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 Proterozoic and late Archean inheritance patterns that require revised tectonic models to account for the proximity of the Talkeetna arc to evolved crustal blocks.

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 Phanerozoic 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 Imlay (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 tectonostratigraphic 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,

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Data Repository item 9980 contains additional material related to this article.

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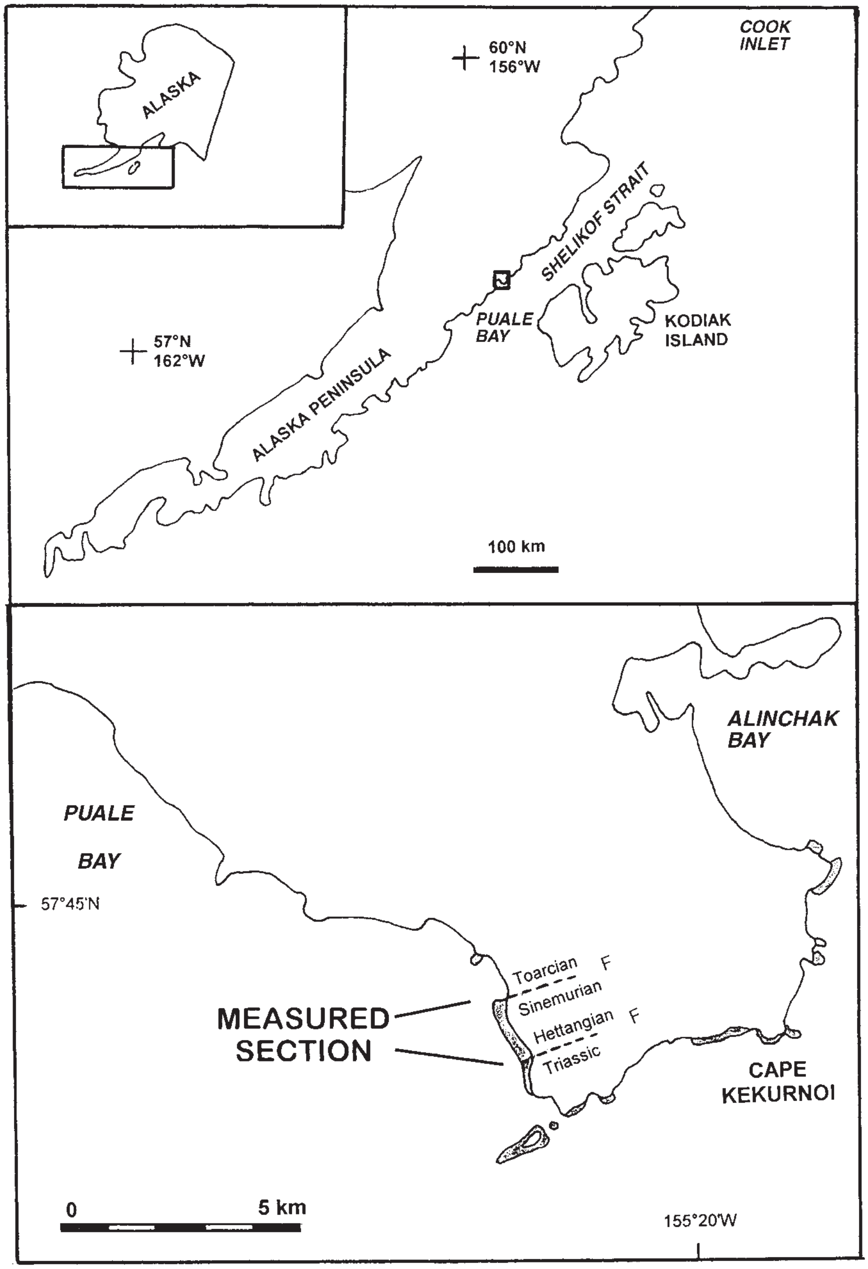

Figure 1. Location map of the Puale Bay section. F—fault.

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).

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-bedded, 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

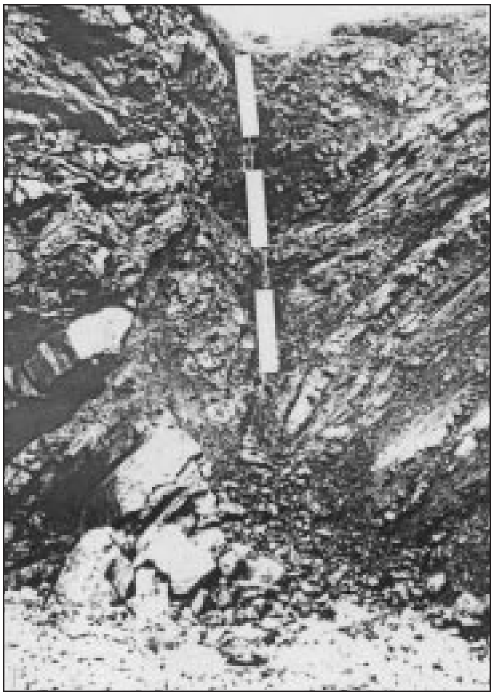

Figure 2. Normal fault separating the lowest Jurassic (middle Hettangian) ammonite-bearing beds to the left from unfossiliferous, lithologically very similar, presumably uppermost Triassic rocks to the right. Field of view is ~3 m wide.

Detterman et al., 1985; Wang et al., 1988; Newton, 1989; and this study). Above the fossiliferous Norian beds are approximately 50 m of trace-fossil–bearing strata apparently devoid of macrofossils (Newton, 1989). A slight and gradual decrease in carbonate content occurs upsection. We found the lowest Jurassic ammonoid-bearing beds immediately above a normal fault of unknown (but probably not large) offset (Fig. 2). Rocks on either side of the fault appear lithologically indistinguishable. The Hettangian–Sinemurian section above the fault was measured in detail and is shown in Figure 3. It contains an abrupt transition from fine-grained, calcareous sedimentary rocks to andesitic volcaniclastic rocks. The latter is referred to as the Talkeetna Formation, a widespread, predominantly volcanogenic unit of the Peninsular terrane (Nokleberg et al., 1994). In the Puale Bay section, we suggest drawing the base of the Talkeetna Formation at the lowermost massive green tuff, 60 m above the fault at the base of the measured section. This differs from the traditional approach that approximately equates the Triassic-Jurassic system boundary with the Kamishak-Talkeetna formational boundary by arbitrarily dividing the nonvolcanogenic sedimentary sequence (Nokleberg et al., 1994, and references therein). The lower 120 m of the Talkeetna Formation consists mainly of green tuff, volcanic breccia, and agglomerate with minor volcanogenic sandstone. The rocks are interpreted as subaqueous deposits of a major volcanic episode in moderate proximity to the eruptive centers. Overlying the basal tuffs is approximately 200 m of predominantly green-gray, coarse tuffaceous sandstone that is commonly thick bedded to massive and locally cross-stratified. Shale interbeds occur only rarely. The abundant volcanic detritus was likely derived from the active parts of the Talkeetna island arc.

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 Yakounensis Zone (Jakobs, 1997; Jakobs et al., 1994). Our collection of *Pleydellia* sp. confirms the presence of uppermost Toarcian. Beds a few meters upsection from this uppermost Toarcian level yielded *Tmetoceras*, 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 volution, 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. Homeomorphy 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[1].

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). *Kammerkarites*? 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. *portlocki* (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-

[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.

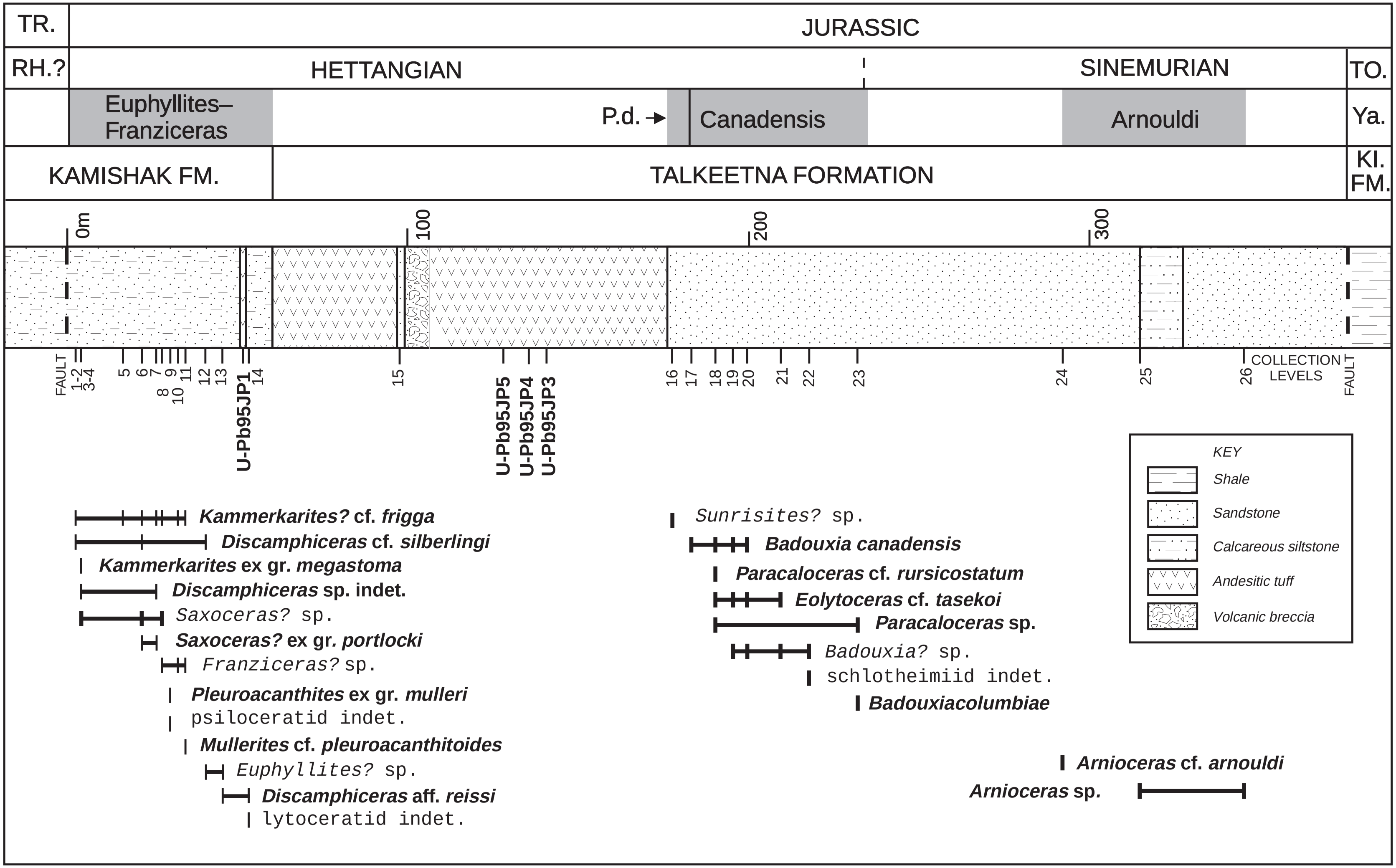

Figure 3. Measured lowest Jurassic stratigraphic section showing fossil collection levels, ammonite ranges, and U-Pb sample sites at Puale Bay, Alaska. Bold italic font denotes taxa with higher confidence in species and/or genus identification. Light Courier font denotes tentative identifications where a genus may be only provisionally suggested. Zonal correlation with zones and informal assemblages of the Hettangian (Tipper and Guex, 1994), Sinemurian (Pálfy 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; KI. FM.—Kialagvik Formation.

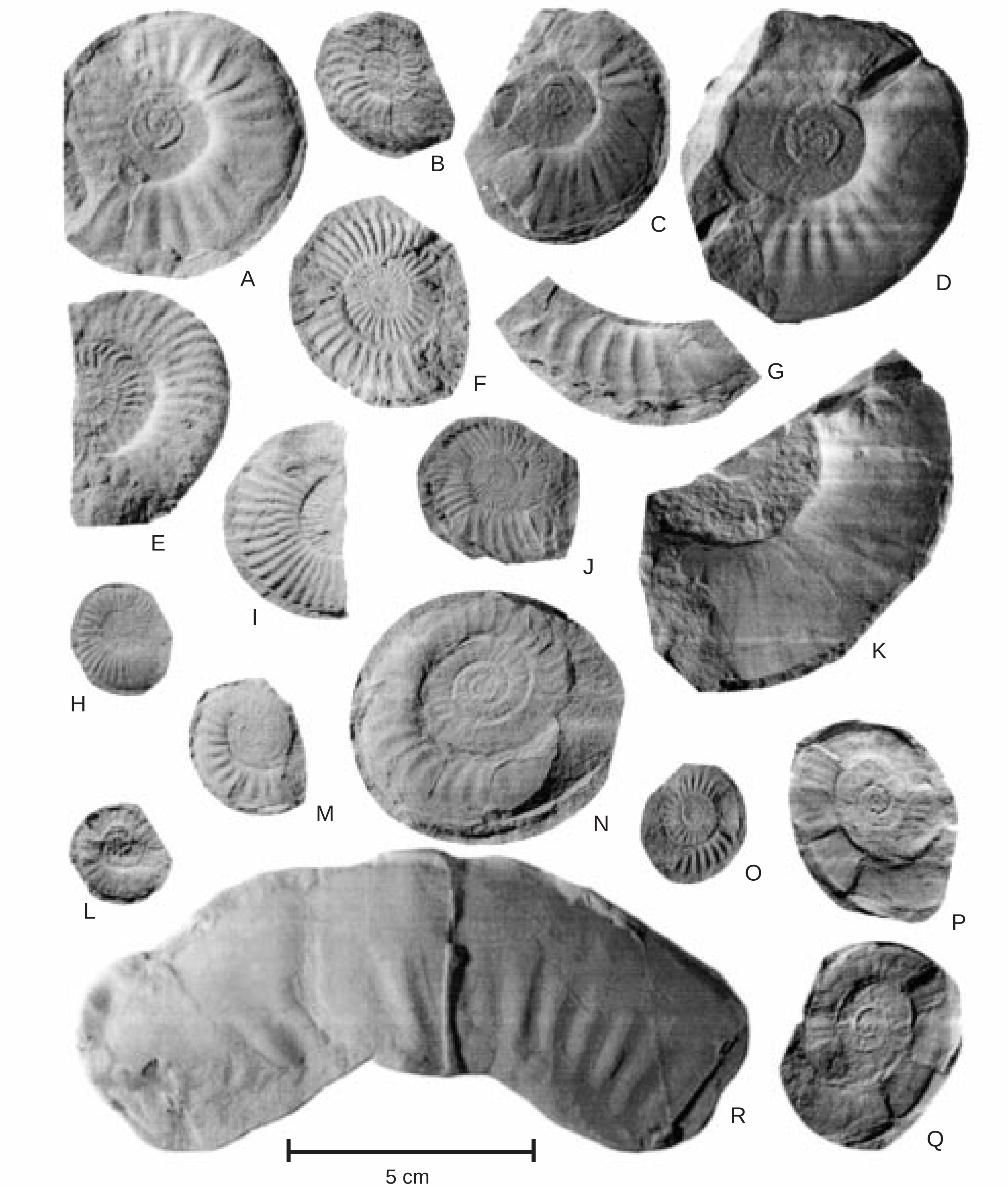

Figure 4. Middle Hettangian ammonite fauna of Puale Bay. Collection levels are shown in Figure 3. Specimens are deposited in the type collection of the Department of Earth and Ocean Sciences, University of British Columbia, under the type numbers with the prefix UBC. (A) *Discamphiceras* cf. *silberlingi* 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 *Sunrisites*? 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. columbiae* [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 monogeneric *Arnioceras* fauna (Fig. 5, J and K).

Correlation and Biochronologic Dating

The standard chronostratigraphy of the Jurassic is based on the northwest 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 *Kammerkarites* ex gr. *megastoma* corroborates this conclusion. The only species that apparently contradicts this correlation is *Mullerites pleuroacanthitoides*, 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. *Sunrisites*, 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 columbiae* 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 ^{207}Pb/^{235}U and ^{207}Pb/^{206}Pb 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 ^{206}Pb/^{238}U 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 ^{206}Pb/^{238}U age (198.3 ± 0.7 Ma). Notably, fractions E and F abraded to a lesser degree, yielded the youngest ^{206}Pb/^{238}U 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 ^{206}Pb/^{238}U age of A and its range of error. Thus, a conservative best estimate for the age of the rock is 200.4 $^{+2.7}/_{-2.8}$

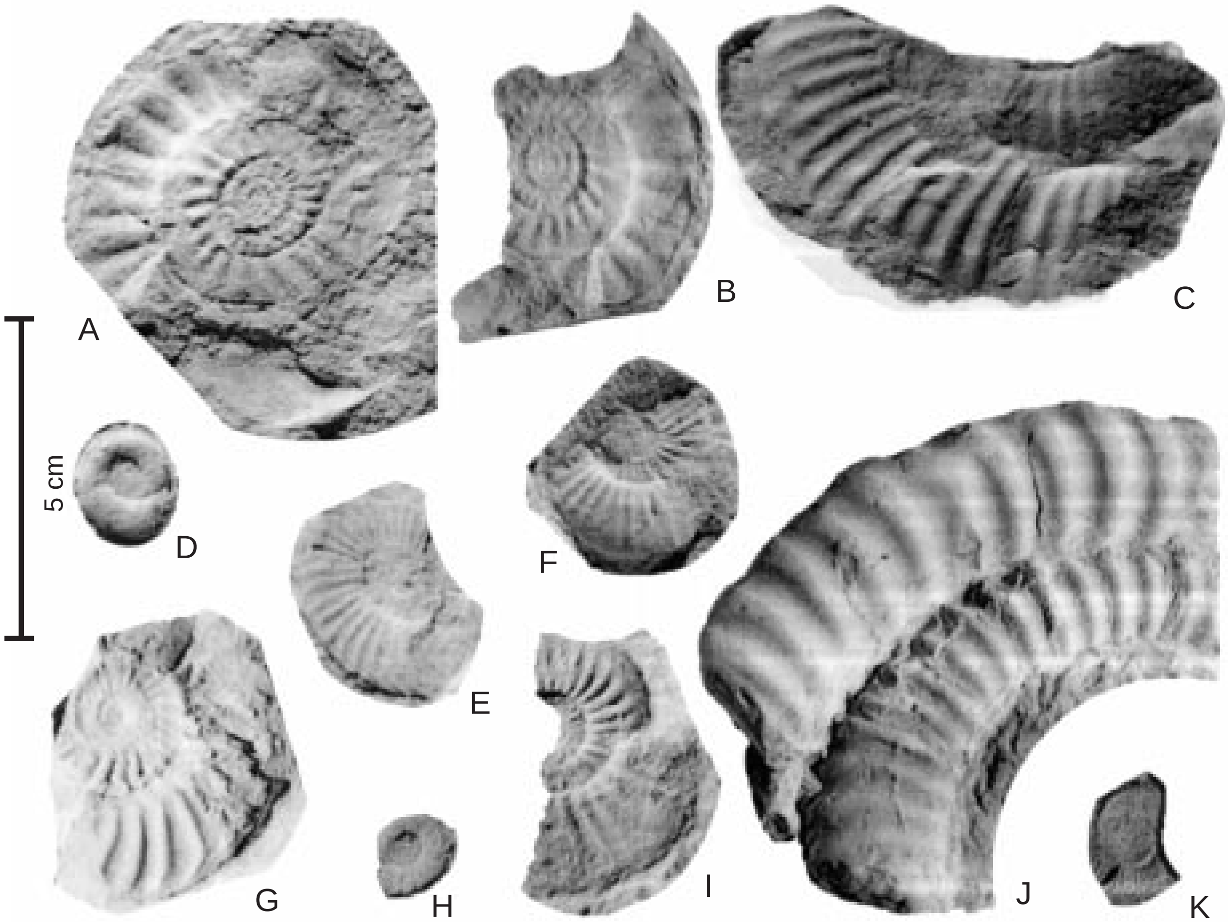

Figure 5. Late Hettangian through early Sinemurian ammonite fauna of Puale Bay. Collection levels are shown in Figure 3. Specimens are deposited in the type collection of the Department of Earth and Ocean Sciences, University of British Columbia, under the type numbers with the prefix UBC. (A and B) *Sunrisites*? sp., level 16, UBC 035 (counterparts of the same specimen); (C) *Paracaloceras* cf. *rursicostatum* Frebold, level 18, UBC 036; (D) *Eolytoceras* cf. *tasekoi* Frebold, level 19, UBC 037; (E) *Badouxia*? sp., level 22, UBC 038; (F) *Badouxia*? sp., level 21, UBC 039; (G) *Badouxia columbiae* (Frebold), level 23, UBC 040; (H) *Eolytoceras* cf. *tasekoi* Frebold, level 19, UBC 041 (nucleus only); (I) *Badouxia canadensis* (Frebold), level 18, UBC 042; (J) *Arnioceras* cf. *arnouldi* (Dumortier), float specimen, UBC 043; (K) *Arnioceras* sp., level 9, UBC 044 (inner whorls).

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 $^{206}Pb/^{238}U$ 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 $^{206}Pb/^{238}U$ age, is slightly discordant, likely due to Pb loss not completely removed by abrasion. The other six fractions yield a weighted mean $^{206}Pb/^{238}U$ 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 $^{206}Pb/^{238}U$ age of the concordant fraction B (198.6 ± 0.4). Thus, the best age estimate of this sample is $197.8^{+1.2}/_{-0.4}$ 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-

STAGE	STANDARD ZONE	NORTHWEST EUROPE (Standard subzone)	ALPS (Regional zone)	NEVADA (Local zone)	QUEEN CHARLOTTE IS. (Local assemblage)	SOUTH AMERICA (Regional zone)
HETTANGIAN	Angulata	16 Complanata	23 Marmorea	38 *Paracaloceras*	(Lower part) 45 Canadensis	57 *S. marmorea*
		15 Extranodosa		37 *S. sunrisense*	44 *P. doetzkirchneri*	56 *S. montana*
	Liasicus	14 Laqueus	22 Megastoma	36 *A. proaries*	43 *Franziceras*	55 *D. reissi*
		13 Portlocki		*Franziceras* 35		
				E. occidentalis	*Euphyllites* 42	
				P. mulleri 33		"*Curviceras*" 54
	Planorbis	12 Johnstoni	21 Calliphyllum	32 *P. polymorphum*	41 *Psiloceras*	53 *P. rectocostatum*
						52 *P. primocostatum*
		Planorbis 11		*P. pacificum* 31		*P. tilmanni* 51

Figure 6. Biochronologic correlation chart of Hettangian ammonite zonations proposed for key regions. Only approximate correlation is implied. Units are numbered to facilitate comparison with Figure 7. Compiled from the following sources: Northwest Europe—Dean et al. (1961); Alps—Wähner (1886); Nevada—Guex (1995); Queen Charlotte Islands—Tipper and Guex (1994); South America—Hillebrandt (1994).

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.

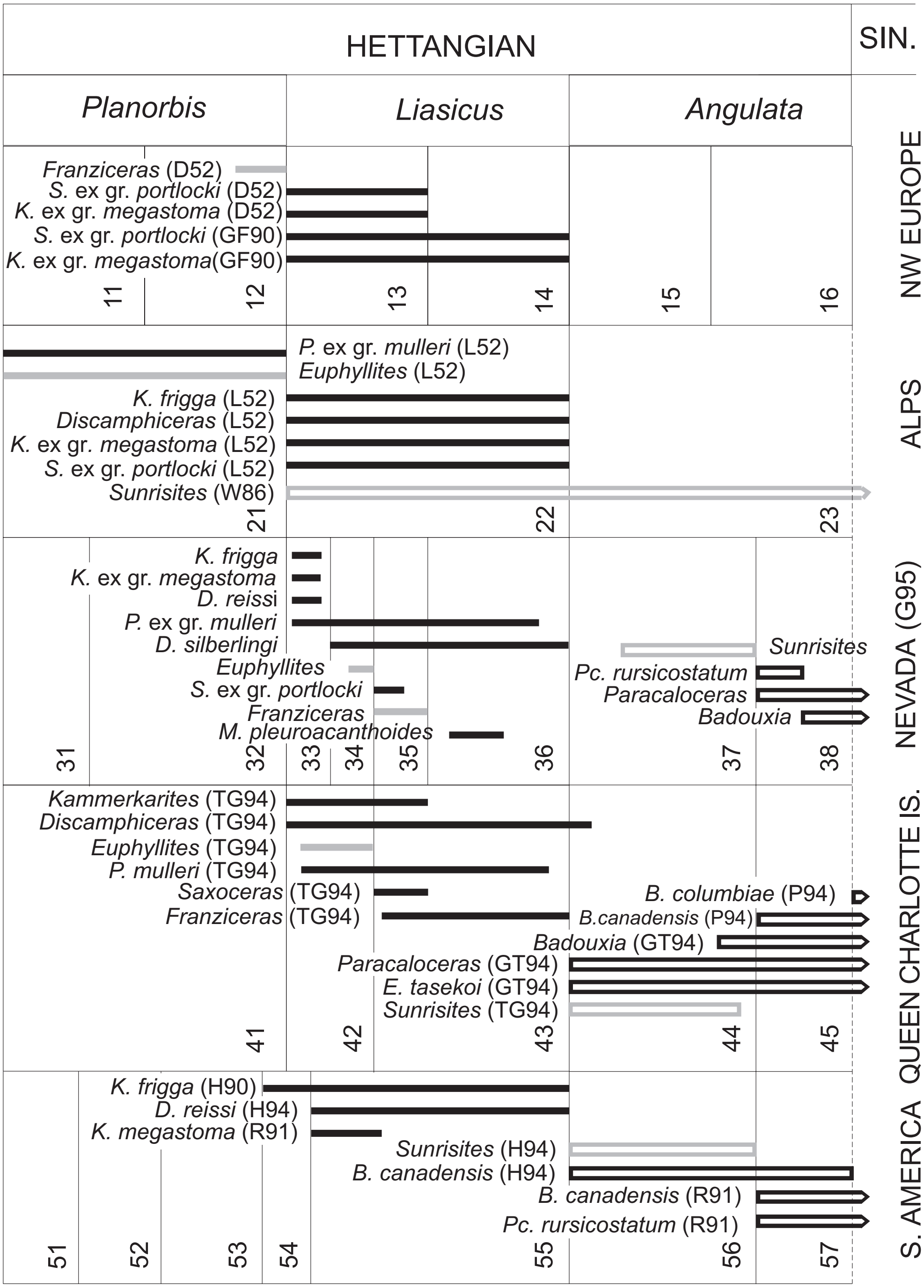

Figure 7. Ranges of Hettangian ammonite taxa known from Puale Bay as established in other regions. Numbered biochronologic units are the same as in Figure 6. All taxa listed in the taxonomic remarks (see Data Repository item 9980, and footnote 1) as included in the identified species groups are considered. 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); H94—Hillebrandt (1994); L52—Lange (1952); P94—Pálfy et al. (1994); R91—Riccardi et al. (1991); R93—Rakús (1993); TG94—Tipper and Guex (1994); W—Wähner (1882–1898).

TABLE 1. U-Pb ANALYTICAL DATA

Sample and fraction[†]	Wt (mg)	U (ppm)	Pb*[§] (ppm)	^{206}Pb[#]/^{204}Pb	Pb** (pg)	^{208}Pb[††] (%)	Isotopic ratios (±1σ %)[§§]			Calculated ages (±2σ Ma)[§§]	
							^{206}Pb/^{238}U	^{207}Pb/^{235}U	^{207}Pb/^{206}Pb	^{206}Pb/^{238}U	^{207}Pb/^{206}Pb
95JP1[†††]											
A [>134, N1, e+p+s, s-a]	0.175	233	7	9493	8	8.4	0.03124 ± 0.17%	0.2156 ± 0.16%	0.05006 ± 0.08%	198.3 ± 0.7	197.9 ± 3.6
B [>134, N1, e+s+t, s-a]	0.095	277	9	4331	12	8.9	0.03105 ± 0.10%	0.2147 ± 0.21%	0.05015 ± 0.12%	197.1 ± 0.4	202.2 ± 5.5
D [>134, N2, p+e, s-a]	0.143	261	8	7505	10	8.9	0.03206 ± 0.25%	0.2227 ± 0.29%	0.05038 ± 0.11%	203.4 ± 1.0	212.4 ± 5.0
E [<74, N1, n+e, m-a]	0.062	324	10	4360	9	10.1	0.03089 ± 0.10%	0.2136 ± 0.20%	0.05016 ± 0.12%	196.1 ± 0.4	202.4 ± 5.5
F [74-134, N1, n+e, m-a]	0.083	239	7	1868	21	9.4	0.03066 ± 0.11%	0.2117 ± 0.24%	0.05006 ± 0.15%	194.7 ± 0.4	198.0 ± 7.0
G [74-134, N1, p, s-a]	0.125	268	8	3787	17	9.1	0.03097 ± 0.16%	0.2144 ± 0.23%	0.05020 ± 0.13%	196.6 ± 0.6	204.3 ± 6.1
H [74-134, N2, p+e, s-a]	0.177	318	10	6776	16	9.5	0.03104 ± 0.11%	0.2149 ± 0.20%	0.05021 ± 0.10%	197.0 ± 0.4	204.8 ± 4.8
I [>134, N2, s-a]	0.111	245	7	3428	15	8.7	0.03091 ± 0.10%	0.2131 ± 0.19%	0.05000 ± 0.12%	196.2 ± 0.4	195.2 ± 5.6
J [74-134, N2, s-a]	0.054	308	9	1907	17	8.8	0.03044 ± 0.26%	0.2084 ± 0.38%	0.04964 ± 0.32%	193.3 ± 1.0	178.0 ± 14.8
95JP3[†††]											
A [>104, N5, p+eq, s-a]	0.026	295	9	2322	7	10.9	0.03122 ± 0.10%	0.2171 ± 0.18%	0.05044 ± 0.17%	198.2 ± 0.5	215.2 ± 9.3
B [74-104, N5, p+t, s-a]	0.043	193	8	2596	8	10.7	0.03997 ± 0.10%	0.3335 ± 0.22%	0.06051 ± 0.14%	252.7 ± 0.5	621.8 ± 6.1
C [<74, N5, ah+sh, s-a]	0.041	149	5	3050	4	11.0	0.03477 ± 0.11%	0.3160 ± 0.21%	0.06592 ± 0.13%	220.3 ± 0.5	803.8 ± 5.4
D [>104, N5, s-a]	0.004	306	10	257	10	11.3	0.03111 ± 0.19%	0.2124 ± 1.1%	0.04952 ± 0.97%	197.5 ± 0.8	172.7 ± 45
E [<104, N5, s-a]	0.006	472	32	1068	12	4.1	0.07033 ± 0.14%	0.6546 ± 0.36%	0.06750 ± 0.30%	438.2 ± 1.2	853.3 ± 12.3
95JP4[†††]											
A [74-134, N2, eq, n-a]	0.032	398	24	735	64	11.4	0.05727 ± 0.25%	0.5875 ± 0.36%	0.07440 ± 0.20%	359.0 ± 1.7	1052.3 ± 8.1
B [<74, N2, eq, sh, n-a]	0.045	239	15	1466	30	8.5	0.06274 ± 0.10%	0.6524 ± 0.22%	0.07542 ± 0.13%	392.2 ± 0.8	1079.6 ± 5.4
95JP5[†††]											
A [>134, N1, el+p, s-a]	0.121	98	3	2381	10	11.9	0.03119 ± 0.09%	0.2146 ± 0.23%	0.04990 ± 0.15%	198.0 ± 0.4	190.2 ± 6.9
B [>134, N1, p, s-a]	0.295	113	4	4253	15	11.6	0.03128 ± 0.09%	0.2160 ± 0.20%	0.05009 ± 0.12%	198.6 ± 0.4	199.3 ± 5.4
C [>134, N1, s+p, s-a]	0.381	88	3	3181	21	10.8	0.03112 ± 0.10%	0.2153 ± 0.21%	0.05017 ± 0.12%	197.6 ± 0.4	203.1 ± 5.7
F [>134, N1, p+el, s-a]	0.230	142	5	3457	19	11.8	0.03109 ± 0.12%	0.2150 ± 0.22%	0.05016 ± 0.12%	197.4 ± 0.5	202.5 ± 5.8
G [104-134, N1, p, s-a]	0.265	140	4	5162	14	11.7	0.03112 ± 0.11%	0.2152 ± 0.20%	0.05015 ± 0.11%	197.6 ± 0.4	202.1 ± 5.1
H [>134, N1, s-a]	0.165	113	4	2289	16	11.6	0.03079 ± 0.14%	0.2135 ± 0.26%	0.05030 ± 0.19%	195.5 ± 0.5	208.7 ± 8.6
I [104-134, N1, s-a]	0.104	102	3	990	21	11.5	0.03113 ± 0.14%	0.2149 ± 0.32%	0.05007 ± 0.24%	197.6 ± 0.5	198.2 ± 11.1

[†]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 (N) 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-a—non-abraded, l-a—lightly abraded, m-a—moderately abraded, s-a—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.

[††]Radiogenic Pb.

[§§]Corrected for blank Pb, U, and initial common Pb based on the Stacey and Kramers (1975) model at the age of the rock or the ^{207}Pb/^{206}Pb age of the fraction.

[†††]Location data: SE shore of Pulae Bay, Map Karluk C-4/5, Grid reference: 95JP1 – UTM 6400950N, 357630E; 95JP3 – UTM 6401320N, 357420E; 95JP4 – 6401300N, 357430E; 95JP5 – UTM 6401280N, 357440E.

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 *Kammerkarites*, *Saxoceras*, and *Franziceras* than found elsewhere. *Euphyllites*, if correctly identified, occurs above *Mullerites*. The succession of *Sunrisites*? and *Badouxia* 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 biochronology. Sample 95JP1 comes from within the lower fauna, i.e., it belongs in the middle Hettangian (Liasicus Zone equivalent). This thin tuff layer predates the onset of a major volcanic phase that is dated by the other three samples (95JP5, 95JP4, and 95JP3). They are not older than middle Hettangian (Liasicus Zone equivalent) and not younger than late Hettangian (Angulata Zone equivalent). The isotopic ages of the middle Hettangian and the middle or upper Hettangian samples overlap within error. Therefore the duration of these Hettangian ammonite zones cannot be directly estimated but were likely short.

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., 1994) used interpolation based on the equal duration of biochronologic units. This method is ill-suited for the period of biotic recovery following the end-Triassic mass extinction events. Smith (1990) demonstrated disparate zonal durations in the Hettangian using Milankovitch cyclicity. Accepting that the Planorbis Zone is not longer than average, the Triassic-Jurassic boundary is likely to fall in the 200–205 Ma interval. This estimate is younger than those in most current time scales with the exception of Odin's (1994) (Fig. 9). It is also compatible with the 201–202 Ma boundary age suggested for the Newark basin (Olsen et al., 1996b) through the integration of cyclostratigraphy (Olsen et al., 1996a), U-Pb dating (Dunning and Hodych, 1990; Hodych and Dunning, 1992), and palynostratigraphy (Fowell et al., 1994).

The presence of inherited Proterozoic zircon in the Talkeetna Formation is documented here for the first time. Five fractions in two of the

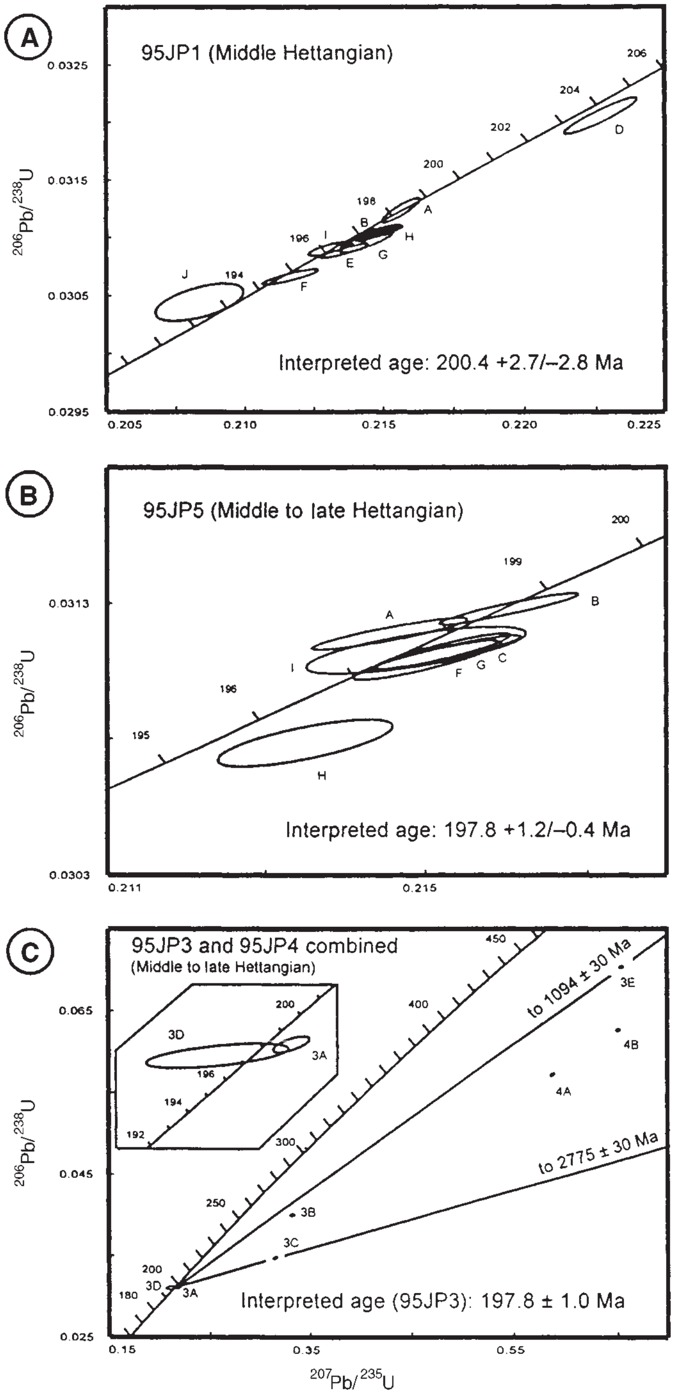

Figure 8. U-Pb concordia diagrams for samples from the Hettangian section at Puale Bay. (A) Sample 95JP1, middle Hettangian, crystal tuff from near the top of Kamishak Formation(?); (B) Sample 95JP5, middle to late Hettangian, tuff from the Talkeetna Formation; (C) Samples 95JP3 and 95JP4, tuff from the Talkeetna Formation.

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.

TABLE 2. COMPARISON OF IDENTIFICATIONS

This report	Imlay (1981)
Eolytoceras cf. *tasekoi*	—
Pleuroacanthites ex gr. *mulleri*	—
lytoceratid indet.	? *Psiloceras* cf. *P. planorbis*
Discamphiceras cf. *silberlingi*	*D.* cf. *D. toxophorum*
Discamphiceras aff. *reissi*	—
Euphyllites? sp.	? *Psiloceras* cf. *P. planorbis*
psiloceratid indet.	—
Kammerkarites? cf. *frigga*	*Waehneroceras* cf. *W. tenerum*
Kammerkarites ex gr. *megastoma*	—
Saxoceras? ex gr. *portlocki*	*Waehneroceras* cf. *W. portlocki*
Saxoceras? sp.	*Waehneroceras* cf. *W. portlocki*
Franziceras? sp.	—
—	*Schlotheimia* sp.
schlotheimiid indet.	—
Mullerites cf. *pleuroacanthitoides*	—
—	*Laqueoceras* cf. *L. sublaqueus*
Sunrisites? sp.	—
Badouxia canadensis	*Badouxia canadensis*
B. columbiae	—
Badouxia? sp.	—
Paracaloceras cf. *rursicostatum*	*Paracaloceras* cf. *rursicostatum*
Arnioceras arnouldi	*Arnioceras* cf. *A. densicosta*

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

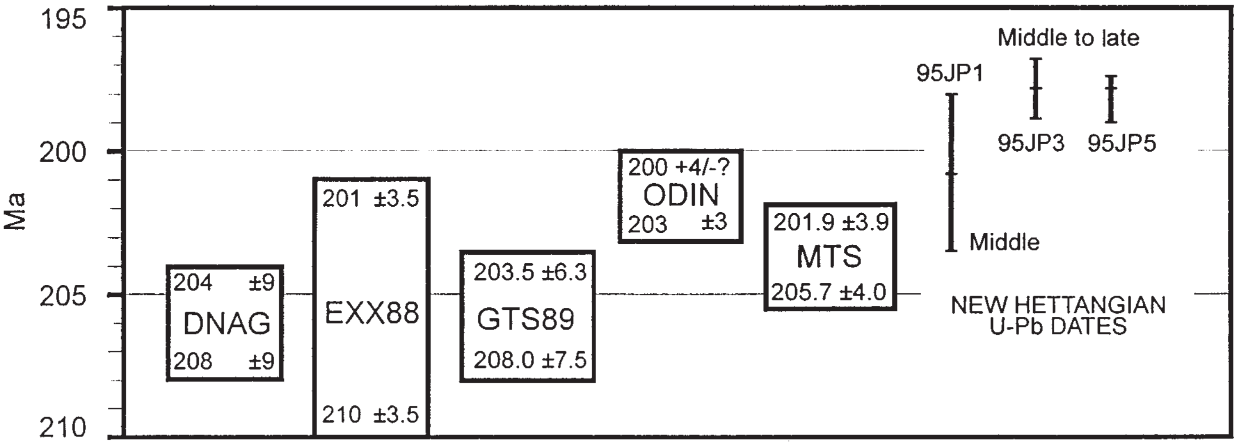

Figure 9. Comparison of Hettangian stage boundary age estimates in recent time scales and the new Hettangian U-Pb dates reported here. Sources of time scales quoted: DNAG (Kent and Gradstein, 1985; Kent and Gradstein, 1986; Palmer, 1983); EXX88 (Haq et al., 1987; Haq et al., 1988); GTS89 (Harland et al., 1990); Odin (Odin, 1994); MTS (Gradstein et al., 1994, 1995).

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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