.0  | 198.0 ± 7.0      |
| 95JP1††† G          | 0.125   | 256        | 8             | 3787         | 17           | 9.1         | 0.03097 ± 0.16% | 0.2144 ± 0.23% | 0.0502 ± 0.13% | 196.8 ± 0.6   | 204.3 ± 6.1  | 204.3 ± 6.1      |
| 95JP1††† H          | 0.177   | 318        | 10            | 6776         | 16           | 9.5         | 0.03104 ± 0.11% | 0.2149 ± 0.20% | 0.0502 ± 0.10% | 197.0 ± 0.4   | 204.8 ± 4.8  | 204.8 ± 4.8      |
| 95JP1††† I          | 0.111   | 245        | 7             | 3428         | 15           | 8.7         | 0.03091 ± 0.10% | 0.2131 ± 0.19% | 0.0500 ± 0.12% | 196.2 ± 0.4   | 195.2 ± 5.6  | 195.2 ± 5.6      |
| 95JP1††† J          | 0.054   | 118        | 9             | 1907         | 17           | 8.8         | 0.03944 ± 0.26% | 0.2084 ± 0.38% | 0.04964 ± 0.32% | 193.3 ± 1.0   | 178.0 ± 14.8 | 178.0 ± 14.8     |

† All zircon fractions. Listed in brackets: grain size range in microns; side slope of Franz magnetic separator (in degrees) at which grains are non-magnetic (% or magnetic (M), using 20° front slope and 1.8A field strength; grain character: b—broken pieces, e—elongate, eq—equant, n—needles, p—prismatic, s—stubby, t—tabular, ah—anhedral, sh—subhedral; degree of air abrasion: n—non-abraded, i—lightly abraded, m—moderately abraded, s—strongly abraded.

‡ Radiogenic Pb.

§ Measured ratio corrected for spike and Pb fractionation of 0.0043/amu ± 20% (Daly collector) and 0.0012/amu ± 7% (Faraday collector).

** Total common Pb in analysis based on blank isotopic composition.


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dated samples (95JP3 and 95JP4) contained a strong inherited zircon component. The lack of co-linearity in the discordant fractions is probably attributed to the mixing of inherited zircons of different ages. The two bounding chords (Fig. 8C) suggest a range from at least late Middle Proterozoic (1094 ± 30 Ma) to late Archean (2775 ± 30 Ma) upper intercept ages. The admixing of such old zircon requires the proximity of evolved Precambrian crust during the magmatic processes, a scenario that is not compatible with some current tectonic models. On the basis of elemental abundances, Barker et al. (1994) found the Talkeetna volcanics transitional between tholeiitic and calc-alkaline type and proposed an intra-oceanic volcanic arc as their likely tectonic setting. In another geochemical study, DeBari and Sleep (1991) documented high Mg and low Al “bulk arc” composition for the Talkeetna arc and suggested that the magma was sourced from a mantle wedge rather than a subducting plate. A new tectonic model for the Talkeetna arc should account for the observed zircon inheritance pattern while remaining compatible with the geochemical affinities.

CONCLUSIONS

The lowest Jurassic, ammonite-bearing, volcano-sedimentary sequence of the Puale Bay section was successfully dated using ammonite biochronology and U-Pb geochronometry. The oldest Jurassic ammonites in the Puale Bay section are of middle Hettangian age (Liasicus Zone, probably Portlocki Subzone equivalent). No record of basal Hettangian was found, and the Triassic–Jurassic transition is probably missing locally due to a small fault. The andesitic volcanism recorded in the Talkeetna Formation started during or immediately after the middle Hettangian and was terminated, at least locally, before the end of Hettangian time. Hettangian and early Sinemurian ammonite faunas are closely comparable with those of the other major North American localities in Nevada and the Queen Charlotte Islands, permitting global correlation at approximately the zonal level.

Three new U-Pb zircon dates from the biostratigraphically tightly constrained Hettangian volcanic units furnish calibration points for the Jurassic time scale. A thin tuff layer from within the correlatives of the middle Hettangian Liasicus Zone is dated at 200.8 +2.7 /–2.8 Ma. Tuffs of the Talkeetna Formation bracketed by middle and late Hettangian ammonites yield crystallization ages of 197.8 +1.2 /–0.4 and 197.8 ± 1.0 Ma. Zircon inheritance patterns reveal the proximity of the Talkeetna arc to evolved, Proterozoic to late Archean crustal components, which is not compatible with current tectonic models.

The new dates suggest that the Hettangian-Sinemurian boundary is younger than 199 Ma, and its age is overestimated in nearly all currently used...
time scales. The age of the Triassic-Jurassic boundary is likely between 200 and 205 Ma, younger than most current estimates.

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